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NON-LINEAR MATERIAL THREE DEGREE OF FREEDOM ANALYSIS OF
SUBMARINE DRYDOCK BLOCKING SYSTEMS

by

LIEUTENANT COMMANDER RICHARD DANIEL HEPBURN, U.S. NAVY

B.S. Ocean Engineering
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Submitted to the Department of Ocean Engineering in partial fulfillment of the requirements for the degrees of Naval Engineer and Master of Science in Naval Architecture and Marine Engineering.

ABSTRACT

U.S. Naval shipyards where submarines are drydocked are located in regions of the United States where significant earthquakes are known to occur. The graving dry docks at these shipyards are currently designed to withstand earthquake accelerations up to 0.26 g's. This thesis develops a non-linear material model for wood drydock block caps which more closely represents its actual behavior than linear elastic material models used previously. Using this non-linear model, it is determined that submarine drydock blocking systems would fail at even lower earthquake accelerations than that predicted by linear material models. This confirms that submarine drydock blocking systems would fail at accelerations which are significantly lower than the Navy's 0.2 g survival requirement.

New blocking materials are then analyzed using non-linear models developed in this thesis in order to determine their potential for increasing system survivability. The materials analyzed are natural rubber and dynamic isolators. It is determined that when these materials are incorporated in the blocking systems, significant increases in survivability occur; however, all the systems still fail well below the required 0.2 g level. This thesis makes it clear that the current submarine drydock blocking systems provide inadequate protection of the submarines from accelerations caused by highly probable earthquakes, but the use of new blocking materials can reduce the risk of blocking failure.

THESIS SUPERVISOR: Dale G. Karr, Ph.D.

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BIOGRAPHICAL NOTE

The author graduated from the United States Naval Academy with a Bachelor of Science Degree in Ocean Engineering in 1976. He served aboard the *USS Meyerkord* (FF-1058) as the Damage Control Assistant and Main Propulsion Assistant from 1977 to 1980. At Long Beach Naval Shipyard from 1981 to 1985, he first served as a ship superintendent for the overhauls of the *USS Kinkaid* (DD-965), *USS Tarawa* (LHA-1), and *USS Gridley* (CG-21). He then served as the shipyard Docking Officer for two and half years and drydocked many ships including the *USS Missouri* (BB-63). Finally, he served as the shipyard Production Engineering Officer before reporting to M.I.T. in June 1985.

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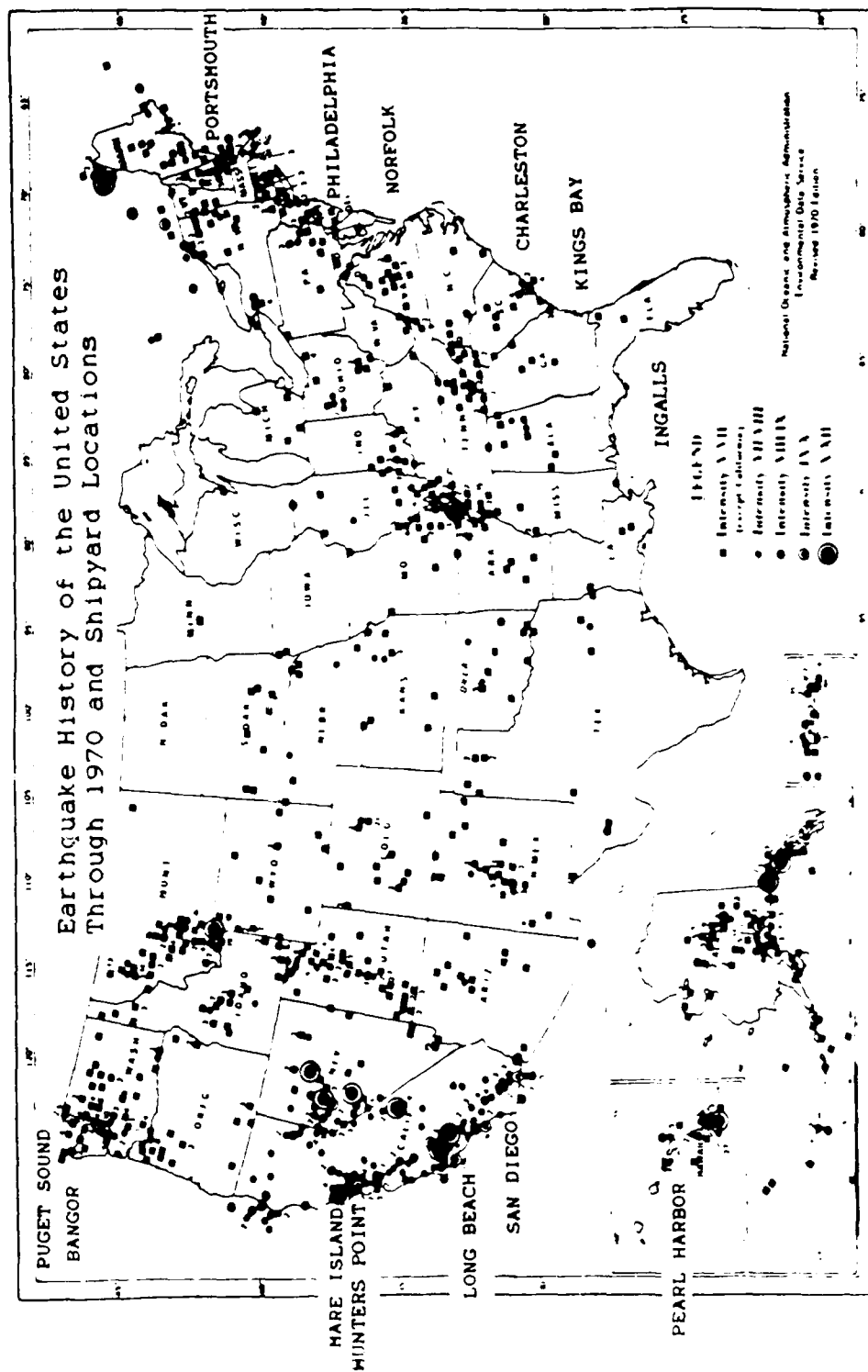
Chapter 1

INTRODUCTION AND DESCRIPTION OF THE EARTHQUAKE THREAT TO SUBMARINE DRY DOCK LOCATIONS

1.0 Introduction

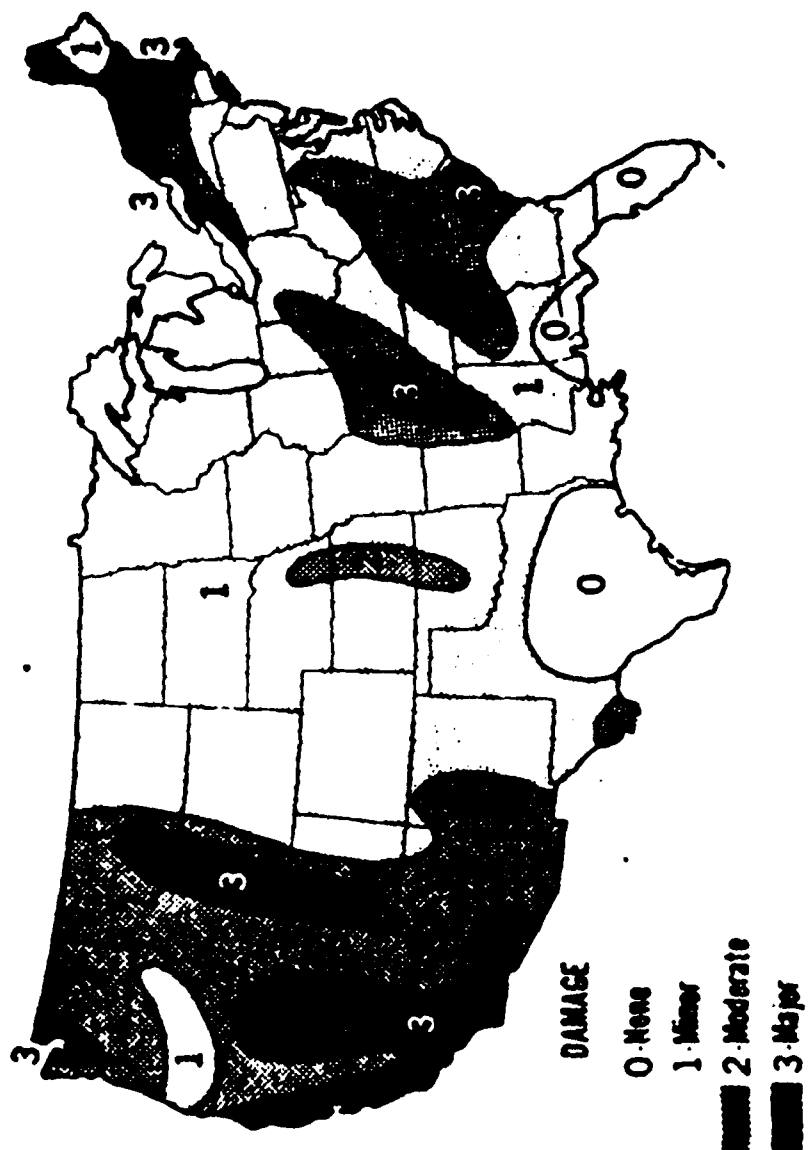
Currently submarines are routinely drydocked in graving docks at three locations on the west coast and five locations on the east coast of the United States. In addition they are drydocked in graving docks in Pearl Harbor, Hawaii. They also can be docked in graving docks and shiplift systems at many additional locations on both coasts if required. Graving docks are docks which have been dug out of the ground. Shiplift systems lift ships out of the water where they are then transported on a carriage assembly to a land based position. When a submarine is in one of these docks it is susceptible to any ground motion that may occur. Figure (1.1) [1] illustrates the locations where submarines can be placed in graving docks. This figure also indicates where earthquakes have historically occurred.

Shipyards, by their nature, need to be located along the coast. Unfortunately the locations of the west coast shipyards coincides with the areas of highest earthquake risk. Even on the east coast, earthquakes of significant magnitude have been known to occur where submarines now are drydocked.



Earthquake (Intensity VII and above) in the United States through 1970

FIGURE 1.1



Seismic risk map for conterminous United States.

FIGURE 1.2

Figure (1.2) [1] indicates the areas in the United States most susceptible to earthquakes. On the east coast, Portsmouth Naval Shipyard and Charleston Naval Shipyard are located in the highest risk zones.

1.1 Dry Dock Seismic Vulnerability

1.1.1 San Francisco Area

Mare Island Naval Shipyard is a submarine repair shipyard located on the northern tip of San Francisco Bay. The Bay itself was created by the motion of the San Andreas fault. San Francisco was built on this fault. The city experienced a devastating earthquake on April 18th 1906. 700 people died in this earthquake. Just south of San Francisco, the fault shifted 16 feet in one minute [2]. This magnitude 8.3 earthquake was one of greatest known shocks in California [1]. It was associated with the largest known length of slip (21 feet) along a fault plane in the contiguous United States. The damage was unevenly distributed due to subsurface conditions [1]. Chimneys remained standing which were mounted on rock. Buildings further away from the epicenter collapsed because they were constructed on land fill. Mare Island Naval Shipyard is also built on land fill.

On April 24th 1984 a 6.2 magnitude earthquake occurred at Morgan Hill, California which is about 45 miles south of Mare Island Naval Shipyard. It was the consequence of a sudden rupture along a 30 km segment of the historically active Calaveras fault. This was the third damaging earthquake to strike the San Francisco Bay region since 1979, and the largest event in the region since 1911. It produced many significant records of ground and structural shaking including the largest horizontal ground acceleration (1.29 g) ever recorded [3].

Six potential nuclear power plant locations were abandoned along the California coast due to their proximity to fault locations and vulnerability to earthquake motions [2]. However, nuclear powered ships are still drydocked in areas susceptible to earthquakes. Hunters Point in San Francisco is still used to drydock nuclear powered surface ships. It is located within 12 miles of the San Andreas fault.

1.1.2 Southern California Area

Long Beach Naval Shipyard is also located in an extremely vulnerable area. Long Beach, California experienced a major earthquake on March 10, 1933 seven years before the construction of the shipyard at Terminal Island. This earthquake measured 6.3 on the Richter Scale and caused

considerable damage and loss of life. The major destruction was in the thickly settled district from Long Beach to the industrial section south of Los Angeles where water-soaked alluvium and other unfavorable geological conditions combined with the presence of much poor structural work to increase the damage [1].

Since Long Beach Naval Shipyard was built, the ground in the shipyard has subsided over 20 feet due to oil being pumped out from the ground beneath the shipyard. The shipyard is located primarily on land fill which is known to be tremendously susceptible to earthquake damage. On October 1st 1987 an earthquake hit Whittier, California which is approximately 20 miles northeast of Long Beach. Initial reports indicated that this earthquake had a magnitude of 6.1 on the Richter Scale [4],[5], but was later downgraded to 5.9 [6]. Six people were killed and over 100 injuries were reported. Eight to ten buildings collapsed, hundreds of homes were damaged, and many buildings were declared unsafe. Local officials stated that most of the buildings that experienced damage were 30 to 40 years old and did not meet modern earthquake resistant structural requirements. Eyewitnesses indicated that the ground appeared to move back and forth up to two feet [2].

Long Beach Naval Shipyard had accelerographs located in graving dry docks 1 and 2. These devices all produced acceleration time histories for this earthquake. Significant motion was felt in the shipyard. The cruiser USS Leahy, which was in dry dock # 3, experienced side block shifting during the earthquake.

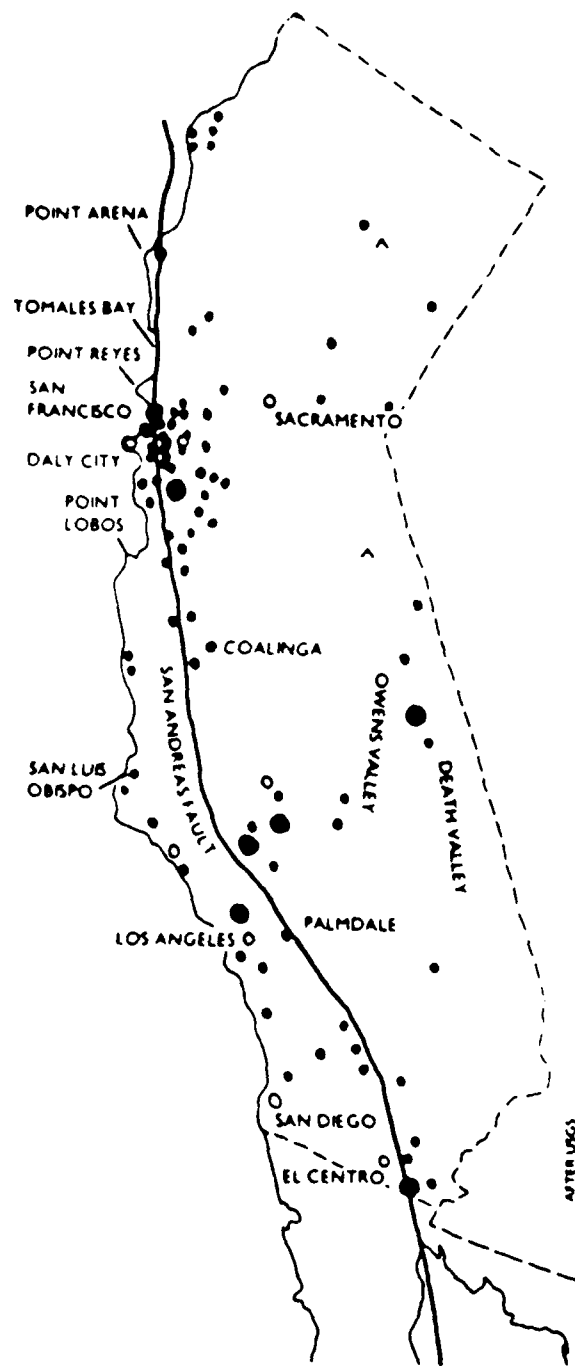
At least sixteen aftershocks occurred measuring greater than 3.0 near the epicenter within three hours. Major sections of freeway were closed due to structural cracks. 250,000 businesses and homes were without power after the earthquake. Over 100 strong motion records were made of the 1 October 1987 Whittier earthquake [7]. The largest ground acceleration measured was .45 g horizontal at 10 km from epicenter. The area south of the quake had relatively low shaking (0.2 g) though only 10 km from the epicenter. Many more distant stations had greater amplitudes.

Other areas in the United States which have graving docks and shiplift systems are vulnerable to earthquakes as is discussed in section 1.3.

1.2 California's Earthquake Potential

The Whittier earthquake epicenter was not located on the San Andreas fault but rather on the smaller Elsenor fault [8]. The San Andreas fault, figure (1.3) [9], is 650 miles long and 20 to 30 miles deep. The PBS series "The Making of a Continent" [2] describes the current geological events occurring on the west coast of the United States. The cause of the earthquakes in that region is due to the location of the coastal areas of California over a spreading center. This is causing the area to the west of the San Andreas fault to gradually shift northward relative to the rest of the continent. Earthquakes occur when this movement is resisted and slippage occurs along the fault. The magnitude of the earthquakes is proportional to the amount of slippage that occurs along the fault. The more time between fault slippage in a particular region the more strain energy is stored and the longer the fault slips when the break finally occurs. This geological scale "stick slip phenomena" causes devastating earthquakes.

The western portion of California from San Francisco Bay to the northern tip of the Gulf of California is on the Pacific Plate. This plate is moving northward at a rate of two inches per year relative to the North American plate along the San Andreas fault. There are many other faults in addition to this major fault in this region.



THE SAN ANDREAS FAULT

FIGURE 1.3

Areas in California which experience continuous small earthquakes may be in a safer condition. In the center of the San Andreas fault, the plates slip smoothly by each other at 3.5 cm's annually triggering no major quakes. But north and south of this region of "creep" plate edges are stalled, locked together by friction [10]. It is currently the southern portion of the San Andreas fault that is considered the most vulnerable to producing a major quake. Currently in an area along the fault near Palmdale, California approximate 13 feet of movement is stored up. When an earthquake occurs in this location and this energy is released, it will be on the order of 8.3 on the Richter Scale. This is the portion of the San Andreas fault which scientists have determined has a frequency of major earthquake occurrence of every 145 years. This earthquake will have the equivalent energy release of a 50 megaton hydrogen bomb [2].

The 1940 El Centro earthquake which had a magnitude of 7.1 on the Richter Scale actually shifted the United States border with Mexico 14'10". Parts of the San Andreas fault near Palm Springs, California have built up as much as 36 feet of stored strain energy. This portion of the fault has an earthquake frequency of one every 500 years [2].

According to a special report by the Emergency Task Force of the California Division of Mines and Geology certain areas of the Los Angeles basin are more vulnerable than others to the effects of a 8.3 magnitude earthquake with an epicenter near Palmdale [2]. Specifically, the cities of Santa Ana and Long Beach have very high potential for ground failure. The ground can behave like quicksand causing catastrophic damage to buildings even though they are 50 miles from the epicenter. Scientists believe that an earthquake of this magnitude in the Los Angeles area will cause "the greatest disaster in the United States since the Civil War" [2].

A Federal Emergency Management Agency Report scenario predicts that 3000 to 14000 people would be killed and 200,000 people would be left homeless in such an earthquake. There would be locally extensive damage to highways. Bridges and power lines would fall. Two of three main water aqueducts would be severed for six months [2].

The 1 October 1987 Whittier earthquake did nothing to relieve the pressure along the San Andreas fault. Dr. Bruce Bolt [8], a seismologist at the University of California at Berkeley said that the Whittier earthquake caused no change in the energy "locked in the rocks" of the San Andreas fault. He said "the Big One will come in the next twenty years".

PBS in December 1987 broadcast a documentary on the potential hazards of the San Andreas Fault. In that broadcast they mentioned that through carbon dating scientists can determine the frequency of past earthquakes. At a point along the San Andreas fault in Southern California, the fault was excavated and the past fault shifts examined. It was determined that the approximate frequency of major earthquakes on the southern portion of the this fault was 145 years. The last major earthquake to occur in this region was in 1857 (Ft. Tejon Earthquake). This earthquake occurred 125 years ago. Scientists feel that there is a very a good chance for another major earthquake to occur in this area in our lifetime. This same program quoted Mr. Alex Cunningham, Director of the California Office of Emergency Services, as saying "It is not a question of if but when the great earthquake will occur in Southern California." Mr. Cunningham stated that this earthquake in the Los Angeles region could occur tomorrow or any time in next 30 years.

The "Big One" is predicted to have a magnitude of about 8.3 on the Richter scale. This will be 800 times larger than the earthquake experienced in San Fernando in 1971. When the last major earthquake hit the Los Angeles area in 1857 only 11,000 people lived there. In 1988, well over 24 million people live in the Los Angeles region. The PBS program stated that a major earthquake in Los Angeles would be "a natural disaster without precedent in American history."

During the February 9th 1971 San Fernando, California earthquake 65 people died and there was more than \$500 million in damage in the Los Angeles area. The earthquake registered 6.4 on the Richter scale. There have been more than 4000 earthquakes in California since 1900. Eight earthquakes greater than 5.0 on the Richter scale have occurred in California in 1987 alone. Since the 1971 earthquake, freeway overpasses have been strengthened, building simulation studies conducted, and buildings such as the San Bernardino County building constructed on rubber isolators. Richard Eisner of the California Department of Emergency Services said it will take decades to strengthen the old buildings in the Los Angeles area so they can resist earthquake motion.

According to the U.S. Geological Survey [1], the San Fernando earthquake injured over 2000 people. Thousands of homes and businesses sustained appreciable damage and hundreds of them had to be abandoned. 174 aftershocks of magnitude 3.0 or greater were recorded. Two of these shocks were magnitude 5.8. The record from the main shock revealed the highest acceleration ever measured to date (1.25 g horizontal and .72 g vertical).

1.3 Earthquake history in other areas of the United States

Other significant earthquakes that have occurred in recent history near Navy graving docks and ship lift systems are as follows:

On April 13th 1949 a magnitude 7.0 earthquake occurred in Olympia, Washington about 36 miles south of the now Puget Sound Naval Shipyard (Bremerton) [1]. On April 29th 1965 a magnitude 6.5 earthquake occurred near Seattle, Washington about 18 miles from Bremerton. Both caused heavy property damage over a wide area of Washington and Oregon. Buildings which apparently had been damaged in 1949 incurred additional damage in 1965 [1].

On November 29th 1975 a magnitude 7.2 earthquake occurred in Honokaa, Hawaii 184 miles from Pearl Harbor Naval Shipyard. This was the largest earthquake in Hawaii since 1868. It was felt in Oahu where the shipyard is located.

Franklin Falls Dam, New Hampshire, 55 miles west of Portsmouth Naval Shipyard, experienced a 4.5 magnitude earthquake January 19th 1982. The maximum horizontal acceleration recorded was .52 g's [11].

New England experiences three to five earthquakes every year [4]. The last major earthquake occurred on November 18th 1755 at Cape Ann, Massachusetts which is approximately 40 miles south of Portsmouth, New Hampshire. It had a magnitude of approximately 6.0 on the Richter scale. The shock was felt from Chesapeake Bay to Nova Scotia. In Boston, walls and chimneys were thrown down. Waves like the swelling of the ocean were reported on the surface of the earth. Many people on vessels felt shocks like the ships were striking bottom [1]. The amount of earthquakes that New England experiences in 150 years California experiences in 1 year. Although east coast earthquakes are more infrequent, due to the more homogeneous geological conditions, earthquakes are more widely felt when one occurs.

A major earthquake occurred August 31st 1886 fifteen miles northeast of Charleston, South Carolina. A series of severe shocks left more than 60 dead and many more injured. There was serious property damage. Much of Charleston was built on land fill which contributed to the damage. Earth waves similar to ocean ground swells were seen. They were estimated to be two feet high in certain places. There were severe flexures of railroad track. The area of severe effect was large. Within an area of 100 miles the destruction would have been severe but settlements were few and far between [1].

Between December 1811 and February 1812, three extremely large earthquakes (greater than 8.0 in magnitude) devastated New Madrid, Missouri which is 380 miles north of where Ingalls Shipbuilding is located today. These earthquakes, the largest of which was magnitude 8.6, are among the greatest earthquakes in known history. Topographic changes occurred over an area of 30,000 to 50,000 square miles. The total area shaken was over 2,000,000 square miles as shown in figure (1.4).

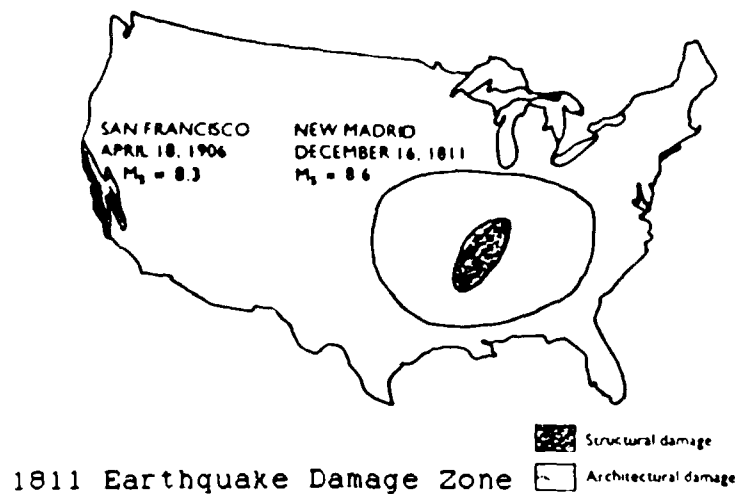


Figure 1.4

The direction of the Mississippi River was changed for a period of time due to this earthquake. For several days following the final earthquake the earth was in constant tremor. After shocks lasted for two years. The shock was felt from Canada to New Orleans, Louisiana and as far east as

Boston, Massachusetts 1100 miles away. The shock was felt distinctly in Washington D.C. and people were badly frightened. Fissures were created that were up to 500 feet long and 20 feet deep.

1.4 The Earthquake Challenge

As has been shown, earthquakes can occur virtually anywhere in the United States where submarines can be drydocked. They can produce tremendous forces and ground displacements which seriously threaten the safety of drydocked submarines.

Earthquakes usually occur without any warning. They reach maximum strength within seconds. It is impossible to take precautions such as an emergency undocking. Presently there is no reliable means of predicting the occurrence of earthquakes. Therefore, if submarines are to continue to be drydocked in earthquake high risk areas the drydock blocking systems must be designed to resist expected earthquake excitation [12].

CHAPTER 2

SUBMARINE DRYDOCK BLOCKING SYSTEM ANALYSIS HISTORY

2.0 Background

The major objective in the design of the docking block arrangements for Navy ships is to provide blocking systems which are adequate to support the ship's weight and to survive earthquake motions up to an intensity which will destroy the dock itself. Presently, these design methods involve approximating the seismic response by using a specified horizontal acceleration, the magnitude of the peak acceleration being 0.2 g. The potential for overturning, sliding, or crushing of the blocking system is then assessed on an "equivalent static" basis with a horizontal force applied at the ship's center of gravity.

A more rigorous examination of the seismic response of submarines was undertaken by B. V. Viscomi (1981) [13] using a dynamic equation of motion. This analysis involved determining peak ground accelerations which would cause the submarine to lift off one set of side blocks for a variety of blocking arrangements. The submarine was considered to be a rigid body with a single (rotational) degree of freedom. The docking blocks were thus necessarily assumed to be stable and to respond elastically to load.

Using the quasi-static method it was found that present drydock blocking systems could survive an earthquake of the magnitude of the 1940 El Centro earthquake (0.45 g peak acceleration). However, studies conducted at MIT under the direction of Professor Karr analyzing the problem using one degree of freedom (Karr,1985) [14], two degree of freedom (Barker,1985) [15], and three degree of freedom (Sigman,1986) [16] models indicated that failure would occur at substantially lower earthquake magnitudes.

This significant discrepancy warranted further examination and verification. Each of the governing differential equations of motion used for the one, two, and three degree of freedom models were rederived and confirmed correct. More precise drydock block stiffnesses were calculated using accurate block dimensions and block numbers obtained from the submarine docking plans. This block information was then input into drydock block stiffness calculation spreadsheets (Hepburn & Luchs,1986) [17].

It was verified that the computer code correctly calculated the solutions to the equations of motion. Specifically, in the three degree of freedom case, the Fourth Order Runge-Kutta method used for solving the non-linear, coupled, system of second order differential equations was found to be correct. All eleven submarine drydock block

systems studied, including four submarine classes (SSBN 616, SSBN 726, SSN 688, and SSN 637), were then analyzed using the updated programs and data files.

The results from the one, two, and three degree of freedom computer runs indicated that the eleven submarine systems could withstand approximately 13 to 25 percent of the El Centro Earthquake ground motion amplitudes. This range is slightly lower than that determined by Sigman and is a worse condition. The one, two, and three degree of freedom models gave very similar results which helped to verify the validity of each method, especially since the one and three degree of freedom methods were based on a totally different method of solution. However, a two or three of degree of freedom method is required to determine the exact blocking system failure modes. The four modes of failure of the blocking system addressed were:

- (1) Crushing of the keel and bilge blocks.
- (2) Sliding of the block interfaces.
- (3) Overturning of the blocks.
- (4) Lifting off of the ship from port or starboard side blocks or keel blocks.

For all the blocking systems, the dynamic analysis indicated failure at lower earthquake magnitudes than would be indicated by the quasi-static approximations. Detailed descriptions of the analysis and findings of one, two, and three degree of freedom response of submarines are discussed in the "Docking Under Seismic Loads Final Report" (Karr, 1987) [18].

2.1 Thesis Outline

The purpose of this thesis is to investigate the effects of incorporating the non-linear properties of existing and potential blocking materials into the three degree of freedom model. This study includes the procedures used in determining blocking material stiffness, damping, and frictional characteristics.

Chapter 3 summarizes the results of previous research using linear blocking materials. The computer program used in this research to determine system response is described. Chapter 4 investigates existing and potential blocking material non-linear characteristics such as stress-strain behavior, damping, and anisotropic properties. In addition, chapter 4, describes how the stiffnesses were determined for multi-layered blocking piers.

Chapter 5 examines the properties of the wood material currently being used in blocking systems. Specific characteristics of Douglas fir and oak are discussed. Results of drydock block compressive tests are used to model wood as a bilinear stiffness material. A computer program subroutine is developed to include this bilinear characteristic of the wood in the main three degree of freedom model.

Rubber is evaluated in chapter 6 as a potential blocking material. Compressive test data is also used to model rubber as a different type of bilinear stiffness material. Another computer program subroutine is developed to include this behavior in the main program.

Chapter 7 describes the use of dynamic isolators in the blocking system. The isolators' horizontal bilinear behavior is incorporated into the main three degree of freedom program using the same bilinear subroutine used for wood. The isolators' physical characteristics and previous applications are described.

The original eleven systems evaluated in previous research are reexamined in chapter 8 taking into account the non-linear properties of the wood and rubber actually used in these systems. Chapter 8 then compares the results of the non-linear material analysis to previous linear material models. In chapter 9, conclusions are drawn and recommendations are made for further study in this area.

2.2 Description of the Three Degree of Freedom System and Equations of Motion

The three degree of freedom model of the submarine drydock blocking system at rest as developed by Sigman (1986) [16] is shown in figure (2.1). This is the system used as a baseline for this thesis. This figure is a two dimensional representation of the submarine and dry dock with the keel and side block piers modeled as horizontal and vertical springs and dashpots.

The point CG_1 , figure (2.1) is the initial location of the center of gravity of the submarine. The point K is the initial location of the keel of the submarine. The point K' , insert figure (2.2), is the location of the keel after horizontal and vertical translation has occurred, rotation occurs about this point. KG is the distance from the keel to the center of gravity. The distance b_r is the transverse distance between the center of the caps of the port and

starboard side blocks. The horizontal and vertical spring constants are as designated in the figure.

The system is excited by horizontal and vertical drydock accelerations $\ddot{x}_0$ and $\ddot{y}_0$ respectively. The entire dry dock and submarine system moves relative to a fixed reference frame. The excited system is shown in figure (2.2). The system of equations are expressed in terms of motion of the submarine relative to the dry dock. Motion in the longitudinal, z direction, is ignored.

The point CG2, figure (2.2), is the location of the center of gravity of the submarine relative to the fixed reference frame after horizontal displacement u and vertical displacement v . The point CG3 is the location of the submarine's center of gravity after the additional absolute rotation θ . The insert at the bottom of figure (2.2) is a close up of the keel area of the submarine during this motion. The displacements illustrated are described as follows:

The relative horizontal displacement coordinate x is the displacement of the submarine keel with respect to the dry dock. The displacement u is the position of the keel relative to the fixed reference frame. With ground motion x_0 the following equations hold:

$$\begin{aligned}
 x &= u - x_0 \\
 u &= x + x_0 \\
 \ddot{u} &= \ddot{x} + \ddot{x}_0
 \end{aligned}
 \tag{2.1}$$

Similarly for vertical translation the following equations hold:

$$\begin{aligned}
 y &= v - y_0 \\
 v &= y + y_0 \\
 \ddot{v} &= \ddot{y} + \ddot{y}_0
 \end{aligned}
 \tag{2.2}$$

The coupled non-linear three degree of freedom equations describing the system motion as developed by Sigman are as follows:

$$M\ddot{x} + M\overline{KG}\ddot{\theta} + C_1\dot{x} + C_{10}\dot{\theta} + (2khs+kxk)x = -M\ddot{x}_0 \tag{2.3}$$

$$M\ddot{y} + C_2\dot{y} + (2kvs+kvk)y = -M\ddot{y}_0 \tag{2.4}$$

$$\begin{aligned}
 I_p\ddot{\theta} + M\overline{KG}\ddot{x} - M\overline{KG}\ddot{y}\theta + C_3\dot{\theta} + C_{30}\dot{x} + [(br^2/2)kvs \\
 -WKG] \theta = -M\overline{KG}\ddot{x}_0
 \end{aligned}
 \tag{2.5}$$

The diagram shows a mechanical system with a central mass M and a central spring K_G . The mass is connected to two fixed supports (indicated by hatched areas) via two parallel branches. Each branch contains a spring K_{VS} in series with a spring K_{HS} . The displacement of the mass is denoted by x_G (horizontal) and y_G (vertical). The distance between the two supports is labeled br . The central spring K_G is connected to the mass at point K and to a fixed support at point G . The springs K_{VS} and K_{HS} are connected to the mass at points K and K_{HS} respectively, and to fixed supports at points V and H respectively.

FIGURE 2.1

Three Degree of Freedom Submarine Drydock Blocking System Model Excited

Diagram illustrating the Three Degree of Freedom Submarine Drydock Blocking System Model Excited. The diagram shows a cross-section of a submarine hull supported by a central vertical column and two side columns. The central column is connected to the hull via a spring K and a damper hvs . The side columns are connected to the hull via springs Khs and dampers hvs . The hull is excited by a horizontal force Xg and a vertical force Yg . The center of gravity is $CG1$, and the center of buoyancy is $CG2$. The angle of heel is θ . The diagram also shows a detailed view of the central column and the hull's internal structure, including the keel and the blocking system. The diagram is labeled "SEE INSERT BELOW".

FIGURE 2.2

FIGURE 22

In equations 2.3 through 2.5, M is the mass of the submarine, I_k is the rotational moment of the submarine about the keel, and W is the weight of the submarine.

In order to solve these differential equations Sigman (1986) [16] used the fourth order Runge Kutta method and computed the solutions using a Fortran program. The damping coefficients were calculated in the program using the modal analysis method. The program includes several flags which identify various failures of the submarine drydock blocking system and are listed in section 2.0. This computer program with the failure modes is utilized as a baseline program for this thesis. The program is modified to include material properties. These changes are discussed later.

CHAPTER 3

SUMMARY OF PREVIOUS RESEARCH USING LINEAR MATERIALS AND SIMPLE GEOMETRY

3.0 Description of Systems Analyzed

The eleven typical submarine drydock blocking systems used by Sigman (1986) [16] are the baseline systems for this thesis. The submarine drydock blocking parameters corresponding to each system and the appropriate Naval Sea Systems Command (NAVSEA) docking drawings are shown in Table 3.1.

TABLE 3.1

SUBMARINE DRYDOCK BLOCKING SYSTEMS

SYSTEM #	HULL #	BLOCK TYPE	LONGITUDINAL SPACING	NAVSEA DRAWING #
1	616	COMPOSITE	8 FT	8452006640
2	616	COMPOSITE	16 FT	8452006640
3	616	TIMBER	8 FT	8452006640
4	616	TIMBER	16 FT	8452006640
5	616	TIMBER SIDE COMPOSITE KEEL	16 FT	8452006640
6	726	COMPOSITE	8 FT	8454862749
7	726	COMPOSITE	12 FT	8454862749
8	726	COMPOSITE	16 FT	8454862749
9	688	COMPOSITE SIDE TIMBER KEEL	12 FT	8454403511
10	637	COMPOSITE SIDE TIMBER KEEL	12 FT	8452140554
11	637	COMPOSITE SIDE TIMBER KEEL	16 FT	8452140554

Composite is the term used to describe a "standard" Navy drydock blocking pier which consists of concrete blocks and wood layers. The concrete block dimensions are usually 42 inches wide and 48 inches long. Its height can range from 30 to 60 inches. A six inch oak cap is attached to the top and bottom of this block and is included in its dimensions. On top of the concrete block is a layer of oak with a two to four inch cap of Douglas fir. The Douglas fir is used to protect the hull from stress concentrations due to slight hull discontinuities.

A timber pier uses no concrete. Oak is used from the dock floor to the cap. A pier is the block layer arrangement required for one side block or one keel block. Keel piers are normally butted together (cribbed) along the entire length of the keel. Longitudinal spacing is the longitudinal distance between the side block caps along the hull.

3.1 Assumptions Used in Barker's and Sigman's Analyses

Barker (1985) [15] and Sigman (1986) [16] assumed that all of the blocking materials were linear, elastic, and isotropic. Because small deformations were expected the side block and keel block heights were assumed to be the same (60 inches in all cases); therefore, horizontal and vertical blocking stiffnesses were completely uncoupled. The actual

height of the side blocks above the keel baseline was also not taken into account when calculating sliding forces.

The submarine was assumed to be a rigid body. The mass of the blocks was neglected. Five percent critical damping was used throughout. The model was assumed to be valid as long as the drydock blocks remained rigidly attached to the dock floor, the blocks did not slide, and the submarine remained in contact with all the blocks. Whenever any of these conditions broke down the computer program flagged the condition as a failure.

3.2 Results of Sigman's Analysis

All of Sigman's [16] results were based on an excitation by the 1940 (0.45 g) El Centro earthquake acceleration time history. These accelerations were applied at the base of the dry dock, and coupling of the ground and dock floor was ignored. The El Centro earthquake records are used throughout the civil engineering community as a standard for structural design. Figure (3.1) is a plot of the first twenty seconds of the acceleration time history used by Sigman in his analysis.

1940 EL CENTRO EARTHQUAKE

ACCELERATION TIME HISTORY

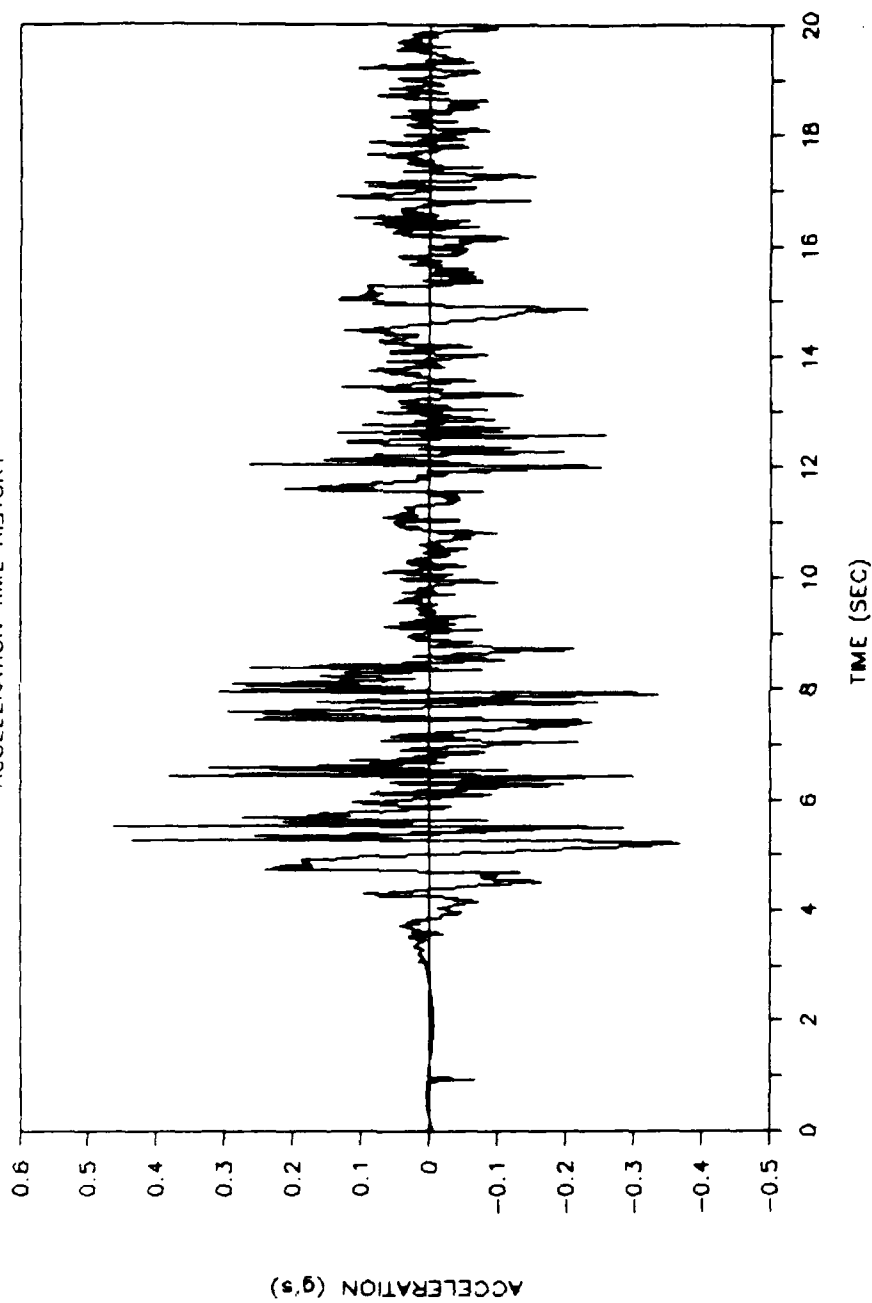


FIGURE 3.1

Upon analyzing the submarine drydock blocking systems, Sigman found that all eleven systems failed well below the 0.2 g peak acceleration requirement as set forth in NAVSEA Technical Manual 997 [19]. All eleven systems failed by side block liftoff. Survival ranged from 0.06 to 0.18 g's, as determined by the computer program described section 3.3. The graving docks at Long Naval Shipyard and Mare Island Naval Shipyard are designed to withstand a peak of acceleration of 0.26 g's before construction joint failure occurs [20]. Sigman's analysis shows that current submarine drydock blocking systems will fail well prior to the dry dock itself. His analysis also showed that the quasi static method currently used by the U.S. Navy for seismic response analysis seriously underestimates the forces the systems will experience. This unsatisfactory condition is the motivation for the research conducted in this thesis.

Figure (3.2) illustrates the survival percentage of the eleven submarine systems subject to the 1940 El Centro Earthquake. Included in this figure is the line above which dry dock failure would occur. This clearly illustrates that inadequacy of current blocking system design.

SIGMAN'S SURVIVAL PERCENTAGES

SUBMARINE SYSTEMS 1-11

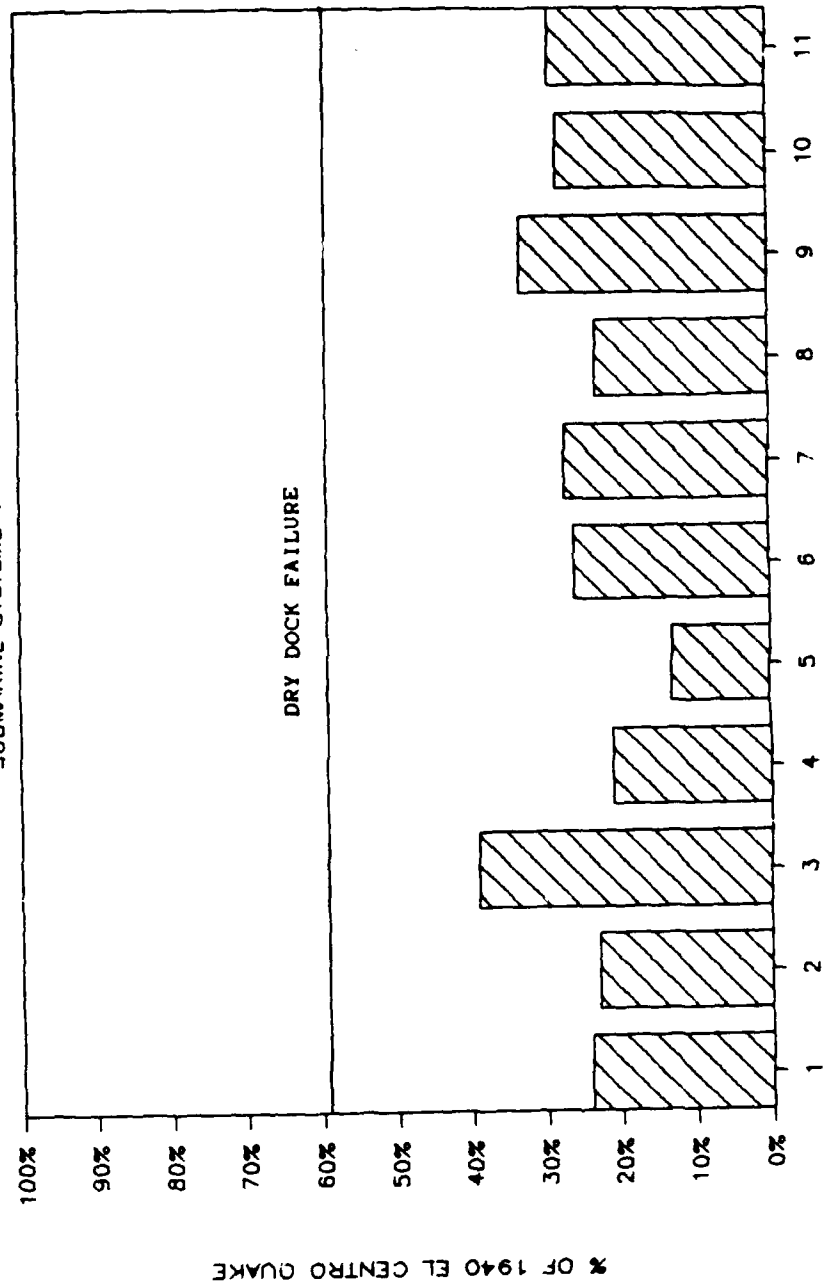


FIGURE 3.2

3.3 Description of the Computer Program Used in This Thesis

The computer program used to analyze the submarine drydock blocking systems in this thesis was developed jointly with Luchs [21] and is based on the program developed by Barker [15] and Sigman [16]. The most significant modifications with respect to this thesis made to this program included the addition of subroutines to incorporate non-linear stiffnesses of blocking materials. Two specific subroutines were developed to model the materials. They were the "BILINALL" and "RUBBER" subroutines which are described later. The main program and subroutine listings are included in Appendix 1.

The main program called "3DOFRUB" first reads submarine drydock blocking system parameters from a data file. It then calculates system's modal masses, stiffnesses, and natural frequencies. Modal analysis is used to determine damping coefficients using the specified percent critical damping. The horizontal acceleration time history (and vertical if applicable) are input from data files. Variables and flags are initialized.

The main loop of the program then begins. This loop implements the Runge-Kutta equations. The appropriate blocking material stiffnesses are recalculated each time step. Based on the blocking material input data the appropriate

subroutines are used by the program to calculate their stiffnesses.

Each time step, keel and side block forces are calculated. Then the system is tested for failure and the appropriate failure modes are flagged. The program begins by using 100 percent of the input acceleration time history. If failures occur, it carries out repeated loops through the whole history each time decreasing the input acceleration. This continues until the system survives a complete loop through the time history. In order to speed up the processing, the acceleration time history are limited to 2000 inputs which, for most records, means twenty seconds of the earthquake. For most earthquakes this captures the worst portion of the excitation and is considered adequate for design purposes. Finally, the program output includes displacements, failure modes, and times of failures for each percent of the earthquake acceleration tried. In addition, force and displacement data files are created as chosen by the user for use in plotting system response. A sample input data file and output file are also included in Appendix 1.

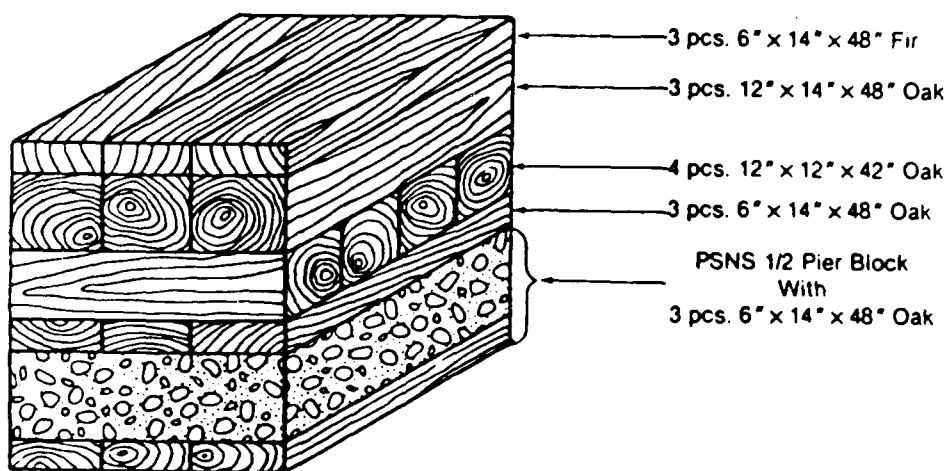
CHAPTER 4

EXISTING AND POTENTIAL BLOCKING MATERIAL CHARACTERISTICS AND PROPERTIES

4.0 Existing Blocking Materials

Virtually all U.S. Naval shipyards and private yards which dock U. S. Navy ships use soft and hard woods as drydock blocking materials. Concrete is used in the base of most of the blocking piers; however, the wood products comprise the upper portion of the blocking system which is in contact with the ship. A drawing of a typical Navy composite keel block is illustrated in figure (4.1) [22]. The soft wood is used in a "soft cap" (2 to 6 inches) on top of the hardwood to protect the hull from stress concentrations.

Previous analyses assumed that all the blocking materials were linear, elastic, and isotropic. While these are reasonable assumptions for concrete, that is not the case for wood. Typically the soft wood used in drydock blocking systems is Douglas fir or woods of similar properties. The hard wood used is usually white oak or similar hard woods. The capping and hard wood materials that shipyards receive from their suppliers have highly variable properties.



57" BUILD-UP

Typical Navy Composite Keel Block

FIGURE 4.1

4.1 General Wood Properties

4.1.1 Variation in Wood Types

When a drydock blocking system is constructed by a shipyard, either new wood just obtained or old wood on hand is used. This applies to the soft cap and hard wood portions of the system. Sometimes new wood is combined with old wood in random ways in the same blocking pier.

The wood received from suppliers comes from various cuts from trees. Sometimes the cuts include the "boxed heart" (center pith material) of the wood where properties of the wood vary widely. Sometimes the grain of the wood in the timber is primarily horizontal or vertical depending on the location of the cut. The wood used comes from various parts of the country; therefore, the moisture contents and ring sizes and thus strength properties of the wood vary dramatically. Therefore, blocking piers in use today for drydocked submarines contain materials which have uncertain characteristics.

Panshin [23] found that for temperate zone woods, the portion of the timber formed in the early part of the growing season has larger cells and relatively lower density than that formed in the later season. This part is called the early wood and the denser and usually darker wood formed in the last

part of the growing season is called late wood. The transition between the early and late wood may be gradual or abrupt giving rise to differentiations between certain hard woods and between ring-porous and diffuse-porous hardwoods.

Panshin also states that wood produced by trees of the same species is often mistakenly assumed to be identical in all structural and physical characteristics. In fact, different specimens of wood even from the same tree are never identical and are similar only within broad limits.

4.1.2 Anisotropic Properties of Wood

A material which has physical properties which depend upon direction is said to be anisotropic. The cell wall in wood exhibits definite anisotropy because of the structural organization of the materials composing it. According to Panshin (1980) [23], the nature of the thin walled tubular cells in wood and their arrangement with respect to the axis in the stem contributes to this nonuniformity. As a consequence, compressive, tensile, and shear strengths vary widely between the longitudinal and lateral directions of wood.

Bach (1968) [24] describes non-linear wood properties as follows:

"The structural anisotropy of wood is a recognized factor that determines its elastic stress-strain relations. Wood cut from near the bark of mature trees has approximately orthotropic symmetry which requires nine elastic constants (3 Young's moduli, 3 shear moduli, and 3 Poisson's ratios) to define its response to generalized stress. In turn, the nine elastic constants for a given wood specimen are functions of time, moisture content, temperature, and stress history."

For this thesis wood is assumed to be an orthotropic material having different properties in each of three principle directions. These three directions are shown in figure (4.2) [25] below.

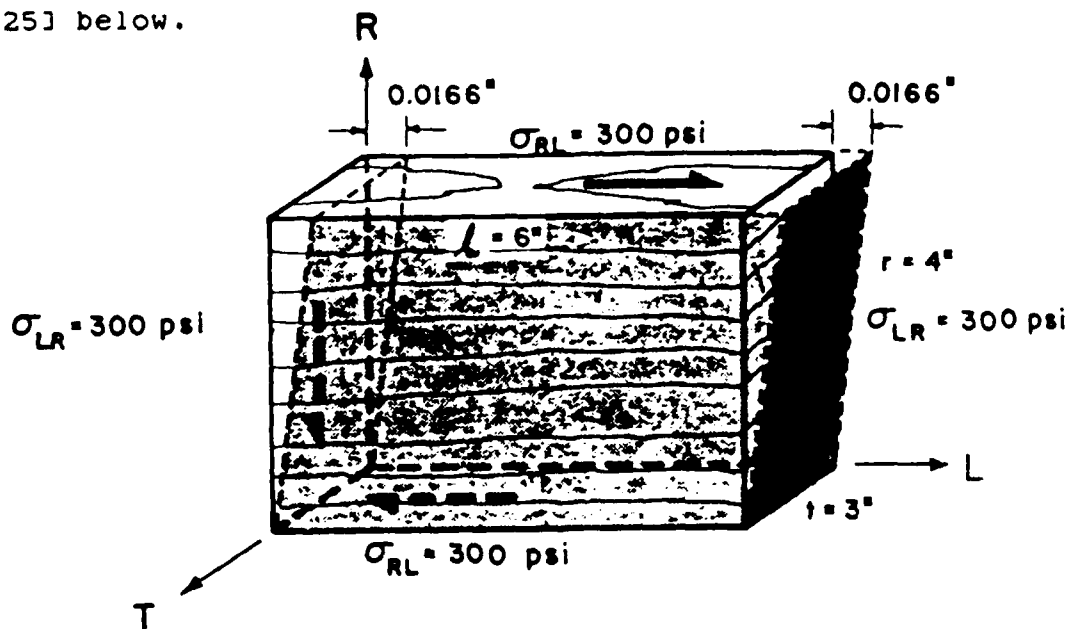


FIGURE 4.2

Distortion of a wood block caused by shear stress σ_{RL} (σ_{LR}).

The three principle directions shown in figure (4.2) are tangential, T, longitudinal, L, and radial, R. The modulus of elasticity of wood perpendicular (tangential) to the grain is designated as E_T . The modulus of elasticity in the longitudinal direction is E_L , and the modulus of elasticity in

the radial direction is E_R . G_R is the modulus of elasticity, also called the modulus of rigidity, due to shear, τ_{LR} in the plane LR as shown in figure (4.2).

Bodig (1983) [25] states that the ratios of the three moduli of elasticity for wood vary with species, moisture content, temperature, rate of loading, and a number of other variables. In spite of the many sources of variation, in general the moduli are approximately related according to Bodig by the following ratios:

$$E : E_R : E_T \quad 20 : 1.6 : 1 \quad (4.1)$$

$$E : G_R \quad 14 : 1 \quad (4.2)$$

The Wood Handbook's [26] number for $E/G_R = 13.68$.

A simple relationship for shear strain of wood subject to shear stress, τ_{LR} , is described by Bodig as follows:

$$\gamma_{LR} = \tau_{LR} / G_R \quad (4.3)$$

4.1.3 Strength Variations in Wood

Panshin (1980) [23] states that wood is 4 to 12 times stronger in compression parallel to the grain than it is perpendicular to the grain. Figure (4.3) [23] is a graphic representation of the actual variation for compression

strengths as the angle between grain orientation and direction of load application varies (1) from parallel to perpendicular to the grain and (2) between the radial and tangential directions with respect to the growth rings. This figure is for a species of Scotch pine.

Most wood products literature lists compressive strengths and moduli in the parallel direction for major wood species. The compressive strength is a measure of the ability of a piece to withstand loads in compression parallel to the grain up to the point of failure. Because of the submarine drydock blocking systems' geometry, loads vary from perpendicular to parallel; therefore, the wood blocking material strengths and moduli were varied appropriately using figure (4.3).

Specific gravity of wood, according to Panshin [23], because it is a measure of the relative amount of solid cell wall material is the best index for predicting strength properties of wood. He also mentions that the specific gravity of wood depends upon: (1) the size of the cells, (2) thickness of the cell walls, (3) the interrelationship between the number of cells of various kinds in terms of (1) and (2).

Compressive Strength of Wood at Various Grain Angles

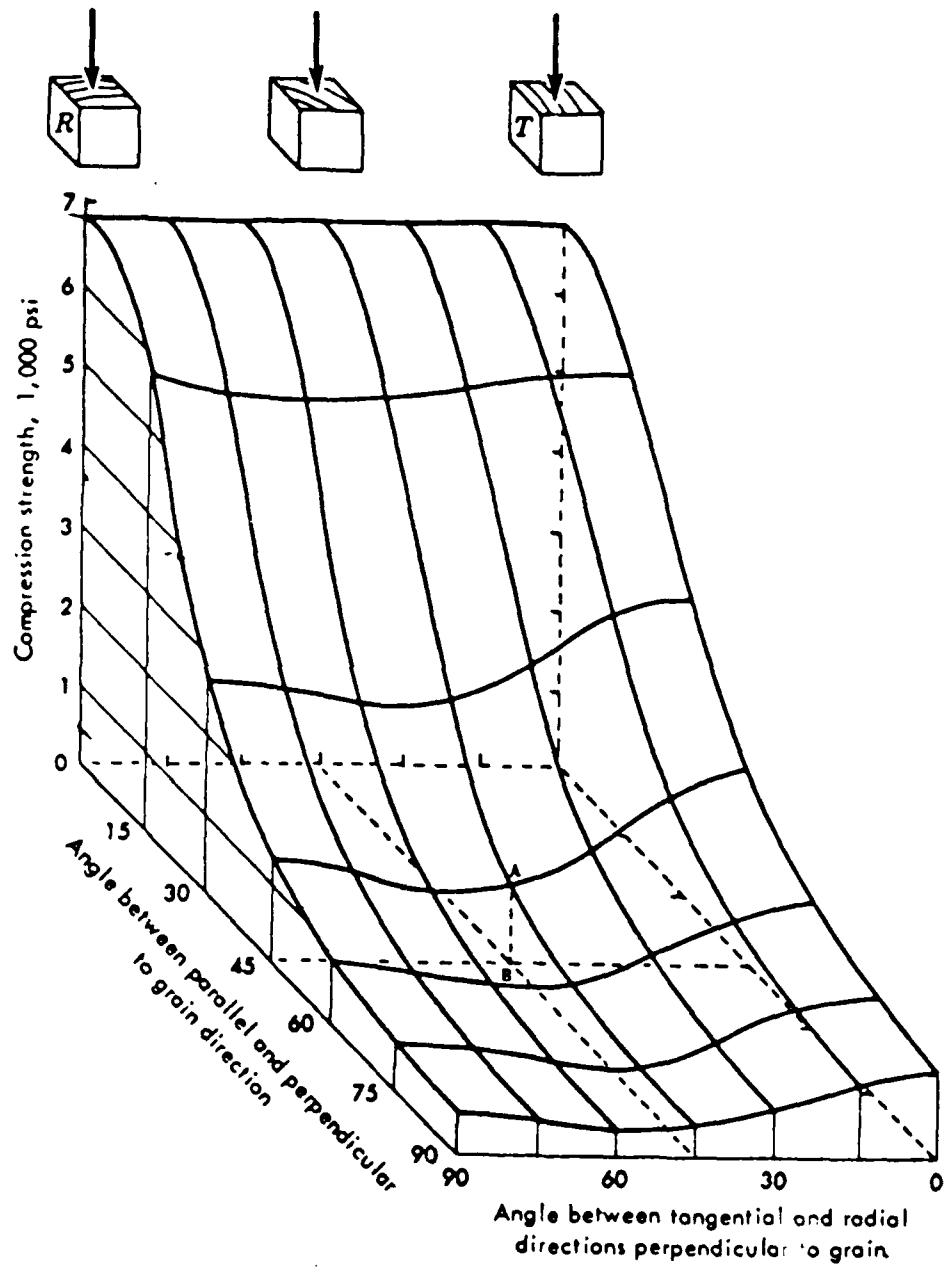


FIGURE 4.3

4.1.4 Non-linear Properties of Wood

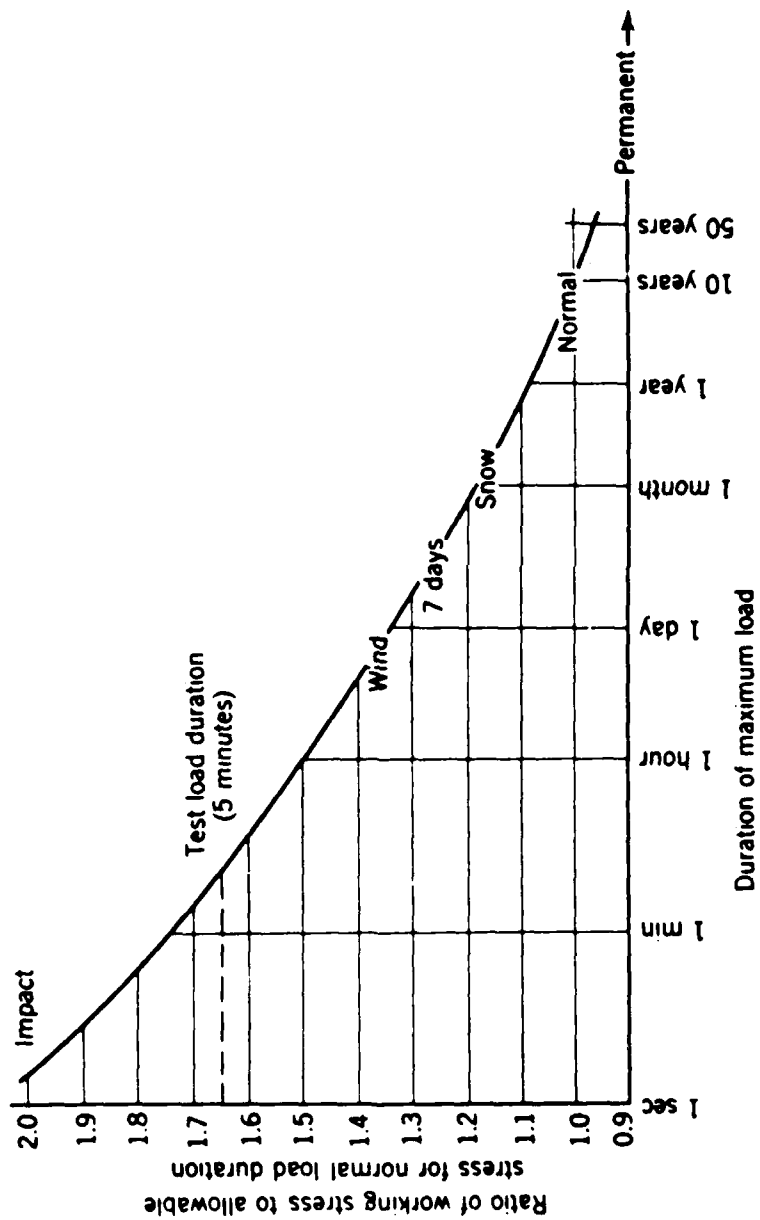
For any given piece of wood subject to stress, the load deformation curve reaches a proportional limit, beyond which the total deformation is non-recoverable and some permanent set is imposed on the specimen. Permanent displacement on a stress/strain curve, an indication that the strain did not return to zero when the applied load was removed is called "permanent set". The stress/strain relationship is also highly dependent on the rate at which the load is applied. Increasing the rate of load application results in higher strength values [25].

The steepness of the slope of the elastic line is a measure of the magnitude of the elastic modulus. In some kinds of wood there is almost no demarcation of the end of the elastic portion of the curve. The proportional limit can scarcely be defined. The set is attributed to plastic deformation of the wood. This deformation increases with applied load above the proportional limit until the piece breaks or fails in some manner. The area under the stress-strain curve represents the amount of energy absorbed by the wood during its deformation.

4.1.5 Wood Loading Rate Effects

During an earthquake the blocking material is loaded at a rate ranging between 0.5 to 20 cycles per second. Repeated removal and the application of load at a frequency that is much smaller than the natural frequency of the body is defined as "cyclic loading". According to Bodig (1983) [25] a higher rate of loading will produce higher stiffnesses, approaching the true time independent value more closely as the rate increases.

The Timber Construction Manual (1985) [27] included information on wood using tabulated design values for normal duration of loading. Normal load duration anticipates fully stressing a member to the full design value by the application of the full design load for a duration of approximately 10 years. For other durations of load, either continuously or intermittently applied, the appropriate factor determined from figure (4.4) [27] should be applied to adjust the tabulated design values. This manual states that the duration of load modifications are not applicable to the modulus. Bryant (1987) [28] confirmed that this strength/loading rate relationship applies to timbers in drydock blocking systems. Therefore, even though the modulus for Douglas fir remains the same during earthquake loading, the load at which this cap material reaches its proportional limit is increased.



Duration of load factors, derived from Forest Products Laboratory Report No. R 1916.

Effect of Load Duration on Wood Strength

FIGURE 4.4

Since earthquake durations are usually less than one minute, creep is not considered a factor during the earthquake. Kellogg (1960) [29] found that although it is known that repeated loading in tension parallel to the grain does in time reduce the ultimate strength of wood, it was found that in general 100 cycles of stress of short duration are not sufficient to incur any appreciable decrease in strength.

4.2 NAVSEA Blocking Material Study

4.2.1 Description of Tests

The large differences in the properties of wood and the increase in the loading of blocks due to heavier ships prompted the Naval Sea Systems Command to fund a blocking material study at the University of Washington [22]. Recent design changes resulting in heavier ships with smaller bearing areas have increased loads on the docking blocks to such an extent that the possibility of failure has increased.

Tests were conducted to determine the compressive strength properties of Douglas fir and oak timbers and the effect of age, size, temperature, and grain orientation on these properties. In addition, the timbers were tested in multi-layer and species configurations in full-size and scale-

model keel blocks under lateral and axial loading, and with several combinations of wood and steel interfaces to evaluate friction and cribbing properties. The tests were conducted at the University of Washington Structural Research Laboratory between October 1984 and September 1985.

4.2.2 Strength Properties of Timbers

According to this study [22], the individual timber tests showed a wide range of strength values (FSPL's) for both Douglas fir and oak. There is also a considerable overlap in the distribution of FSPL between the two species. Old timbers tended to vary more in strength than new timbers. The study also states that blocks built up with timbers that have a wide range of strength values are themselves subject to wide variations in strength, with stronger blocks carrying a larger share of the load than the weaker blocks.

The range of strength values (FSPL's) were found to vary from 241 to 821 psi for old oak and 279 to 570 psi for Douglas fir. This shows that some timbers in service are below the desired strength. The modulus of both old and new timbers that have been compressed beyond their proportional limits are significantly lower than the average moduli of unused new timbers. As expected, compressive strengths varied less between piers than between tests on individual timbers. The

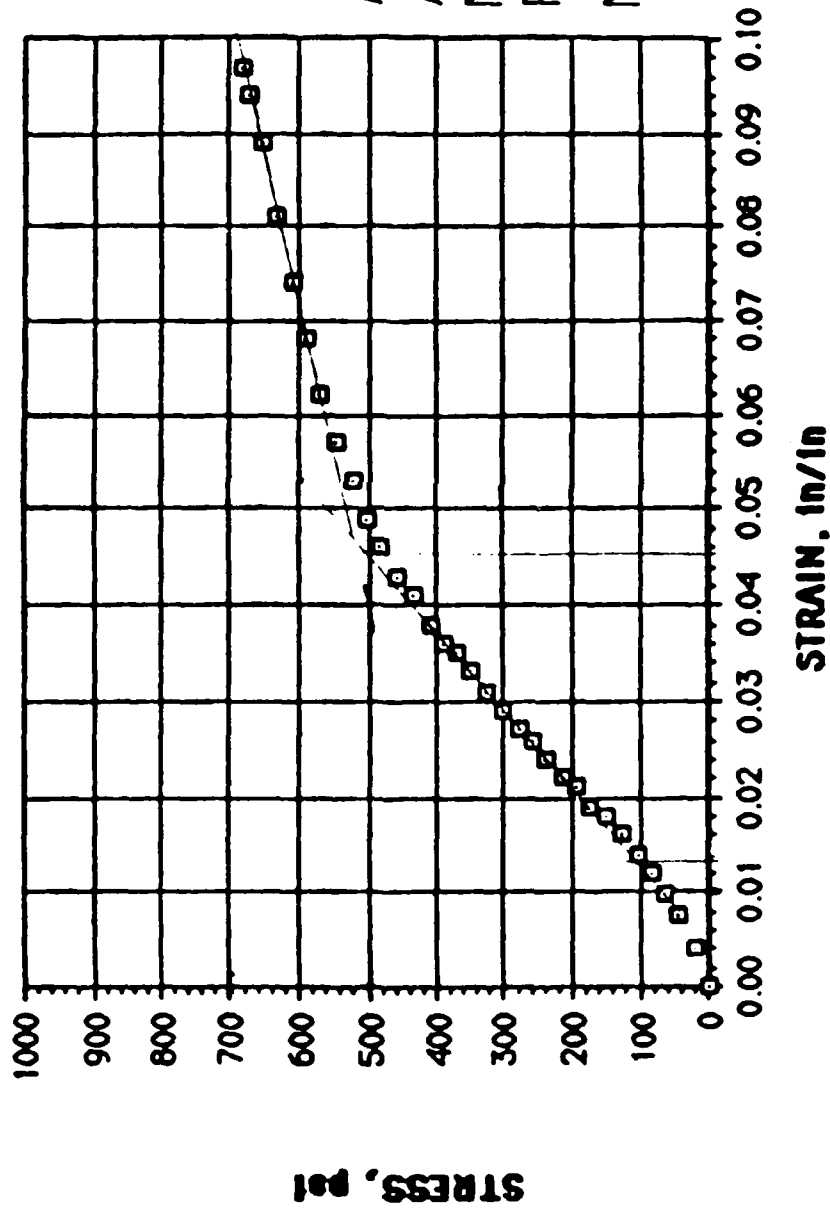
values suggest that the typical keel block in service has lost some compressive strength (FSPL) compared to new timbers and that it has lost a substantial portion of its stiffness (modulus). Test data results [22] showed that for 39 new timber samples of Douglas fir the average FSPL was 367 psi. The range was 258 to 533 psi. The standard deviation was 89 psi. The mean modulus of elasticity for this Douglas fir was 26810 psi and it varied from 11850 to 38570 psi. The standard deviation was 6160 psi.

The blocking material study found that Douglas fir capping material is subject to permanent set. During docking if the load applied to any individual timber in the block exceeds its FSPL, the timber cannot return to its original thickness even though it appears to be undamaged. Therefore, variations in the thickness of ship blocking timber should be carefully examined.

4.2.3 Stiffness Properties of Blocking Piers

The compressive stress-strain curve used in this thesis for determining the stiffness properties of the Douglas fir cap is illustrated in figure (4.5) [22]. It is based on compressive tests done on layers of old Douglas fir timbers.

Data from BM005 ("OLD")



AT 500 PSI
 APPARENT
 MOE 10492 PSI
 FSPL 411 PSI
 MOE 12945 PSI

Stress/Strain Curve for Old Douglas Fir Timbers

FIGURE 4.5

This figure shows the very bilinear stress-strain characteristic of Douglas fir. The two moduli used for Douglas fir were determined from this figure. In this thesis oak is assumed to remain linear and the compressive perpendicular to the grain modulus for oak (23980 psi) was obtained from the blocking material test [22] using three layers of old oak timbers. This is considered to be typical of oak used in submarine drydock blocking systems.

4.2.4 Blocking Pier Frictional Coefficients

This study also included an analysis of wood on wood and wood on steel frictional coefficients. The values for these coefficients in this thesis came from this study. They are as follows for dry conditions:

Oak/Oak	Oak/Steel
0.43	0.53

The oak on oak was used for block sliding and oak on steel was used for ship on block sliding. Fir on steel values were not available in this study.

4.2.5 Blocking Study Recommendations:

The blocking study [22] recommended that since visual identification of low strength timbers is difficult at best, a non-destructive testing system be developed to aid in identifying timber strength properties. The study strongly recommended that to increase the uniformity of drydock blocking materials laminates should be used. For example, if laminated oak timbers are judged to be suitable they would exhibit a minimum of 1/4 of the strength variation of solid timbers. They would not have the inherent defects of large sawn timbers such as grain slope, checks, shakes, and boxed hearts.

Since the study found that average strength values of Douglas Fir are not significantly less than those of oak, the use of Douglas fir as a "soft cap" does not fulfill the desired purpose. The present use of Douglas fir as a capping material results in a layer that is sometimes stronger and stiffer than the underlying oak. Because some blocks have a low modulus which allows more compression a sufficient height of wood is needed within keel blocks to allow a uniform distribution of the load and to prevent over compression. Another material is recommended which has a higher load carrying capacity than Douglas fir, but a lower modulus of elasticity. Ideally this material would return to its shape after compression and retain its load carrying capacity.

4.3 Potential Use of Rubber as Blocking Material

Rubber has properties which may make it an ideal material for use as a soft cap in a blocking pier. Rubber, commonly designated as an elastic material, is so only in the sense that it returns to its original shape after deformation. Its low modulus indicates ease of deformation under load.

Marshall (1981) [30] evaluated properties of rubber. Soft rubber, similar to natural rubber, and a hard rubber were tested in uniaxial tension and compression. Tests indicated that the rubbers were essentially isotropic in their elastic characteristics. There were no visible creep effects. Both the soft and hard rubbers exhibited linear elastic responses for strains on the order of 6 %. For hard rubber $E = 7.2 \text{ N/mm}^2$ and $G = 2.44 \text{ N/mm}^2$ (where E is modulus of elasticity). For soft rubber $E = 2.9 \text{ N/mm}^2$ and $G = 1.01 \text{ N/mm}^2$ [30].

Properties of rubber are well known and strains can be determined analytically if forces are known. Treloar (1958) [31] found that for elastomers such as rubber, theoretically predicted and experimentally determined stress-strain behavior correlated well unlike wood. An elastomer is a material which at room temperature can be stretched repeatedly to at least twice its original length. Immediately upon release of the

stress, an elastomer will return with force to its original length with no permanent set. At small strains, an elastomers stress-strain curve is approximately linear. But at larger strains an appreciable upward curvature is evident.

According to Treloar [31], the shear stress versus strain curve is approximately linear for rubber in pure shear. The modulus of rigidity corresponding to the initial portion of this curve is 4.0 kg/cm^2 (567 psi). For rubber shear stress versus shear strain is more linear than compressive stress versus compressive strain. Up to very large values of strain, shear remains very close to linear. No biaxial stress data was available for rubber; therefore, the modulus of rigidity and horizontal stiffness of rubber was assumed constant throughout this thesis. For this reason, the vertical stiffness (modulus) due to compression of the rubber was considered uncoupled from the horizontal stiffness (modulus of rigidity).

At low temperatures all rubbery polymers exhibit a sharp rise in elastic modulus and become rigid. If this material is used as a submarine blocking material, in severe cold weather the material will become much stiffer and exhibit different response to loads. According to Morton (1973) [32] coefficients of friction for rubber varied from 0.5 to 0.9. This value is significantly higher than that for wood and is another positive reason for its use as a blocking material.

Blackie (1988) [33] describes a test on natural rubber. A load deflection curve was developed for natural rubber from compressive tests done on a 2 inch thick by 7 inch wide rubber specimen vulcanized to a 3/4 inch steel plate. The length of the piece was 36 inches. From this curve a bilinear stress-strain model of natural rubber was developed. The moduli for natural rubber for this thesis were obtained from this curve.

4.4 Potential Use of Elastomeric Bearings and Damping Materials in Drydock Blocking Systems

4.4.1 General Advantages of Base Isolation of Structures

Pan (1983) [34] discusses the science behind the use of base isolation systems for reducing accelerations on structures during earthquakes. He states that base isolation is an aseismic structural design strategy in which a building is uncoupled from the damaging horizontal components of an earthquake by a mechanism that attenuates the transmission of horizontal acceleration into the structure.

An extensive series of experiments on this concept have been carried out over the last few years using the shaking table at the Earthquake Engineering Research Center, University of California Berkeley. Pan [34] reports that the results from these experiments have established the

effectiveness of this approach to aseismic design and have shown that substantial reductions in the accelerations are experienced by a building on an isolation system over one on a conventional foundation. This advantage is accompanied, however, with large relative displacements at the base level of the superstructure. The typical period of isolated structures is around 2 seconds (approximately 0.5 HZ) [34].

Kelly (1980) [35] states that a further advantage is that any inelastic action will be concentrated in devices such as energy absorbing devices that are replaceable. The ultimate in isolation, according to Kelly, would be to place the entire structure on roller bearings in which case, in principle, no horizontal force would be transmitted into the structure. However, the fact that the systems have no restoring force in the presence of wind load make the roller bearing concept impractical.

Kelly [35] further states that no base isolation system can isolate the building from all earthquake frequencies. With random input such as earthquake ground motion, there will always be some component of the input that will be in resonance with the system. The effects of this resonance can be avoided by providing a degree of damping in isolation system. Rubber bearings provide a certain amount of damping, at best equal to approximately 10 % equivalent viscous damping according to Kelly. Pan [34] also states damping in an

isolation system with elastomeric bearings can be as high as 8 to 10 %. However Kelly states that higher damping may be necessary to reduce displacements.

According to Dynamic Isolation Systems Inc., Berkeley, California, (D.I.S.) [36], seismically isolated buildings can be constructed at costs that compare favorably to the first costs of conventional fixed-based structures. Moreover, owners can reap substantial long term economic benefits in the form of reduced life cycle costs. Following an earthquake, the enhanced protection of building contents inherent in an isolated building will result in significantly reduced repair and replacement costs. The force transmitted to the building is reduced by a factor of five to ten. Instead of amplifying base accelerations, the building moves as a rigid box with uniform motion and little interstory drift.

Mayes (1984) [37] describes the design of the base isolators. The essential feature of base isolation is to ensure that the period of the structure is well above that of the predominant earthquake input. The use of base isolators has become more practical with the successful development and inclusion of mechanical energy dissipators in the base isolators. An energy dissipator has the same function as a shock absorber in a car (i.e. its "soaks up" the energy of the excitation). These dissipators which are now being manufactured and used in the United States were developed by

the New Zealand Department of Scientific Industrial Research and extensively tested over a twelve year period. When used in combination the flexible isolation device an energy dissipator can control the response of the structure by limiting the displacements and forces, thereby, significantly improving seismic performance.

Mayes [37] also reports that the relative displacements are reduced to a practical design level of four to six inches. The seismic energy is dissipated in components specifically designed for that purpose relieving structural elements from energy dissipation roles and thus damage. There are three basic elements in any practical base isolation system. These are: (1) a flexible mounting so that the period of vibration of the total system is lengthened sufficiently to reduce the force response, (2) a damper or energy dissipator so that the relative deflections between building and ground can be controlled to a practical design level, (3) a means of providing rigidity under low (service) load levels such as wind and minor earthquakes.

The most compelling argument, according to Kelly and Hodder [38], for base isolation is the protection afforded internal equipment and piping. The response of non-structural components is determined primarily by the response of the primary structure to earthquake ground motion and not by ground motion itself. While the main structure of a building

or power plant can be protected from the damaging effects of an earthquake attack with relative ease, the necessary strengthening of the main structure increases the seismic loads transmitted to non-structural components and equipment.

4.4.2 Historical Background and Present Uses

Pan [34] states that base isolation has become a practical possibility with the recent development of multi-layer elastomeric bearings. Bearings for use in an aseismic isolation system are a natural development of bridge bearings and of acoustic isolation bearings. According to Pan, experience with bridge bearings for many years has demonstrated that they are reliable and resistant to environmental damage including that from oil and fire.

Kelly [35] states that the concept of base isolation is a natural one based on accepted physical principles. It has not, however, been readily accepted by the structural engineering profession because the concept runs counter to accepted measures of aseismic design. According to Kelly, the design codes in all countries with seismic regulations require that an earthquake attack be absorbed by a structural system through inelastic action. Inelastic action inevitably involves damage, however, not only to the structural system but also to non-structural components and essential equipment.

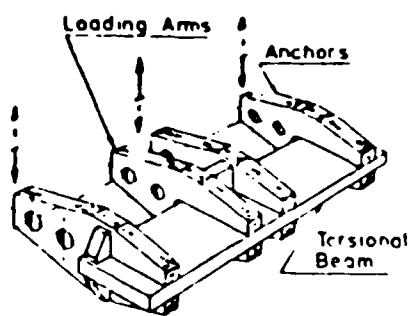
Furthermore, design calculations for the dynamic inelastic response of the building and of the contents to earthquake loading are extremely expensive. The standard approach is to design the building to survive by increasing structural strength and capacity to dissipate energy.

A form of multilayer elastomeric bearings is presently used as fenders on docks and wharves. Recognition of the engineering qualities of rubber has led to the use of elastomeric bearings in several buildings which have been built or are under construction with base isolation systems [33].

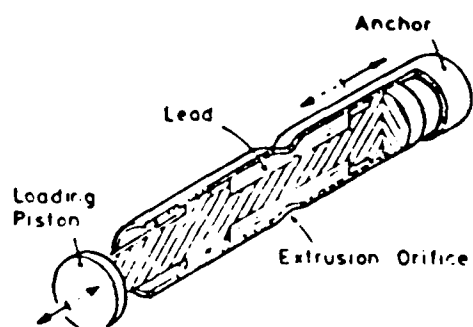
Dynamic Isolation Systems Inc. (D.I.S.), a manufacturer of dynamic isolators states in their literature [36] that 200 structures in 25 countries have been seismically isolated. Applications include buildings, bridges, and nuclear power plants. The eight lane Sierra Point overpass on Highway 101 near San Francisco Airport was protected in 1985 by D.I.S. lead-rubber bearings to decrease seismic forces transmitted to the bridge. This was the first base isolated bridge in the United States.

The first new building in the United States to employ seismic isolation was the Law and Justice Center in San Bernardino, California. This building underwent a 4.9 Richter scale magnitude earthquake on October 2nd 1985. The base

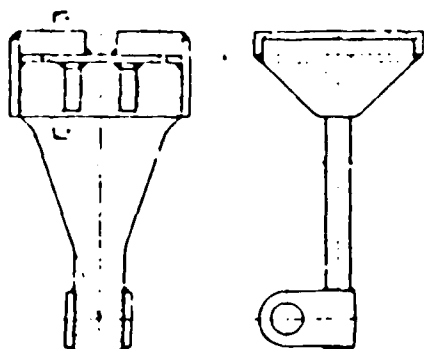
isolation system reduced the 0.04 g peak ground acceleration input to 0.03 g at the roof. Conventional fixed based buildings nearby amplified ground motion to a maximum of 0.15 g. The data was recorded by the California Strong Motion Instrumentation Program (CSMIP). Several mechanical dissipation devices have been developed as shown in figure (4.6) [37].



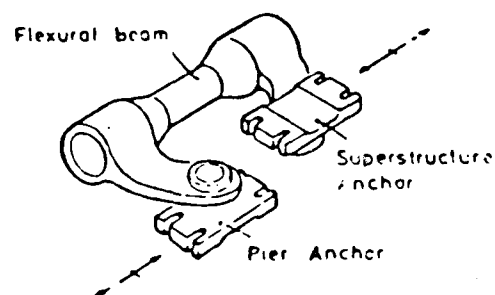
Torsional Beam Device



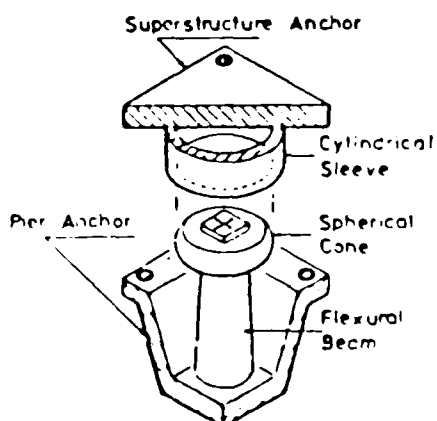
Lead Extrusion Device



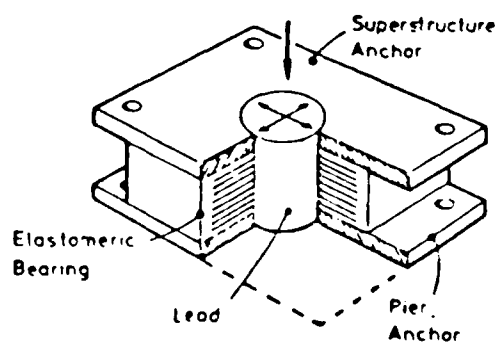
Flexural Plate Device



Flexural Beam Device



Flexural Beam Device



Lead-Rubber Device

Various Mechanical Energy Dissipators

FIGURE 4.6

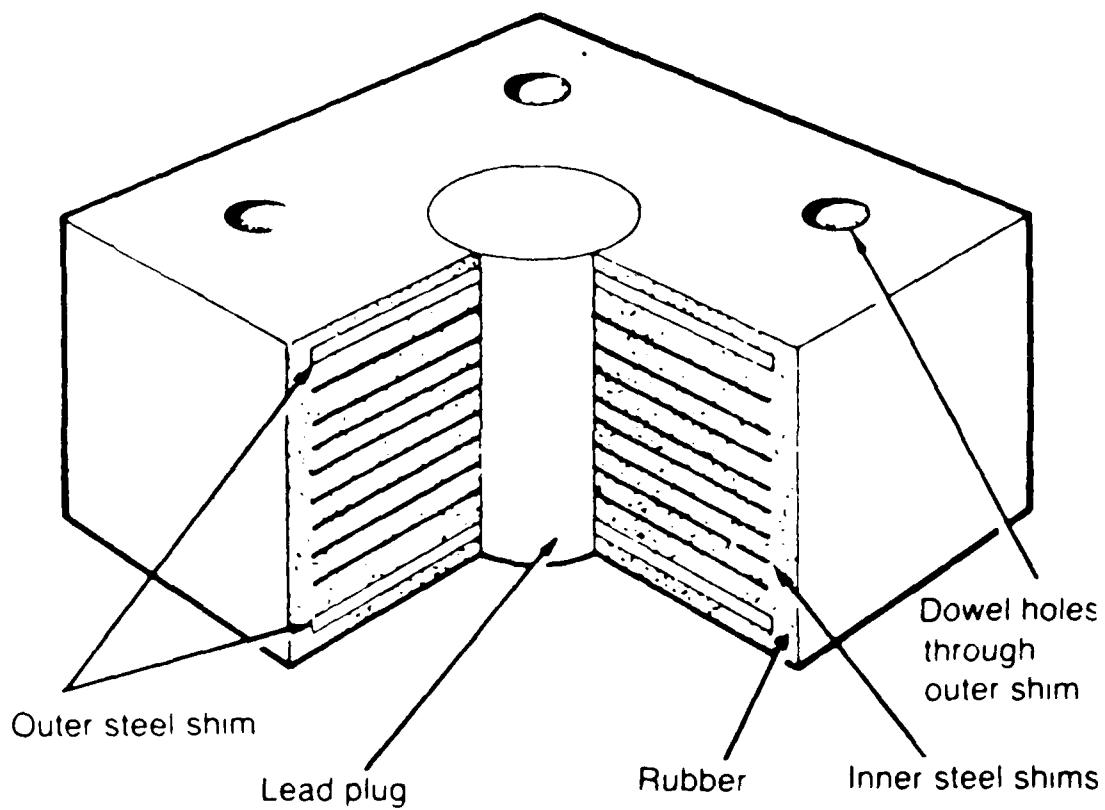
4.4.3 Dynamic Isolation System's Isolator

Description of the D.I.S. lead rubber bearing, the isolator used in this thesis, is shown in figure (4.7) [36]. The isolator is made of alternate layers of rubber and steel encased in a vulcanized rubber cover. The lead plug, which provides wind restraint and seismic damping, is fitted into the center.

While the introduction of lateral building foundation flexibility may be highly desirable additional vertical flexibility is not. Vertical rigidity in the D.I.S. isolator is maintained by constructing the rubber bearings in layers and sandwiching steel shims between each layer. The steel shims which are bonded to each layer of rubber constrain lateral deformation of the rubber under vertical load resulting in vertical stiffness several hundred times the lateral stiffness.

One of the most effective means of providing a substantial level of system damping is through hysteretic energy dissipation. The term hysteretic refers to the difference in the loading and unloading curves under cyclic loading.

THE DIS LEAD-RUBBER BEARING

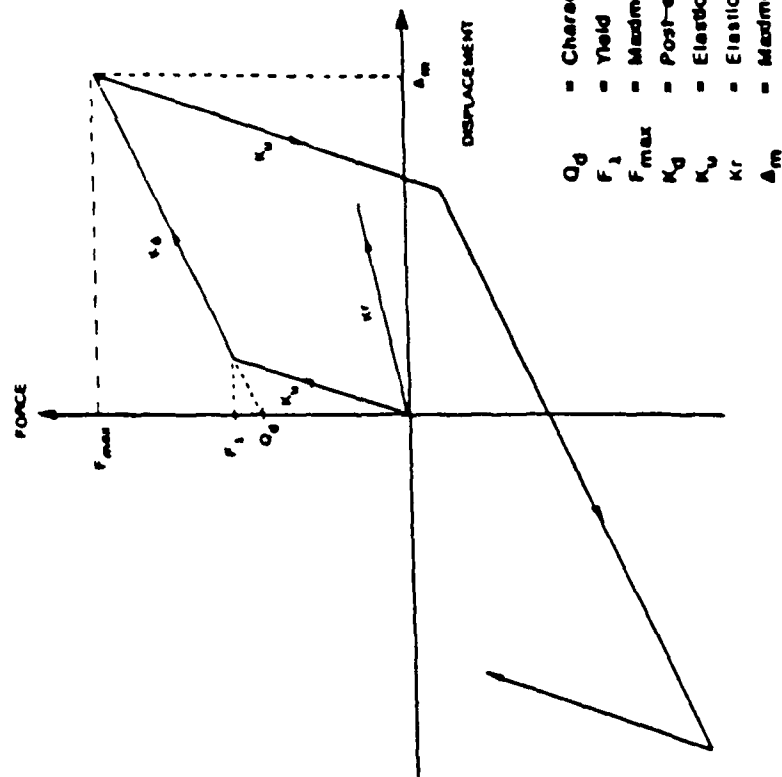


USA Patent No 4 117 637

FIGURE 4.7

Figure (4.8) [37] is a typical idealized force-displacement loop for the D.I.S. isolator. The inclosed area is a measure of the energy dissipated during one cycle of motion. Lead, which is used as the mechanical damper in the D.I.S. isolator, is a crystalline material which changes its crystal structure under deformation but also instantly regains its original crystal restructure when the deformation ceases. For this reason, lead exhibits excellent hysteretic damping properties over many repeated cycles of earthquake motion. The lead rubber bearing provides the low load rigidity by virtue of the high initial elastic stiffness as illustrated by the initial elastic curve in figure (4.8) [37].

The analysis in this thesis will be limited to the D.I.S. isolator as shown in figure (4.7). According to Mayes [37] this is the most highly developed and practical dissipator to date. It combines in one physical unit the flexible element and the energy dissipator. In this application the lead is forced to deform plastically in shear by the steel shim plates. Excellent energy dissipation is possible with this device. Mayes reports that recent work by Kelly and Buckle at the University of California at Berkeley and also by Buckle at the University of Auckland in New Zealand has validated the performance of this device to the point where it can be used in practical applications with the same confidence as with other building materials such as steel or concrete.



Lead-Rubber Bearing Properties

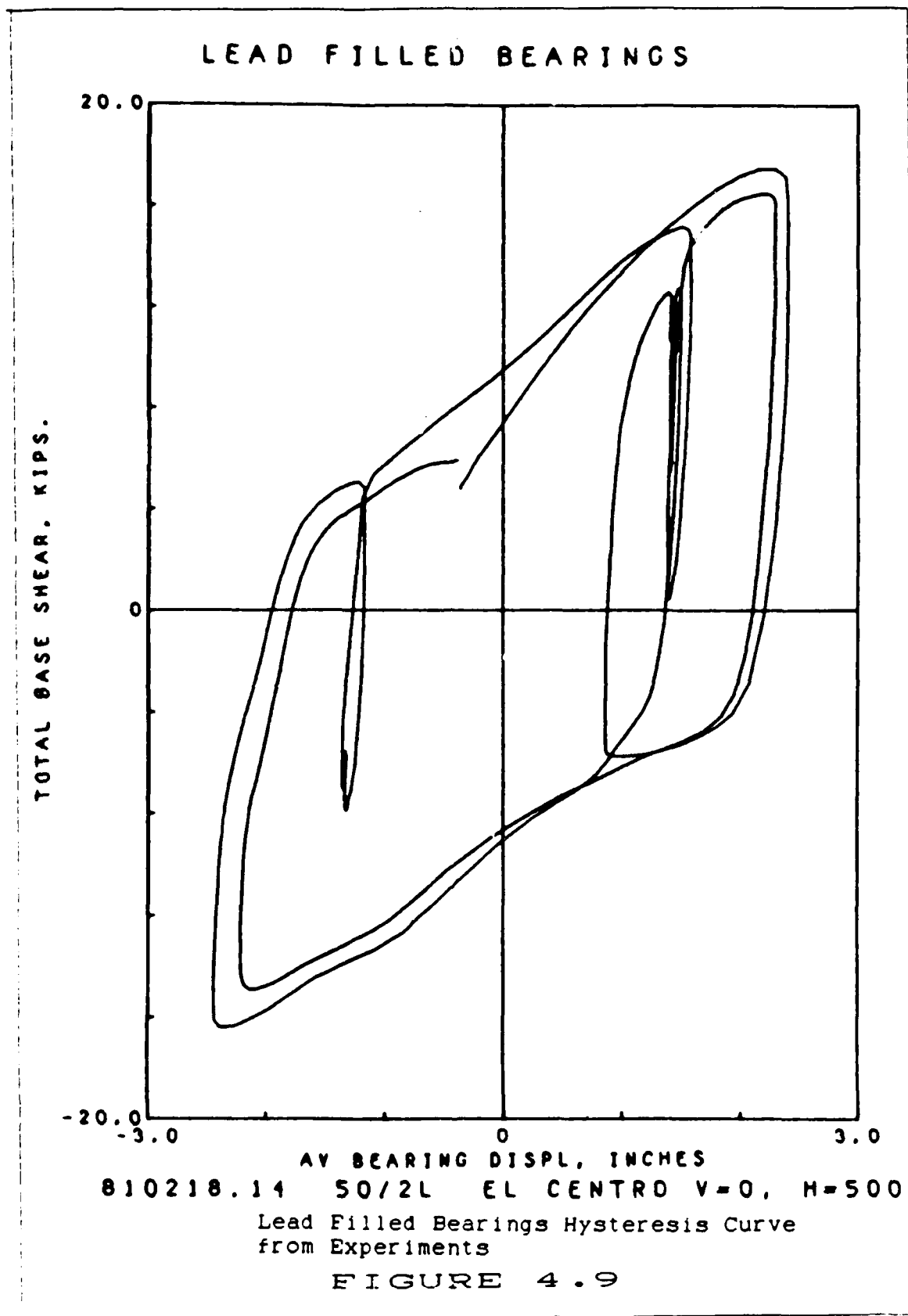
FIGURE 4.8

Design charts [37] have been developed for the D.I.S. isolators, and they can be built in a variety of sizes (footprint), rubber thicknesses, and lead plug sizes. The total rubber thickness for a given bearing footprint defines the degree of isolation provided to the structure. Mayes reports that it is most advantageous to use the rubber thickness corresponding to the longest effective period, if there are no constraints on the height of the bearings or bearing displacement. The thicker the rubber the more isolation and more lateral displacement. Once the desired rubber thickness is decided, the bearing construction (number and thicknesses of rubber layers) may be determined. The standard construction for a given total rubber thickness consists of 1/8 inch internal steel shims and 3/4 inch steel top and bottom plates. Charts have also been developed [37] as a means of rapidly arriving at a lead plug diameter for a given load. Lead plugs may be distributed over the bearings such that individual bearings may have differing yield levels.

Kelly and Hodder (1982) [38] carried out base isolation experiments on cylindrical lead filled laminated elastomeric bearings. The 1940 El Centro NOOE acceleration time history as well as three other earthquakes time histories were used. Hysteresis loops for various filled and unfilled bearings were measured. A simulated five story building on these bearings was excited by a shaker table using the earthquake acceleration time histories.

A typical hysteresis curve for lead filled bearings subject to the El Centro earthquake is shown in figure (4.9) [38]. This exhibits the measured bilinear response characteristic of these bearings. The response of the structural model on the lead filled bearings is markedly different from that on unfilled or elastomer filled bearings. The lead appears to act as if it were almost perfectly plastic with a yield shear stress of approximately 1.4 kips/in² (9.6 kN/mm²). As the lead yields significant energy dissipation occurs, in effect the lead acts as a mechanical fuse and an energy dissipator.

Kelly and Hodder describe the lead/bearing assembly of the D.I.S. isolator as an almost ideal isolation system. Their experiments showed that the bearings are capable of sustaining a relative lateral displacement of 75 % of their diameter without buckling. The reductions in maximum accelerations experienced by the supported building compared to conventionally designed structures vary with earthquake signal, but are not less than a factor of 10 and can be much higher.



4.4.4 Other Current Research

According to Kelly [35], other mechanisms have been tested in combination with elastomeric bearings including a mechanical fuse in the form of a notched pin designed to fracture at a specified level of shear force which acts as a wind restraint. A fail safe skid system has also been tested. This system produces a Coulomb frictional damping and in the event of earthquake ground motion, acts to prevent structural collapse.

4.4.5 Summary and Recommendations

Dominic Zegaint, head of the Structural Branch, Navy Facilities Engineering Command (NAVFAC), has stated that the Navy accepts seismic isolation as one of the techniques available to the structural engineer. He declared that NAVFAC is giving serious consideration to base isolation and is committed to its implementation under appropriate circumstances [36].

Kelly and Hodder [38] state that for nuclear plants the very low probability seismic events for which the plants must be designed could require a much higher design peak acceleration than could be accommodated by a simple rubber bearing base isolation system. The energy dissipating base isolation system in which rubber bearings and lead inserts are

integrated then becomes an ideal choice for seismic protection of these plants. No other structural design strategy can simultaneously protect a structure at such earthquake intensities and limit the forces applied to sensitive internal equipment.

The bearings themselves are not expensive items, particularly if many are manufactured. The cost of one type of lead filled elastomeric bearing is about \$2000 each according to Kelly (1980) [35]. An elastomeric bearing is not the only means of introducing flexibility, but according to Mayes [37] it appears to be the most practical with the widest range of applications.

The use of dynamic isolators in submarine drydock blocking systems has tremendous potential. The footprint of these isolators can be made to be the same as existing drydock blocks. Luchs (1988) [21] determined that base isolators are one method of preventing failure of submarine drydock blocking systems during earthquakes. In this thesis, a method of modeling the effects of substituting the oak layer in submarine drydock blocking systems with D.I.S. isolators is developed.

4.5 Determination of Drydock Blocking Pier Stiffnesses

With the inclusion of many different types of materials in one side block or keel block pier, a method was needed to determine the horizontal and vertical pier spring constants. In this thesis, the piers are modeled in the horizontal direction as cantilever beams and shear elements. In the vertical direction they are modeled as axially loaded columns. In both directions they are considered to be composite elements with different properties along the length.

A LOTUS 1-2-3 spreadsheet was developed to calculate the stiffnesses. A sample vertical and horizontal set of spreadsheets are included in Appendix 2. These spreadsheets apply to a system similar to submarine blocking system number two. The spreadsheets were designed to be able to calculate pier stiffnesses with four block material layers. The example spreadsheets stiffness calculations are for a system with rubber, Douglas fir, oak, and concrete layers.

The first spreadsheet in Appendix 2 is the calculation of keel vertical stiffness. The procedure used was a standard addition of element stiffnesses in series as follows:

$$k_{vk}' =$$

$$1/[(1/k_{v1}) + (1/k_{v2}) + (1/k_{v3}) + (1/k_{v4})] \quad (4.4)$$

Where $k_v k'$ is the stiffness of one keel pier. This required knowing each layer's dimensions and modulus of elasticity. This information was obtained from the appropriate submarine docking drawing. The stiffness of an individual layer is given by:

$$k = EA/L \quad (4.5)$$

E is modulus of elasticity of the layer.
L is the height of the layer.
A is the area over which the vertical force is applied.

For some layers the cross-sections varied over the layer or there were abrupt transitions from one layer to the next. In these cases an effective area was used based on the standard 1 to 3 load distribution slope employed by the Naval Sea Systems Command. Figure (4.10) illustrates how this effective area is determined.

This procedure was used to calculate the stiffness of one individual keel pier. To determine the stiffness of the entire keel system the individual keel pier stiffness was multiplied by the number of keel blocks. Side pier vertical stiffnesses were determined in a similar manner.

The second spreadsheet in Appendix 2 is the calculation of keel horizontal stiffness for this same four layered system.

Blocking Pier Stiffness Effective Area

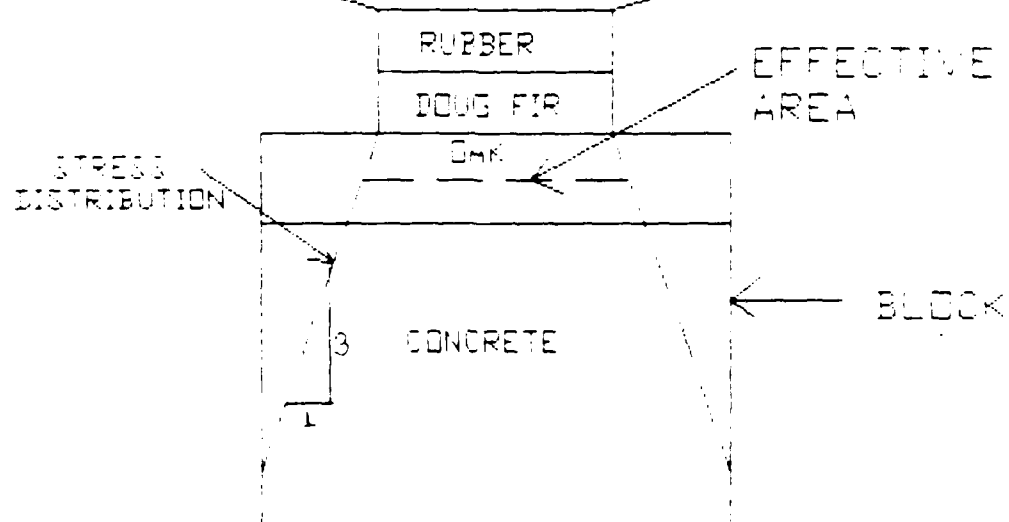


FIGURE 4.10

For the computation of horizontal stiffness, two types of horizontal deformation must be considered: the horizontal cap displacement due to bending and the horizontal cap displacement due to shear. The total keel pier stiffness coefficient for one keel pier (k_{hk}') is then given by:

$$k_{hk}' = P/(d_{b_1} + d_{s_1}) \quad (4.6)$$

Where P is the horizontal force applied to surface of the cap. d_{b_1} is the displacement of the cap's surface due bending and d_{s_1} is the displacement of the cap's surface due to shear.

In the case of bending, the block is modeled as a four element cantilever beam. The displacement of the top of this beam due to the applied force P is determined by the stiffness matrix method. The stiffness matrix equation for the first element is as follows:

$$\begin{bmatrix} Q_1 \\ M_1 \\ Q_2 \\ M_2 \end{bmatrix} = \begin{bmatrix} 12E_1 I_1 / L_1^3 & 6E_1 I_1 / L_1^2 & -12E_1 I_1 / L_1^3 & 6E_1 I_1 / L_1^2 \\ 6E_1 I_1 / L_1^2 & 4E_1 I_1 / L_1 & -6E_1 I_1 / L_1^2 & 2E_1 I_1 / L_1 \\ -12E_1 I_1 / L_1^3 & -6E_1 I_1 / L_1^2 & 12E_1 I_1 / L_1^3 & -6E_1 I_1 / L_1^2 \\ 6E_1 I_1 / L_1^2 & 2E_1 I_1 / L_1 & -6E_1 I_1 / L_1^2 & 4E_1 I_1 / L_1 \end{bmatrix} \begin{bmatrix} q_1 \\ \theta_1 \\ q_2 \\ \theta_2 \end{bmatrix} \quad (4.7)$$

E_1 is the modulus of elasticity of element number 1.
 I_1 is the moment of inertial of element 1's cross section.
 L_1 is the length of element 1.
 Q 's are the nodal forces.
 M 's are the nodal moments.
 q 's are the nodal displacements.
 θ 's are the nodal rotations (radians).

The elemental stiffness matrix equations are determined in a similar fashion for elements 2, 3, and 4. They are then combined to form a ten by ten stiffness matrix as shown in the horizontal stiffness spreadsheet in Appendix (2). The combined stiffness matrix equation is then solved to determine the displacement (d_b) at the top of the beam due to force P. Because Q_1 and M_1 are known and $q_1 = \theta_1 = 0$, by equilibrium solving the 10 by 10 matrix reduces to solving four two by two matrices. This was accomplished in the spreadsheet by using Cramer's rule.

In shear the block is modeled as a composite element subject to shear stress at the top of each layer. For element 1 the following equation holds:

$$\gamma_1 = (P/A_1)/G \quad (4.8)$$

γ_1 is the shear strain in element 1
P is the horizontal force acting on the surface of element 1.
G is the modulus of rigidity of element 1.
 A_1 is the top contact area.

The following formulas were used used in this thesis to determine the moduli of rigidity for the layer materials:

$$\text{Element 1 (concrete) } G = 0.6E [26] \quad (4.9)$$

$$\text{Element 2 \& 3 (D.fir and oak) } G_R = (1/14)E [26] \quad (4.10)$$

$$\text{Element 4 (rubber) } G = 0.339E [30] \quad (4.11)$$

The value of the top contact area, A , was the actual dimensions of the top of the layer if there was complete contact with the layer above. If the footprint of the upper layer was smaller, then the top contact area was assumed to be approximately the average of the footprint area and the actual top area of the layer.

The shear displacement was determined using the following equation:

$$d_s = \chi_1 L_1 + \chi_2 L_2 + \chi_3 L_3 + \chi_4 L_4 \quad (4.12)$$

The total horizontal stiffness for a row of blocks is the value of $k_h k'$ times the number of keel blocks. Similar spreadsheets were used employing four layers to determine the side block pier horizontal stiffnesses.

CHAPTER 5

WOOD BILINEAR MATERIAL PROPERTY MODEL

5.0 Determination of Blocking Wood Properties

As shown previously, Douglas fir and oak used in U.S. Navy drydock blocking systems are non-linear anisotropic materials. Their properties are functions of many different variables. For this thesis, the Douglas fir caps are modeled as bilinear materials. This means that up to the FSPL the Douglas fir has an initial constant modulus of elasticity. When subject to additional stress, the wood undergoes plastic deformation and the modulus of elasticity changes to a lesser value. This modulus is in effect until ultimate stress (about 700 psi) is reached. This model for Douglas fir is based on the compressive stress-strain curve illustrated in figure (4.5) [22]. The two moduli obtained from measuring the slopes off this figure are $E_1 = 12539$ psi and $E_2 = 3474$ psi.

Test results from the University of Washington study [22] gave an average FSPL for Douglas fir timbers of 367 psi. This value was for a test loading which occurred over a period of about five minutes. As shown before, the FSPL of wood varies with the duration of loading. Using an average earthquake load cycle of one second and applying a correction factor of 1.23 obtained from figure (4.4) [27], an earthquake loading FSPL of 450 psi is calculated. From these values an idealized

stress-strain curve for Douglas fir in the side blocks subject to vertical loading is constructed. This is illustrated in figure (5.1).

Due to the anisotropic nature of Douglas fir the FSPL and modulus of elasticity are dependent on grain orientation relative to the applied force. As Bodig showed, the ratio between modulus parallel to the grain, $E_{\parallel}$, and modulus perpendicular to the grain, $E_{\perp}$, is about 20 : 1. For vertical loading of the side blocks the force is almost perpendicular to the grain. For system 1 this cap angle is 68.4 degrees. For horizontal loading this angle is 21.6 degrees. Typically, blocking timbers used in shipyards include "circled hearts" and other irregularities. For this reason the orthotropic model needs to be modified somewhat. As a conservative approximation, a value for $E_{\parallel}/E_{\perp}$ of 14 is used. This coincides with the ratio of parallel to perpendicular compressive strength shown in figure (4.3) [23]. This figure is used to modify the modulus of elasticity of both Douglas fir and oak to account for orientation of the grain relative to applied force.

As shown in figure (5.1), the values for side block modulus for vertical loading is assumed not to be affected by the 68.4 degree load angle with the grain. Figure (4.3) is very flat between 60 to 90 degrees, therefore the perpendicular values are used.

IDEALIZED STRESS/STRAIN CURVE
DOUGLAS FIR
SIDE BLOCK VERTICAL LOADING

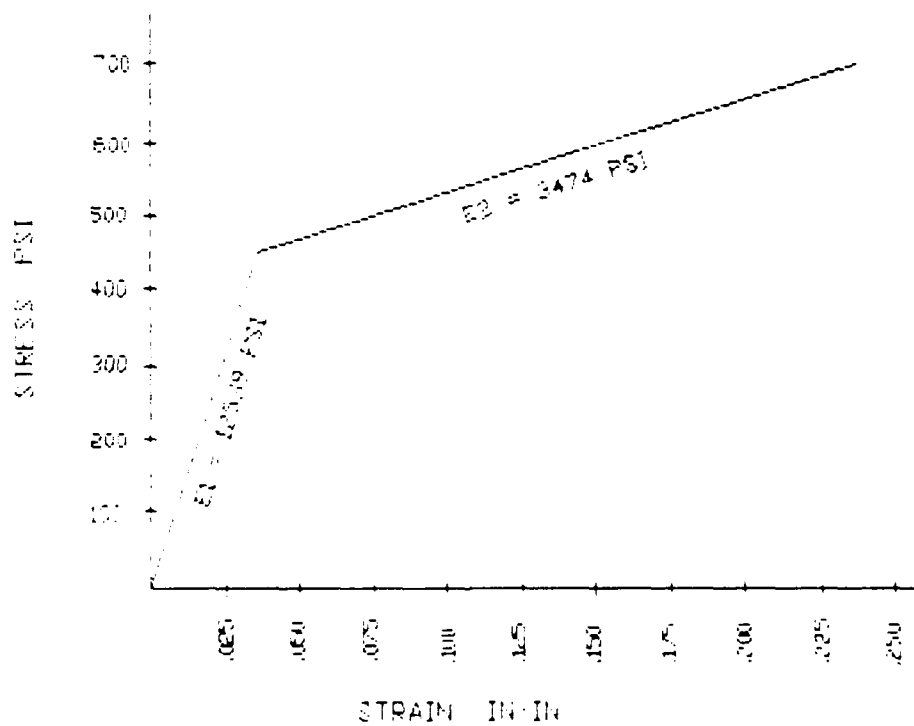


FIGURE 51

For horizontal loading, grain orientation has a very large effect. In this case, the perpendicular values of E_1 and E_2 are multiplied by a factor of 7.6 obtained from figure (4.3) to obtain the horizontal values $E_1 = 95297 \text{ psi}$ and $E_2 = 26398 \text{ psi}$.

In the horizontal direction, the strength of the Douglas fir caps is limited by their shear strength parallel to the grain. From the Wood Handbook [26] a value of 930 psi is obtained for this shear strength. From these values, the idealized stress-strain curve for Douglas fir in the side blocks subject to horizontal loading, figure (5.2), is obtained.

In the case of Douglas fir in the keel blocks, the horizontal applied force is exactly parallel to the grain, therefore, the correction value of 14 is applied. This results in values of $E_1 = 175549 \text{ psi}$ and $E_2 = 48629 \text{ psi}$. The idealized stress-strain curve for Douglas fir in the keel blocks subject to horizontal loading is illustrated in figure (5.3).

Oak is assumed to stay linear. Oak is generally stiffer and the Douglas fir cap areas are smaller and thus subject to higher stresses. However, grain orientation corrections are applied to the oak similar to the Douglas fir corrections.

IDEALIZED STRESS/STRAIN CURVE
DOUGLAS FIR
SIDE BLOCK HORIZONTAL LOADING

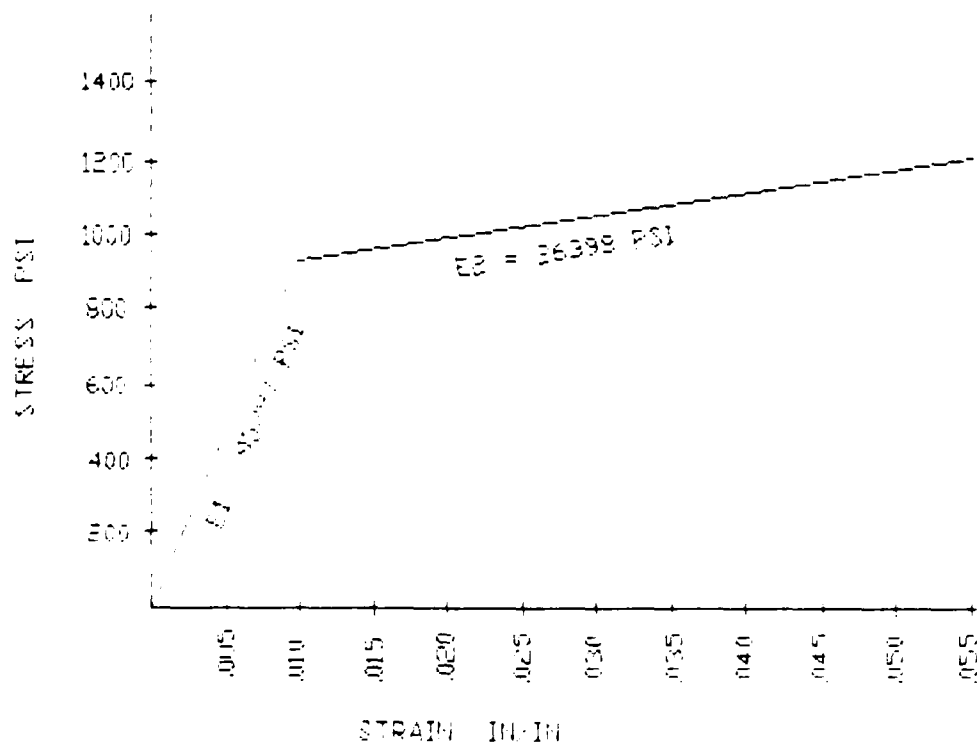


FIGURE 5.2

The modulus of elasticity value used in all cases for vertical loads on oak is 23980 psi obtained from blocking material test data [22]. For horizontal loads the modulus value for oak for keel blocks and side blocks is 335720 psi. Cap angle is assumed to not effect the oak. The oak layer is assumed to be perpendicular to the vertical loads and parallel to the horizontal loads.

5.1 Keel Block System Bilinear Model

Sigman [16] assumed in his research that the submarine drydock blocking systems failed when the Douglas fir caps were loaded beyond their FSPL. This is an unnecessarily restrictive assumption that does not allow taking into account the hysteretic damping effects produced by wood when it plastically deforms. The Douglas fir caps actually remain intact up to a stress beyond 700 psi. This is well beyond the assumed FSPL of 450 psi.

If the blocks are assumed to survive past the FSPL, a new way of modeling the block stiffness other than linear elastic needs to be developed. One way of modeling this behavior is called elasto-plastic. This model is described by Biggs (1964) [39] and Paz (1986) [40]. This model assumes that after the material is loaded past its proportional limit, it becomes purely plastic with stiffness equal to zero. The

material unloads with exactly the same slope (stiffness) as it is loaded.

This elasto-plastic model is fairly close to the behavior of wood; however, as seen in figure (5.3) the stiffness of the Douglas fir in the keel block system does not go to zero past the FSPL. Therefore, the elasto-plastic model must be modified to more closely match the behavior of the Douglas fir.

A curve which matches the behavior of Douglas fir more closely is that of the D.I.S. dynamic isolator shown in figure (4.8). This behavior is called bilinear. Figure (5.4) is an illustration of this model as applied to the horizontal keel blocking system. The entire keel blocking system is assumed to exhibit bilinear behavior. However, all the materials in the keel blocking system are assumed to remain linear-elastic except the Douglas fir which changes its modulus of elasticity as illustrated in figure (5.3) once its FSPL is exceeded. Generally, the Douglas fir caps are small and subject to higher stresses than the larger oak sections of the pier. By inputting these two values for modulus into the horizontal stiffness spreadsheets described earlier (Appendix 2), two values for the keel blocking system horizontal stiffness are obtained.

IDEALIZED STRESS/STRAIN CURVE
DOUGLAS FIR
KEEL BLOCK HORIZONTAL LOADING

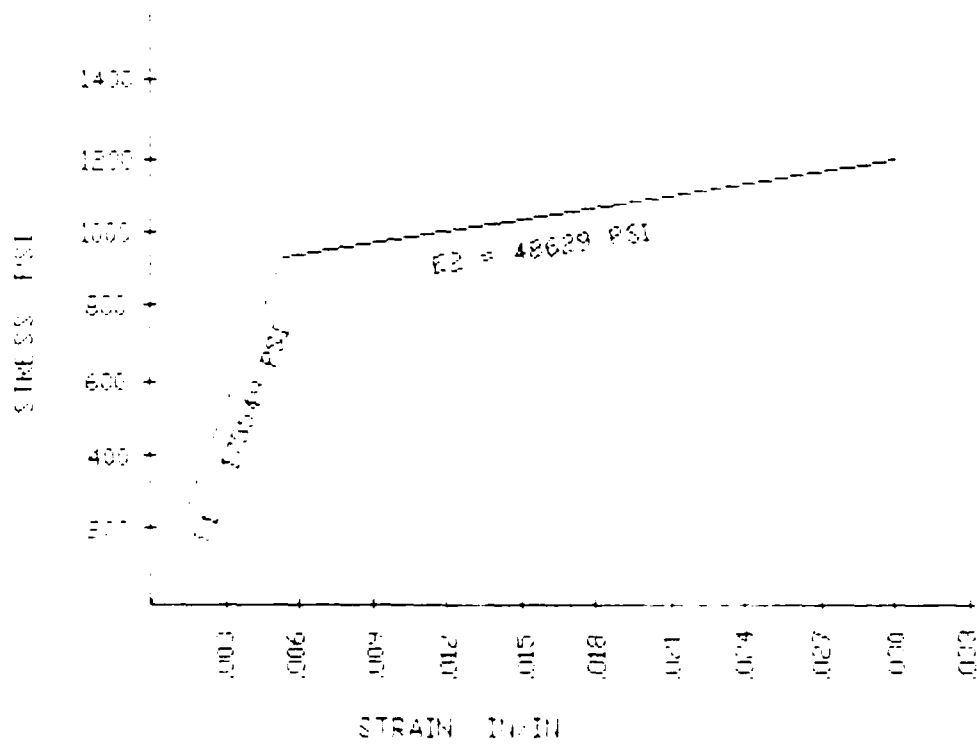


FIGURE 5.3

BILINEAR FORCE/DISPLACEMENT CURVE FOR HORIZONTAL KEEL BLOCKING SYSTEM

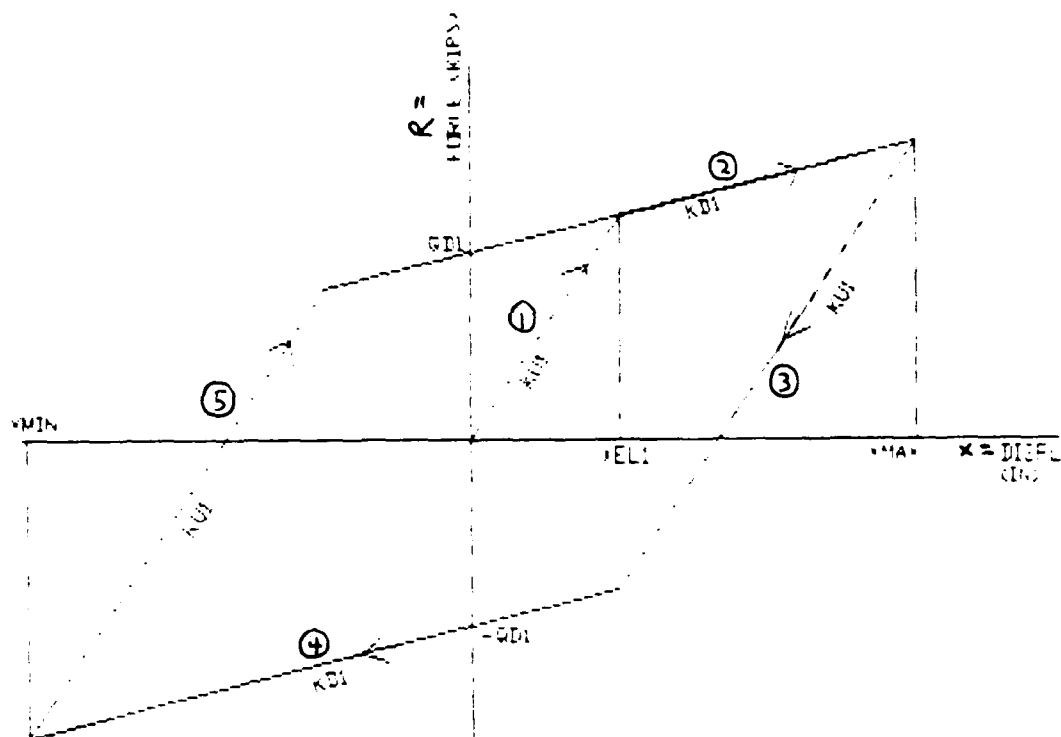


FIGURE 5.4

These two values are $k_{hk} = 59223$ kips/in and $k_{hkp} = 38435$ kips/in where k_{hk} is the initial elastic stiffness value and k_{hkp} is the stiffness after the system has been loaded past the FSPL.

In figure (5.4), $KU1$ is equal to k_{hk} and $KD1$ is equal to k_{hkp} . In this figure, and throughout this thesis the terminology used in figure (4.8) and by Buckle (1987) [41] is followed. The following equations describe the various features of the bilinear loop in figure (5.4):

$$XEL1 = P/k_{hk} = \tau_s A_s / k_{hk} \quad (5.1)$$

$$QD1 = XEL1(KU1 - KD1) \quad (5.2)$$

$$\text{Line 1: } R = KU1 * x \quad (5.3)$$

$$\text{Line 2: } R = KD1 * x + QD1 \quad (5.4)$$

$$\text{Line 3: } R = KU1 * x + (KD1 - KU1) * XMAX + QD1 \quad (5.5)$$

$$\text{Line 4: } R = KD1 * x - QD1 \quad (5.6)$$

$$\text{Line 5: } R = KU1 * x + (KD1 - KU1) * XMIN - QD1 \quad (5.7)$$

Where:

$XEL1$ is the elastic limit for the blocking system in inches.

τ_s is the maximum shear stress parallel to the grain for Douglas fir.

A_s is the keel blocking system cap area.

R is the restoring force of the keel blocking system due to horizontal deformation.

x is the horizontal displacement of the cap surface of the keel blocking system.

XMAX is the horizontal displacement of the cap surface at the point when where the bilinear loop shifts from line 2 to line 3. This is the point when the velocity of the keel blocking system cap changes from positive to negative during earthquake excitation. The blocking system then unloads elastically down line 3 with slope $KU1$.

XMIN is the horizontal displacement of the cap surface at the point when the loop shifts from line 4 to line 5. This is the point when the velocity of the keel blocking system cap changes from negative back to positive during earthquake excitation. The blocking system then unloads elastically up line 5 with slope $KU1$.

A similar procedure is developed to calculate horizontal side block system stiffnesses and vertical side block system stiffnesses. In the vertical case there are some differences. First, the submarine weight causes an initial vertical static deflection in the keel and side blocks. This is taken into account by using a "DELTA" value, the static vertical deflection. "DELTA" changes as the block system stiffness changes and is updated for each time step in the three degree of freedom submarine drydock blocking system program, "3DOFRUB". The incorporation of the "DELTA" value into this computer program is discussed by Luchs [21] in greater detail. The other difference is that in the vertical direction there is no restoring force once the submarine lifts off of the side blocks. The model breaks down at this point and the computer

program flags this as a failure mode. Therefore, only the upper right hand quadrant of the bilinear loop is valid for vertical loading of the side blocks. Lift off occurs if there is zero vertical restoring force.

These procedures are then used to determine the keel and side block horizontal and vertical stiffnesses for all eleven submarine drydock blocking systems. Table (5.1) lists these stiffnesses for each system. KVSP, which is equal to KD3, is the vertical side block stiffness once the vertical FSPL has been exceeded. Similarly, KSHP, which is equal to KD2, is the horizontal side block stiffness once the horizontal FSPL has been exceeded. A complete listing of system (1-11) stiffnesses and values for XEL, QD, KU, KD are included in Appendix 3.

The area inside the bilinear loop is the energy lost to the system due to hysteretic damping during one excitation cycle. Figure (5.4) is an idealized picture of what would occur during one cycle of earthquake excitation. It is typical of what would happen during sinusoidal excitation where the FSPL is exceeded. However, earthquake excitation is much more complex and random in nature. The actual bilinear plot for an earthquake excitation is much more complicated.

TOTAL KEEL AND SIDE PIER STIFFNESS KIPS/IN
BILINEAR SYSTEMS (1-11) PER DOCKING DRAWINGS

SYSTEM	KVK	KVS	KVSP	KHK	KKHP	KHS	KSHP
1	46808.74	10113.39	4025.64	59223.08	38434.86	5825.13	2212.17
2	46808.74	5231.06	2082.23	59223.08	38434.86	3013.00	1144.23
3	31919.89	6178.56	3211.52	28875.45	22849.71	4055.29	1897.66
4	31919.89	3195.81	1661.13	28875.45	22849.71	2097.56	981.55
5	46808.74	3195.81	1661.13	59223.08	38434.86	2097.56	981.55
6	83270.20	43011.07	22269.52	79683.44	53718.39	28797.14	13345.17
7	83270.20	28512.95	14762.94	79683.44	53718.39	19090.24	8846.80
8	83270.20	21747.17	11259.87	79683.44	53718.39	14560.35	6747.56
9	24375.19	8629.57	4065.53	22050.35	17448.87	5842.63	2409.17
10	19442.11	6808.08	3188.10	17587.78	13917.55	4625.36	1890.63
11	19442.11	5236.99	2452.39	17587.78	13917.55	3557.97	1454.33

TABLE 5.1

A BASIC computer program is developed to generate bilinear stiffness for any point in time during system excitation. This program is general in nature so it can handle random earthquake excitations. It is developed based on an elasto-plastic BASIC program developed by Paz [40]. A listing of this program is included in Appendix 3. It includes a detailed explanation of the logic used to compute the bilinear stiffnesses. This program is later translated into FORTRAN and is included as a subroutine in "3DOFRUB". The name of this subroutine is "BILINALL" and is included in Appendix 1.

5.2 System 1 Bilinear Analysis Results

System 1 parameters are entered into "3DOFRUB" and the following results are obtained. First, the system fails at 16 % of the 1940 El Centro Earthquake due to side block liftoff. A copy of the output of this run and input data file are included in Appendix 3.

The system does not deform plastically in the horizontal direction. However, plastic deformation of the side block caps does occur in the vertical direction. Figure (5.5) shows the restoring force, R_4 , as a function of time. R_4 is designated as the force on the right set of side blocks looking forward at the submarine blocking system.

SISTEM 1 BILINEAR P4 VERSUS TIME

15% OF 1940 EL CENTRO EARTHQUAKE

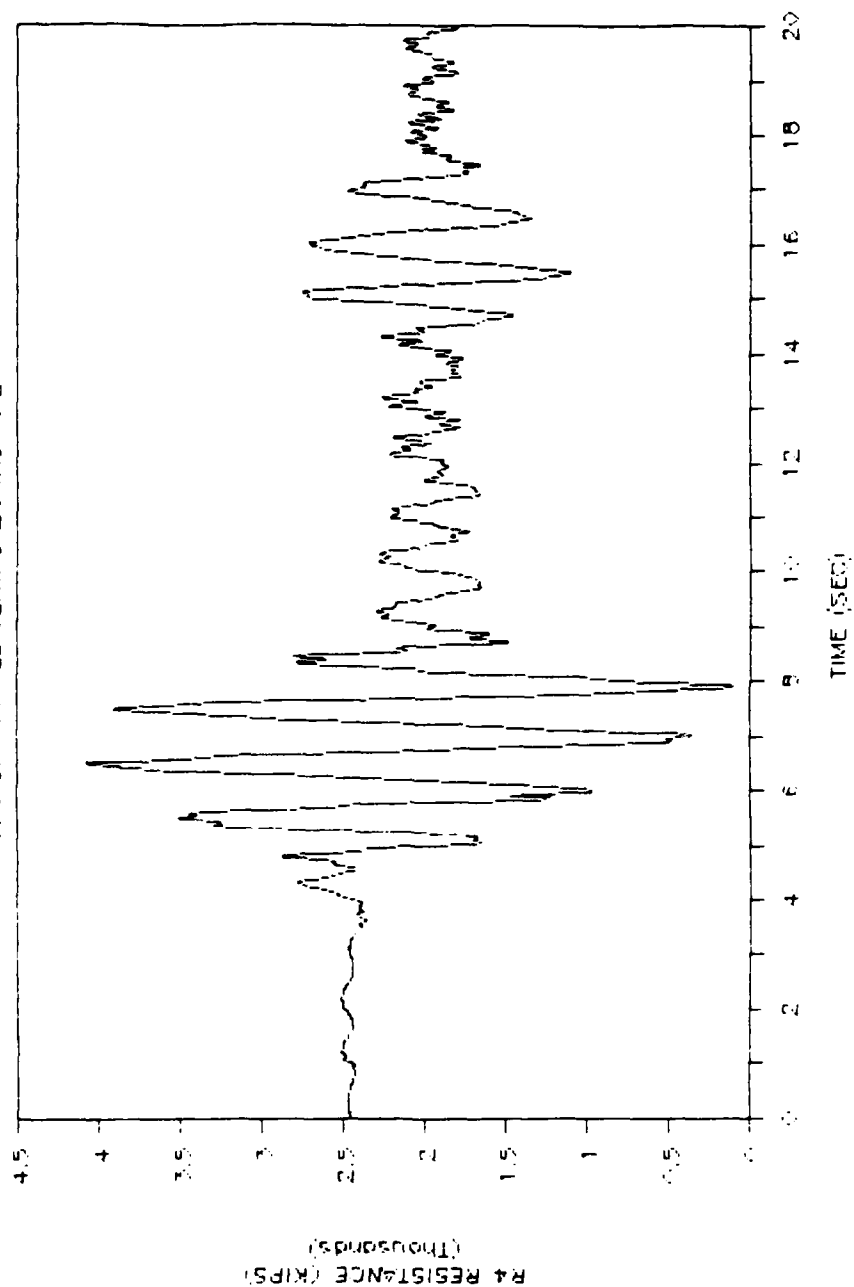


FIGURE 5.5

R4's initial value is a measurement of the portion of the weight of the submarine supported by that set of side blocks. Initially, it is excited about this point. After plastic deformation of the cap occurs, the right set of side blocks incurs a permanent set; therefore, the keel blocks, which do not plastically deform, are deflected to the same point as the side blocks and take more of the load. This reduces the load on the side blocks and causes the R4 plot to oscillate around a new lower value.

Figure (5.6) is a plot of the rotation of the submarine about the keel during this earthquake. There is direct correlation between rotation magnitude and R4 throughout much of the earthquake. This illustrates the dominance of the rotational degree of freedom in this particular system.

The permanent set is most evident in figure (5.7). This plot of R4 versus YPRIME2 (side block vertical deflection) is the upper right quadrant of the bilinear loop. Since this is a plot of the response to 15 % of the 1940 El Centro Earthquake, which the system survives, the plot remains in this quadrant and R4 does not go below zero. However, this plot does indicate that failure is imminent. A permanent set of 0.06 inches can be seen.

SYSTEM 1 BILINEAR THETA VERSUS TIME

15% OF 1940 EL CENTRO EARTHQUAKE

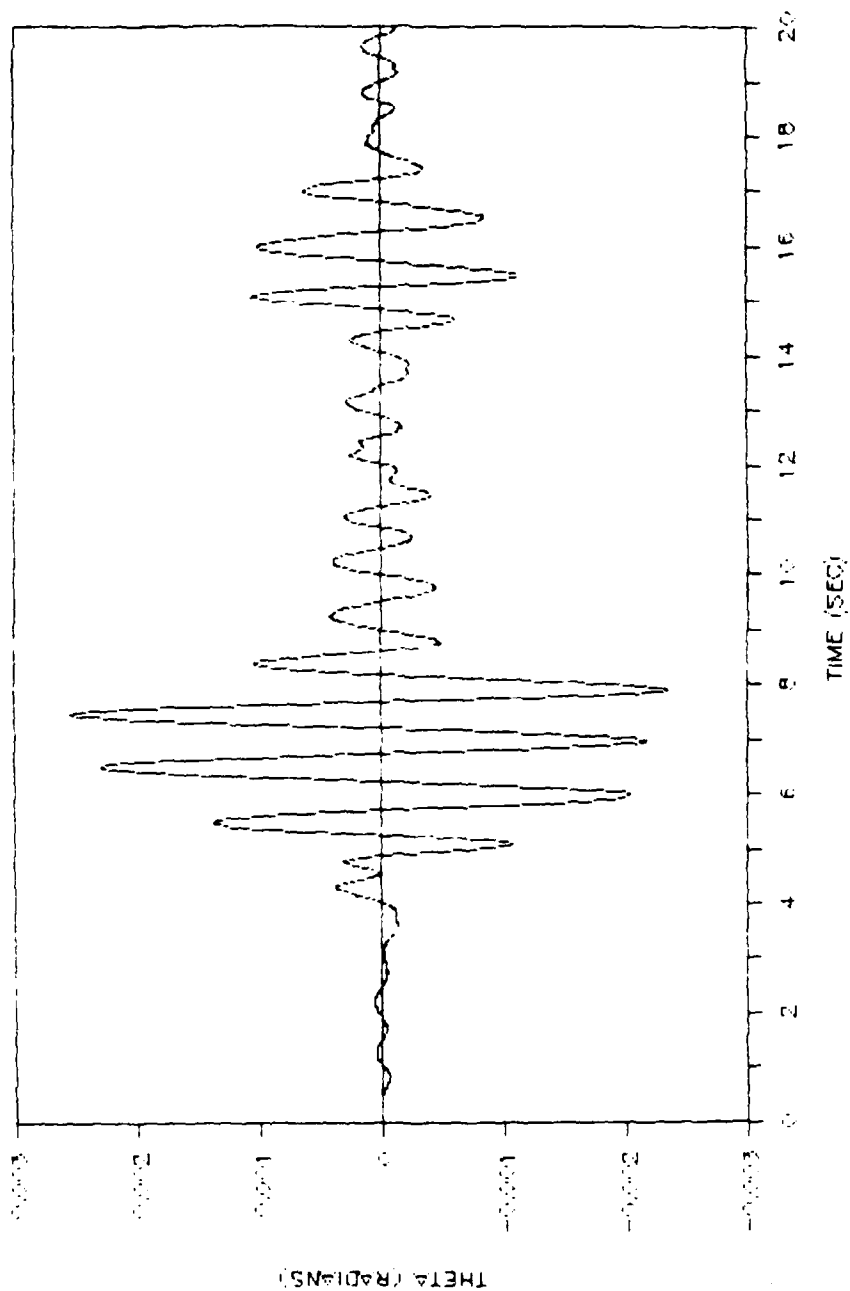


FIGURE 5.6

SYSTEM 1 BILINEAR (PRIME2 VS R4 15% OF 1947 EL CENTRO EARTHQUAKE

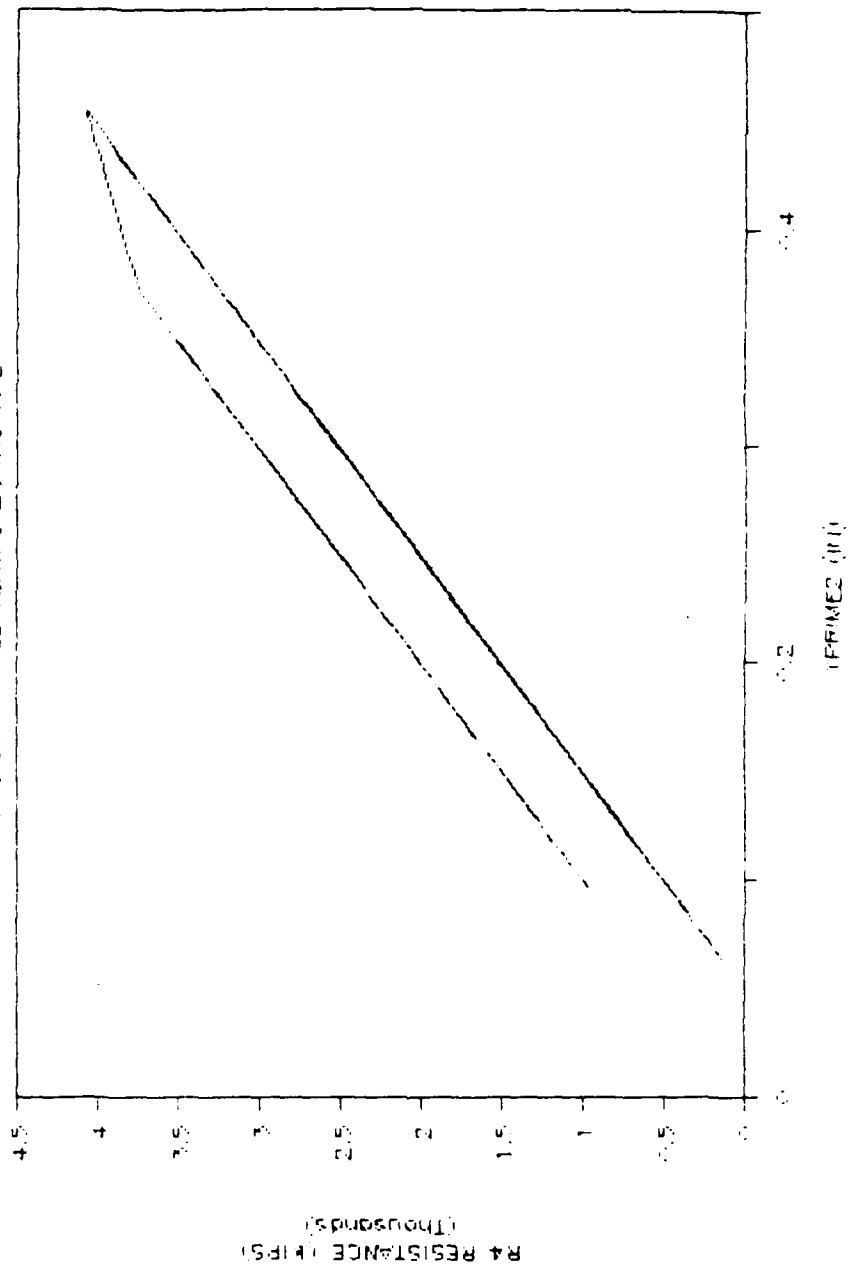


FIGURE 5.7

Failure would occur earlier because the location of the actual side block surface has changed. Lift off would occur at this new lower position. The bilinear behavior of the side blocks is clearly seen in the figure. The two stiffness slopes are evident.

Figure (5.8) is a plot of YPRIME during the 15 % of El Centro. The initial value is the static deflection of the side blocks. The zero displacement line on this curve indicates the initial undeflected position of the side blocks before the submarine weight is added.

Figure (5.9) is typical of the bilinear behavior due to horizontal loading of the keel or side blocks due to earthquake loading. One of the features of the bilinear subroutine logic is that as the velocity of the earthquake suddenly changes and the amplitudes decrease for a short period, the curve oscillates along an elastic line. Many of these oscillations can be seen in figure (5.9). This response is considered reasonable and is confirmed by experimental results done for dynamic isolators as shown in figure (4.9).

SISTEM 1 BILINEAR 1PRIM2 VERSUS TIME

15% OF 1940 EL CENTRO EARTHQUAKE

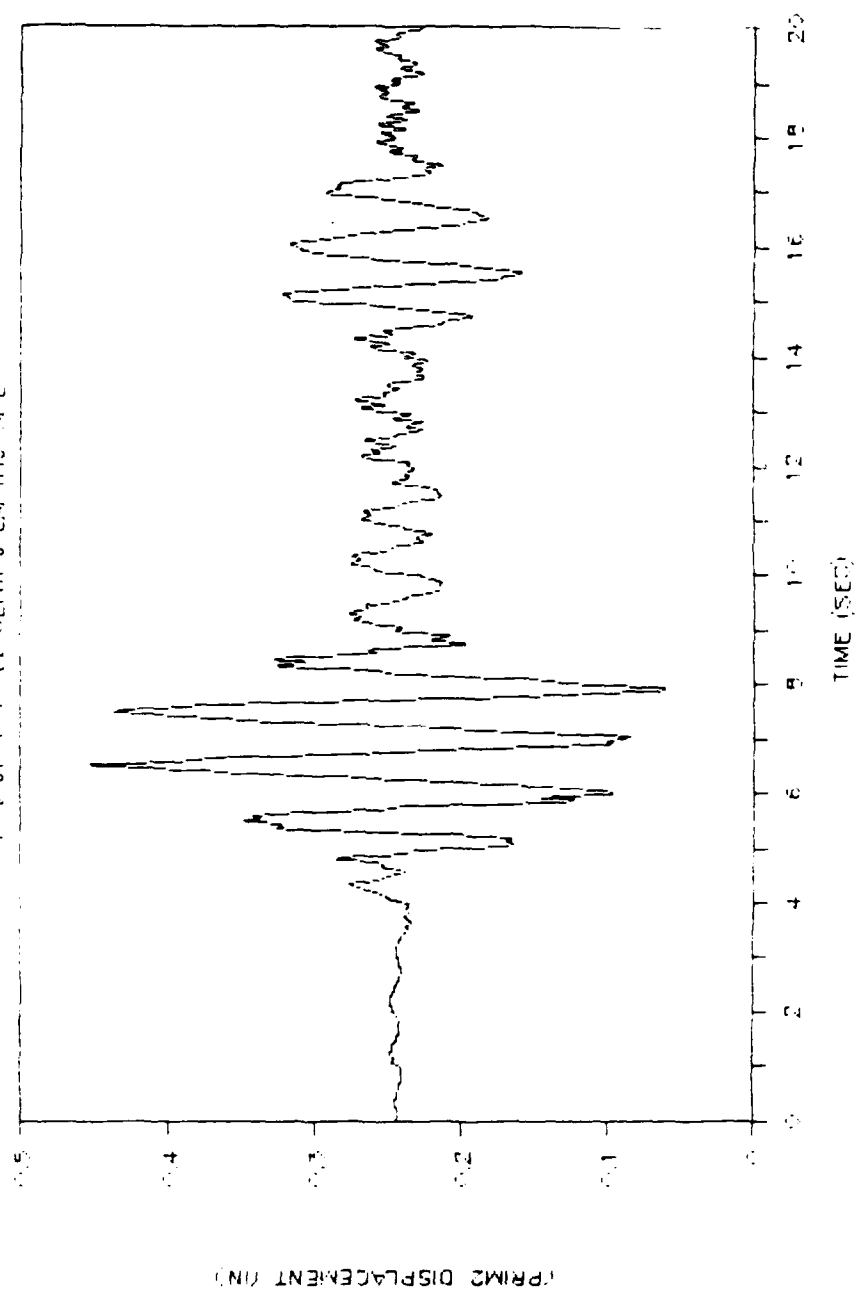


FIGURE 5.8

BILINEAR RESP. 1940 EL CENTRO QUAKE

SYSTEM 1

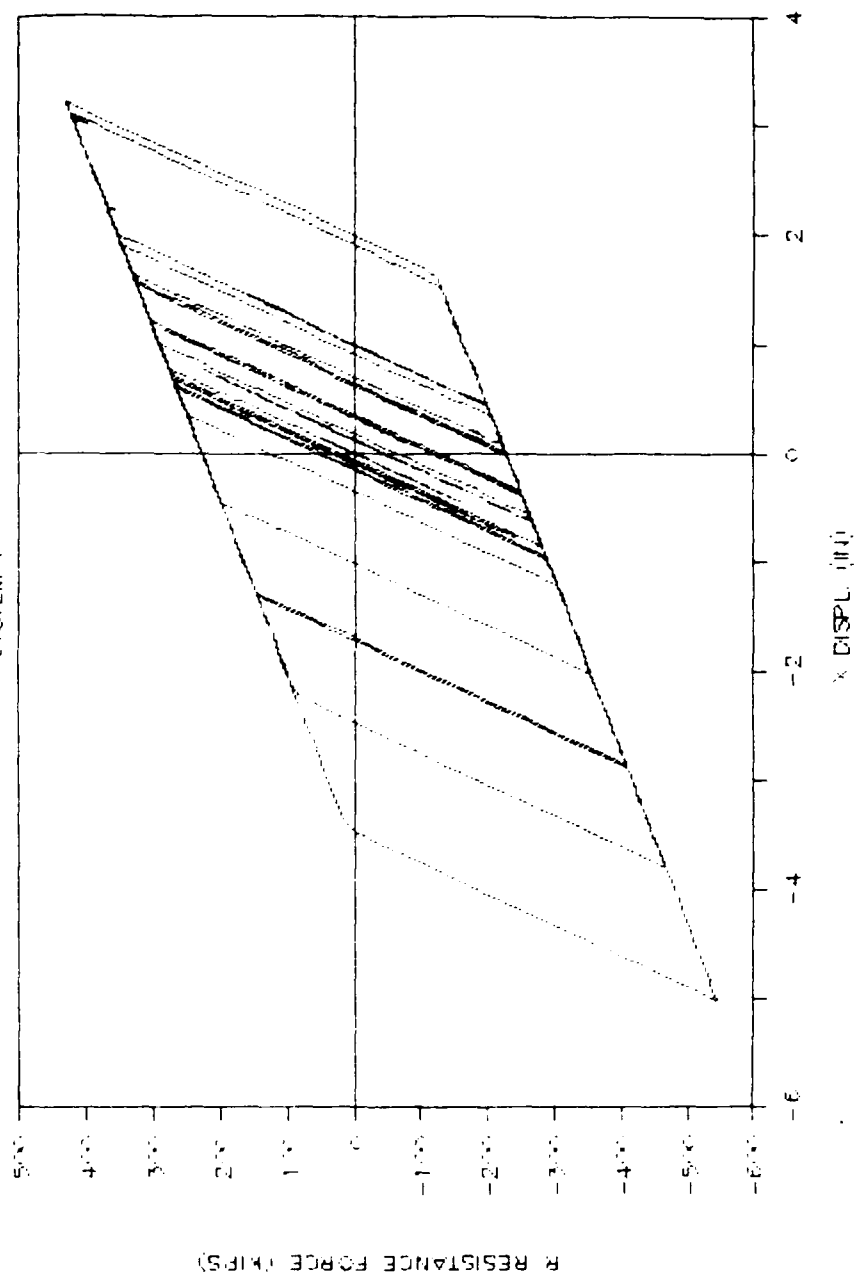


FIGURE 5.9

CHAPTER 6

RUBBER BILINEAR MATERIAL PROPERTY MODEL

6.0 Determination of Rubber Cap Properties

As shown previously, rubber has many properties that make it an ideal capping material for drydock blocking systems. Though rubber is a non-linear material, it is possible to model it as a bilinear material using similar procedures as for wood. Based on data from compression tests conducted by the Johnson Rubber Company of Middlefield, Ohio [33] on natural rubber, a bilinear model is developed. These tests results are shown in figure (6.1).

Two lines are drawn on figure (6.1) to approximate the non-linear load deflection behavior measured. From these lines two values of bilinear modulus of elasticity are computed as follows:

$$\sigma_v = P_v/A = (25 \text{ kips})/(36 \times 7 \text{ in}^2) = 99.2 \text{ psi} \quad (6.1)$$

$$k_1 = P_v/y' = (25 \text{ kips})/(0.2 \text{ in}) = 125 \text{ kips/in} \quad (6.2)$$

$$k_1 = EA/L \quad (6.3)$$

Combining (6.2) and (6.3) gives:

$$EA = k_1 \cdot L/A = (125 \text{ kips/in}) \cdot (2 \text{ in})/(36 \times 7 \text{ in}^2) = 992.1 \text{ psi} \quad (6.4)$$

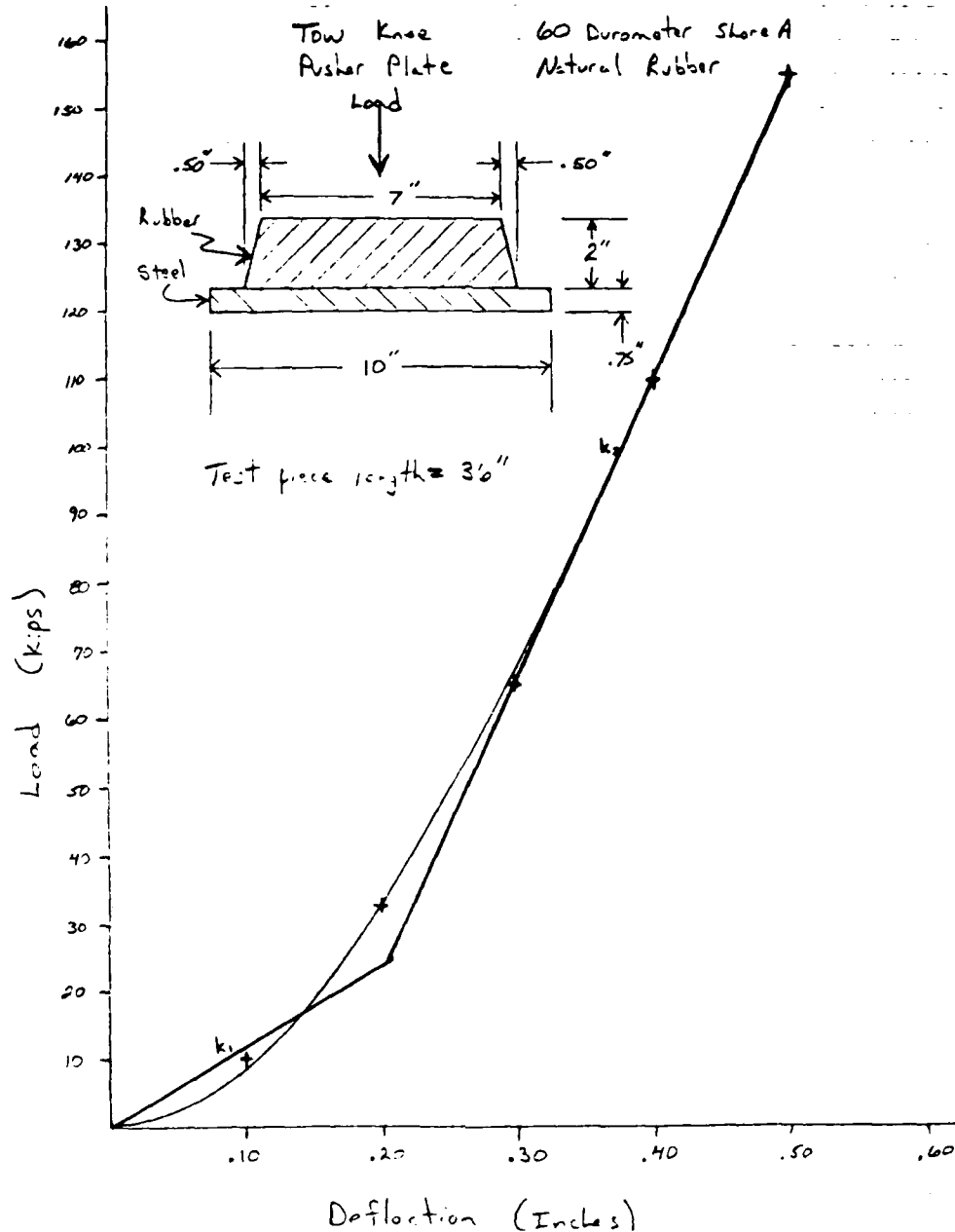
JOHNSON RUBBER CO.
SKETCHES AND COMPUTATIONS

TITLE Load Deflection Test

JOB NO. _____

DATE _____

Turn in with job - make orderly and with notes so anyone can follow.



Rubber Compression Test Results and
 Bilinear Approximation

FIGURE 6.1

For the second slope:

$$k_2 = \Delta P / \Delta y = (110-65 \text{ kips}) / (0.4-0.3 \text{ in}) = 450 \text{ kips/in} \quad (6.5)$$

$$E_2 = k_2 * L / A = (450 \text{ kips/in}) * (2 \text{ in}) / (36 * 7 \text{ in}^2) = 3571 \text{ psi} \quad (6.6)$$

Where:

σ_y is the yield stress for the natural rubber in figure (6.1)
at which point the modulus changes to a higher value.

P_y is the yield load for this test specimen.

A is the cross sectional area of the test piece. The specimen
was 36 inches long by 7 inches wide.

k_1 is the initial stiffness of the rubber specimen which is
the initial slope in figure (6.1).

y' is the deflection of the specimen at the point where the
slopes change.

E_1 is the initial modulus of natural rubber calculated from
this test.

L is the thickness of the test specimen (2 inches).

k_2 is the second stiffness of the rubber specimen which is the
second slope in figure (6.1).

ΔP is the change in load measured along a portion of the
second slope.

Δy is the change in deflection measure along the same portion
of the this slope.

E_2 is the second modulus of natural rubber calculated from
this test.

The initial value of modulus determined from this test specimen (992 psi) correlates very well with other compressive tests [30] conducted on hard rubber giving a modulus of 1044 psi.

Using the two computed moduli and the yield stress for natural rubber, an idealized stress-strain curve for natural rubber for side block vertical loading is constructed. This curve is shown in figure (6.2). This differs from the idealized stress-strain curve for Douglas fir in that rubber starts off initially with a low stiffness and shifts to a higher one at a relatively low stress level. Whereas, Douglas fir exhibits an initial high stiffness and shifts to a second stiffness similar to natural rubber at a much higher stress level.

Since rubber is isotropic, no load orientation modifications has to be made. As mentioned in section 4.3, up to very large values of strain, shear remains very close to linear and does not exhibit the change in stiffness as in the case of compression. Therefore, the modulus of rigidity and thus horizontal stiffness is assumed constant. Applying equation(4.11), the value of shear modulus of rigidity is computed as follows:

$$G = 0.339 \cdot E = 0.339 \cdot 992.1 \text{ psi} = 336 \text{ psi} \quad (6.7)$$

IDEALIZED STRESS/STRAIN CURVE
NATURAL RUBBER
SIDE BLOCK VERTICAL LOADING

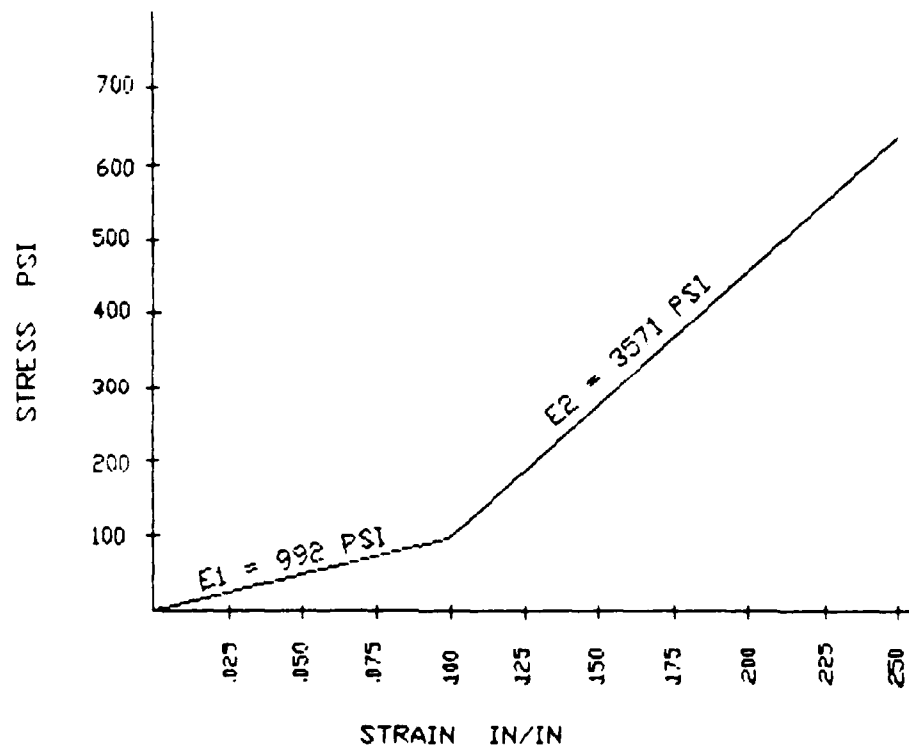


FIGURE 6.2

6.1 Side Block System Rubber Cap Bilinear Model

A modified form of the bilinear model used to represent Douglas fir is used for side block rubber caps under vertical loading. In the vertical direction, there is no restoring force once the submarine lifts off the side blocks; therefore, only the upper right hand quadrant of the bilinear loop is valid in this case. This rubber bilinear model differs from the Douglas fir model in that the rubber unloads down the same path that it is loaded. This is a good approximation of the behavior of rubber since rubber experiences no permanent set even past the point where it changes stiffness. Actual rubber does experience slight hysteresis, but this is taken into account in the "3DOFRUB" program by using 5 % critical damping. For very thick rubber caps 8 % critical damping is used in this thesis.

Figure (6.3) is a depiction of this rubber bilinear model. In this figure $KU3$ is equal to kvs and $KD3$ is equal to $kvsp$. In this case, kvs is the total initial stiffness of one set of side blocks. It is obtained by inputting $E1$ for natural rubber into the vertical stiffness spreadsheets included in Appendix 4. Similarly, $kvsp$ is obtained by inputting $E2$ for natural rubber into the vertical stiffness spreadsheets. The value $kvsp$ is the total stiffness of one set of side blocks once the rubber cap changes stiffness to its higher value.

BILINEAR FORCE/DISPLACEMENT CURVE
RUBBER CAPS
SIDE BLOCKS VERTICALLY LOADED

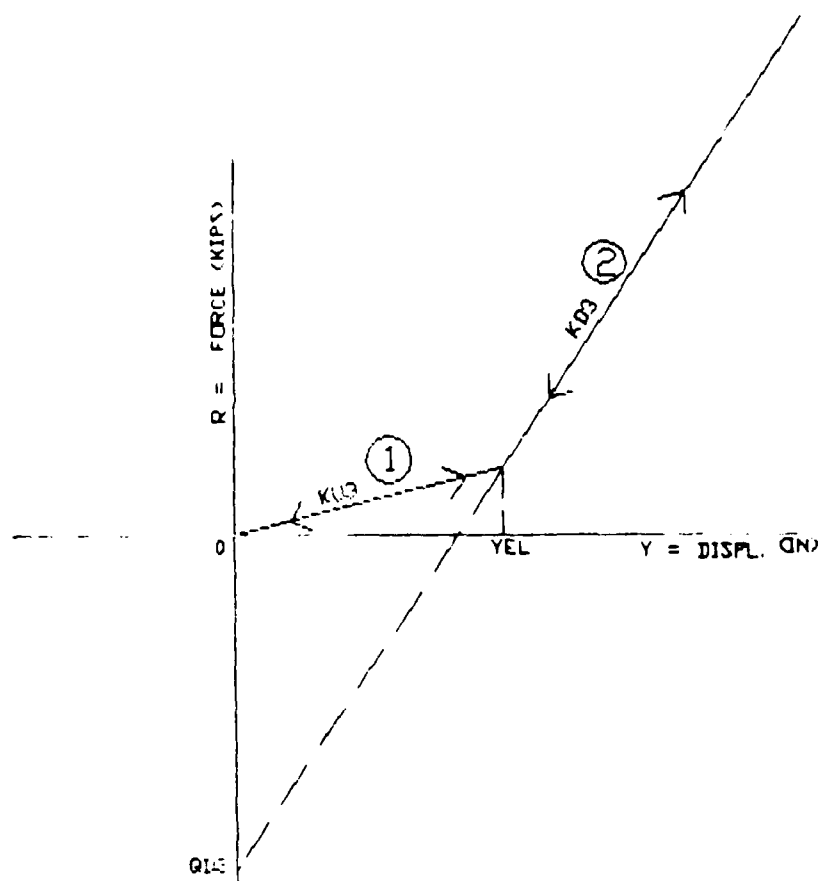


FIGURE 6.3

The following equations describe the various features of figure (6.3):

$$YEL = \sigma_y * A_c / kvs \quad (6.8)$$

$$QD3 = YEL * (KU3 - KD3) \quad (6.9)$$

$$\text{Line 1: } R = KU3 * y \quad (6.10)$$

$$\text{Line 2: } R = KD3 * y + QD3 \quad (6.11)$$

Where:

YEL is the elastic limit for the blocking system in inches.

A_c is the cap area for one set of side blocks.

R is the restoring force of the side blocking system due to vertical displacement.

y is the vertical displacement of the cap surface of the side blocking system.

QD3 is the R intercept of the second stiffness slope.

Since natural rubber exhibits bilinear behavior at a very low stress level, it is necessary to also develop a bilinear model for the keel blocks. This is not necessary for Douglas fir capped keel blocks because they do not reach sufficient stress levels to exhibit bilinear behavior. An approach similar to that used for the side blocks is used to develop the bilinear rubber model for the keel blocks.

An additional subroutine for the "3DOFRUB" computer program is developed to include the rubber bilinear behavior. This subroutine is called "RUBBER" and is included in Appendix 1. The "3DOFRUB" computer program uses the fact that the QD's are negative for rubber as a flag to call the "RUBBER" subroutine. The inclusion of both the "BILINALL" and "RUBBER" subroutines in "3DOFRUB" makes the program sensitive to materials with different types of non-linear behavior.

6.2 Rubber Bilinear Analysis Results

A one inch rubber cap is put on all of the eleven submarine drydock blocking systems. The stiffnesses are calculated using similar spreadsheets to those included in Appendix 4. The tabulated results for stiffnesses, YEL's, KU's, KD's, and QD's for these new systems are also listed in this appendix. System 12 corresponds to system 1 with a 1 inch rubber cap on both the keel and side blocks. Systems 30 through 39 correspond to systems 2 through 11 with similar rubber caps. Chapter 8 of this thesis compares the differences in response due to addition of rubber for all eleven systems.

System 12 parameters are entered into "3DOFRUB" and the following results are obtained. First, the system fails at 33 % of the 1940 El Centro Earthquake due to side block lift off.

Without the 1 inch rubber cap system 1 fails at 16 % of this earthquake. Therefore, the addition of 1 inch of rubber doubled the survivability of system 1. A copy of the output of the system 12 run and a copy of the input data file are included in Appendix 4.

Figure (6.4) is a plot of the restoring force, R_4 , as a function of time. As in the case of wood, R_4 's initial value shows the portion of the submarine weight supported by that set of side blocks. Unlike the wood case, no permanent plastic deformation of the cap occurs, and R_4 oscillates about the initial displacement point. Again in this figure, as is the case for wood, the rotational degree of freedom appears to dominate the response for the side blocks. A plot of the rotation of the submarine about the keel as a function of time is shown in figure (6.5).

The rubber bilinear behavior of the side block system is clearly seen in figure (6.6). This figure shows that the rubber capped side blocks load and unload on the same curve during each cycle of the earthquake. Since this system survives this magnitude of the earthquake the value of R_4 does not go below zero, however, failure is imminent.

SYSTEM #12 P4 VS TIME 32% 1940 EL CENTRO EARTHQUAKE

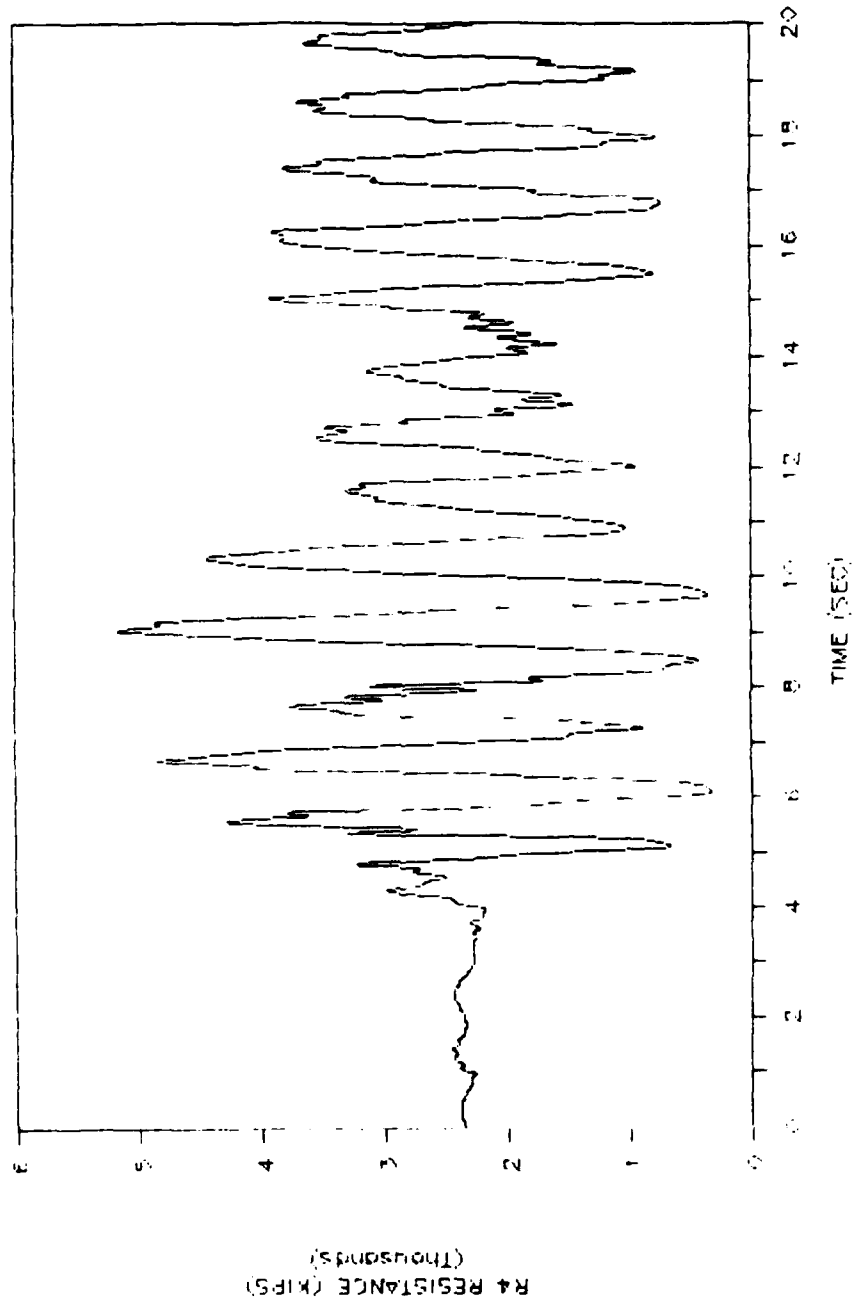


FIGURE 6.4

SYSTEM # 12 THETA VS TIME 32 ° 194° EL CENTRO EARTHQUAKE

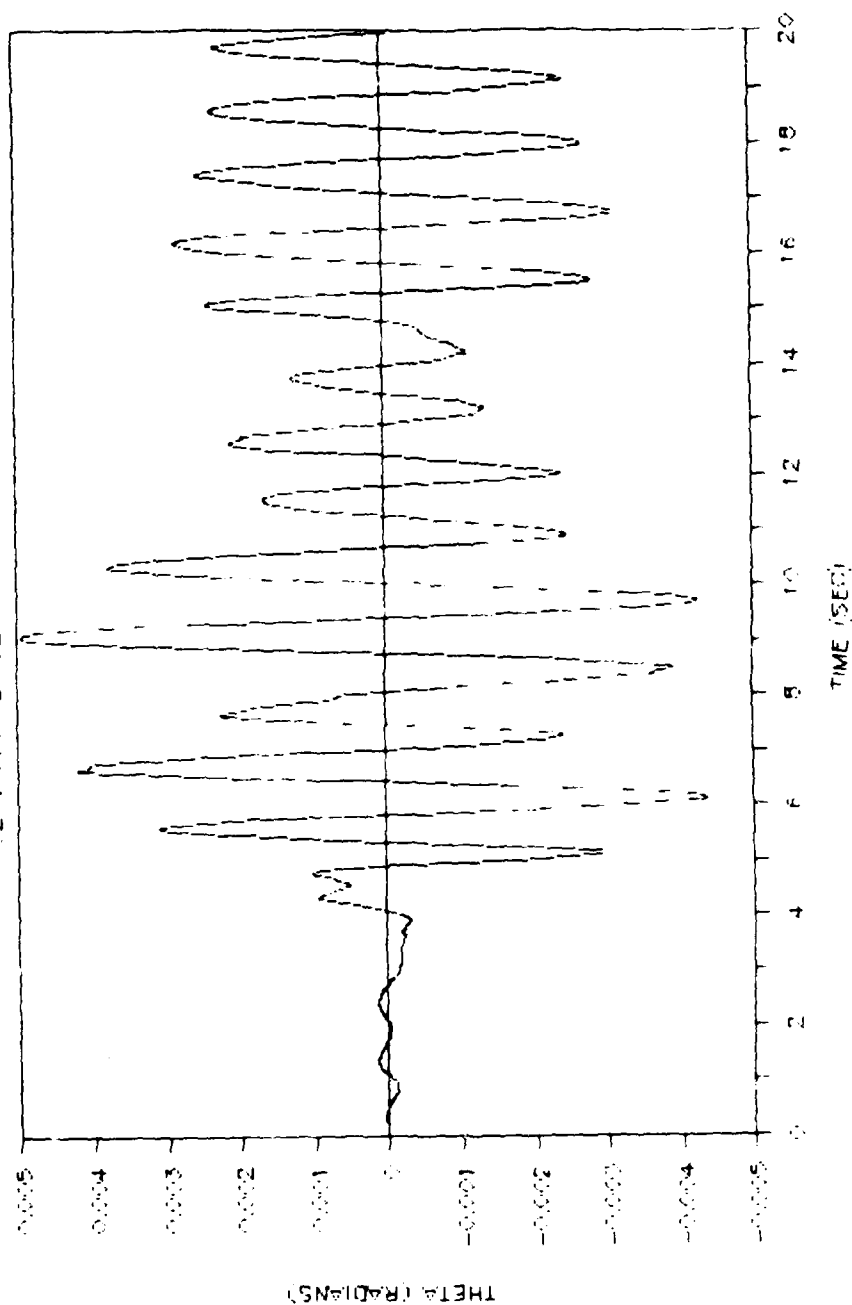


FIGURE 6.5

SYSTEM #12 R4 VS YPRIME2 32% 1941 EL CENTRO EARTHQUAKE

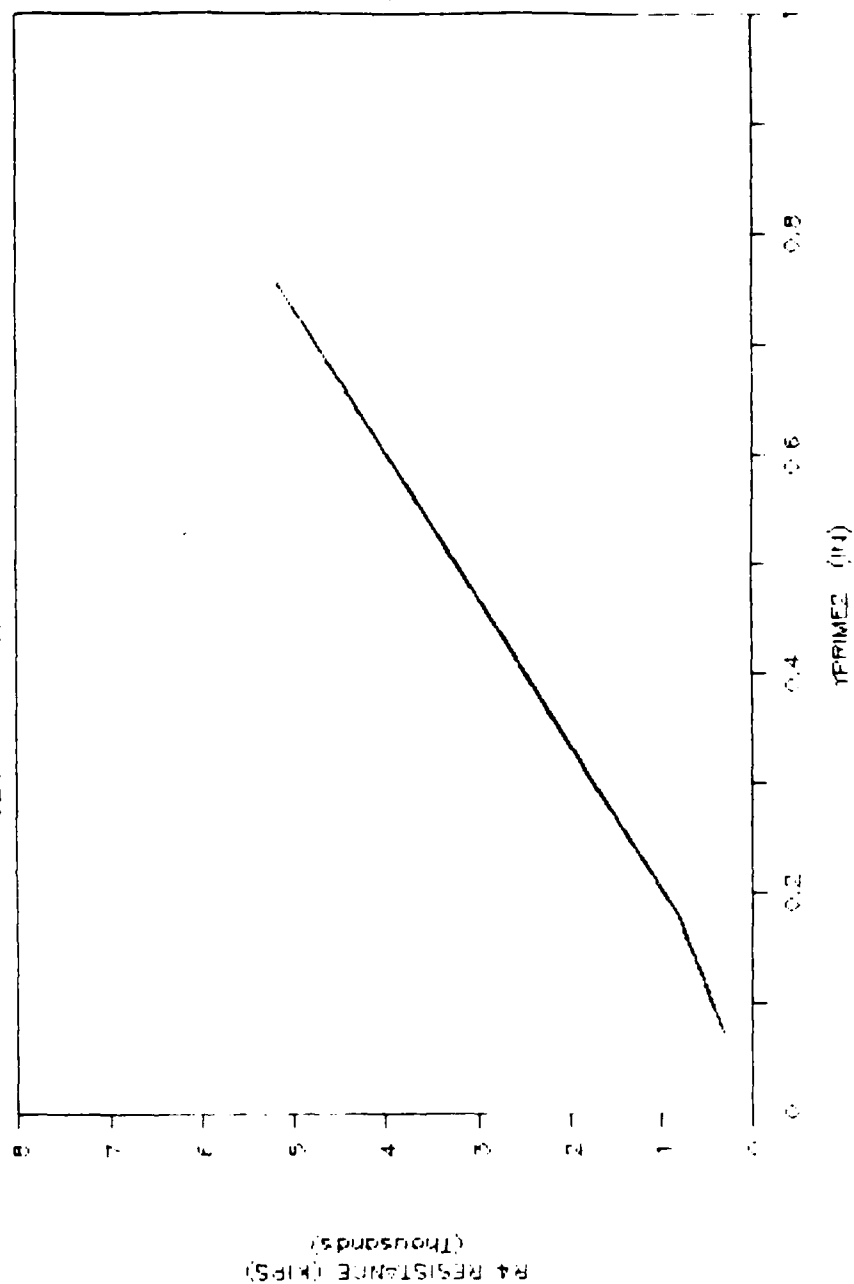


FIGURE 6.6

The key feature of the rubber capping material is displayed in figure (6.6). As the side block system unloads it becomes more difficult for the submarine to lift off the blocks as R4 and YPRIME2 approach zero. This is due to the rubbers' low stiffness at low stress.

Figure (6.7) is a plot of the vertical deflection of the side blocks during the earthquake. The initial deflection is the static deflection caused by the submarine weight. This initial deflection is significantly larger than the deflection which occurs when wood caps are used. This is due to the rubber cap's lower initial modulus of elasticity. For rubber caps, the initial deflection is approximately 0.38 inches; and for Douglas fir caps, this initial deflection is 0.24 inches.

32 Z 1945 EL CENTRO EASTHOLME



FIGURE 6.7

CHAPTER 7

DYNAMIC ISOLATOR BILINEAR MATERIAL PROPERTY MODEL

7.0 Determination of Dynamic Isolator Blocking Properties

The use of dynamic isolators in drydock blocking systems offer many advantages over standard drydock blocking configurations used today in high seismic risk areas. Dynamic isolators decouple the drydocked submarine from horizontal ground accelerations, dissipate earthquake energy, and significantly reduce accelerations seen by delicate equipment inside the submarine. This chapter will analyze the properties of the D.I.S. dynamic isolator described in section 4.4 and shown in figure (4.7).

Table 7.1 lists dynamic isolator bilinear properties supplied by Dynamic Isolation Systems Incorporated [36] for each side block and keel block isolator. These isolators are of sufficient size and strength to be applicable to submarine drydock blocking system 1.

TABLE 7.1

	SIDE ISOLATOR	KEEL ISOLATOR
QD:	4.55 kips	11.03 kips
KU:	17.8 kips/in	31.31 kips/in
KD:	1.83 kips/in	3.72 kips/in
Kvert:	850 kips/in	1845.83 kips/in

(where Kvert is the vertical stiffness of each isolator)

In order to incorporate these isolator properties into blocking pier stiffness calculations, it is necessary to calculate equivalent elastic moduli for these isolators. Appendix 5 includes the spreadsheets used to perform these calculations. These spreadsheets are virtually the same spreadsheets previously used to calculate blocking pier horizontal stiffness. Four blocking layers are maintained in these spreadsheets. The isolator replaces the oak. It is assumed that the isolator has the same dimensions as the oak layer.

To determine an equivalent modulus of elasticity this new isolator layer is modeled as a cantilever beam/ shear element. To accomplish this, the isolator layer is moved to the top of the four layers of the blocking pier and the other layers are made infinitely stiff. The resulting layer stiffness is made equal to the given value from Table 7.1 by adjusting the value of the isolators' modulus of elasticity. The modulus of rigidity is assumed to be one-tenth of the value of modulus of elasticity. Since the output is a total layer stiffness which includes both bending and shear effects, the exact relationship of modulus of elasticity to modulus of rigidity is not important. Moduli are determined in this manner for side and keel block KU's and KD's.

Once the moduli for the isolators are determined, total blocking pier stiffnesses are determined by using the stiffness spreadsheets as before. Portions of these spreadsheets listing the blocking pier stiffness results are included in Appendix 5. Figures (7.1) and (7.2) are the idealized stress/strain curves for side block and keel isolators respectively subject to horizontal load. The isolators' equivalent modulus values (E1 and E2) shown are those obtained from the spreadsheets. The stress at which the curves change slope (σ_{max}) is obtained from the following equations.

$$\sigma_{max} = P_{max}/A_{top} = XEL * KU / A_{top} \quad (7.1)$$

$$XEL = QD / (KU - KD) \quad (7.2)$$

where:

P_{max} is the maximum force the isolator can withstand without changing the modulus of elasticity.

A_{top} is the top cross-sectional area of the isolator.

7.1 Keel Blocking System Dynamic Isolator Bilinear Model

As can be seen in figure (7.1) and (7.2) a D.I.S. dynamic isolator exhibits bilinear material properties. Therefore, these isolators can be described using a bilinear model similar to that used for wood.

IDEALIZED STRESS/STRAIN CURVE
D.J.S. ISOLATOR
SIDE BLOCK HORIZONTAL LOADING

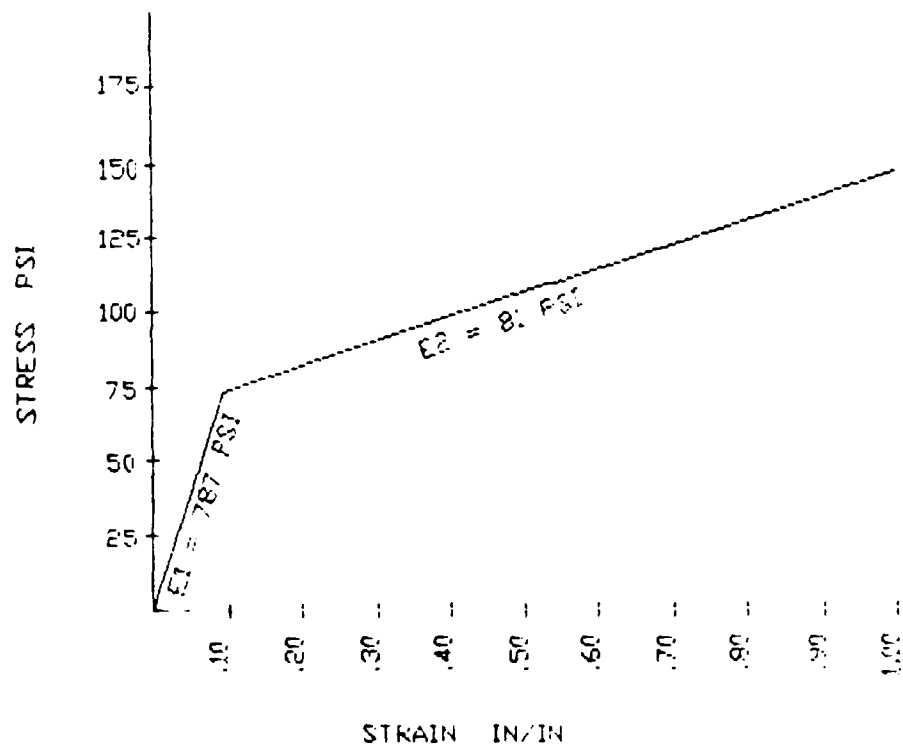


FIGURE 7.1

IDEALIZED STRESS/STRAIN CURVE
D.I.S. ISOLATOR
KEEL BLOCK HORIZONTAL LOADING

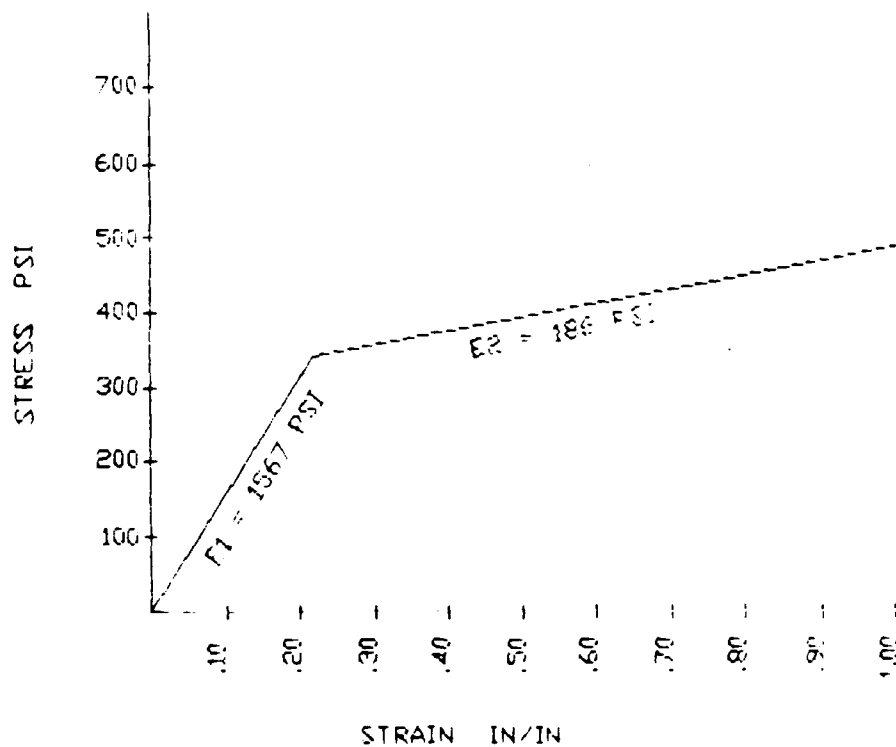


FIGURE 7.2

Figure (5.4), the bilinear force-displacement curve for the horizontal keel blocking system, is a description of the behavior of the D.I.S. dynamic isolator.

The QD value in figure (5.4) for the keel block system (which includes isolators) is obtained using the following equations:

$$XEL1 = P_{max}/KU1 \quad (7.3)$$

$$QD1 = XEL1*(KU1-KD1) \quad (7.4)$$

where:

XEL1 is the elastic limit for the keel blocking system in inches.

QD1 is R intercept of the second stiffness slope for the keel blocking system.

KU1 is equal to the khk.

KD1 is equal to khkp.

Equations (5.3) through (5.7) in section 5.1 describing the features of the bilinear loop are also directly applicable. The side blocking system is modeled in a similar manner. The "BILINALL" subroutine previously described is used to implement the bilinear model for D.I.S. isolators in the "3DOFRUB" computer program.

7.2 System 1 D.I.S. Isolator Bilinear Analysis Results

Submarine drydock blocking system 1 is used as the baseline for this analysis. The isolators are added to this system as described in section 7.1. The parameters from this system are input into the "3DOFRUB" computer program. The results of this run and the input data are included in Appendix 5.

Several modifications are made to the input data file. These include making the side block and keel block widths extremely large to simulate their being rigidly attached to the dock floor. This would be required if base isolators are used due to the large horizontal displacements which occur. Also, the coefficient of friction for the block on block surface is increased to a very large number to simulate the rigid attachment of the isolators to the blocking pier and caps. This attachment is essential for proper isolator performance. The percentage of critical damping is increased slightly to a value (8 %) consistent with the use of elastomeric base isolation systems [34].

The system fails at 37 % of the 1940 El Centro earthquake due to side block liftoff. Figure (7.3) shows the horizontal side block restoring force, R2, as a function of time for this system (system 90) and for the original system 1.

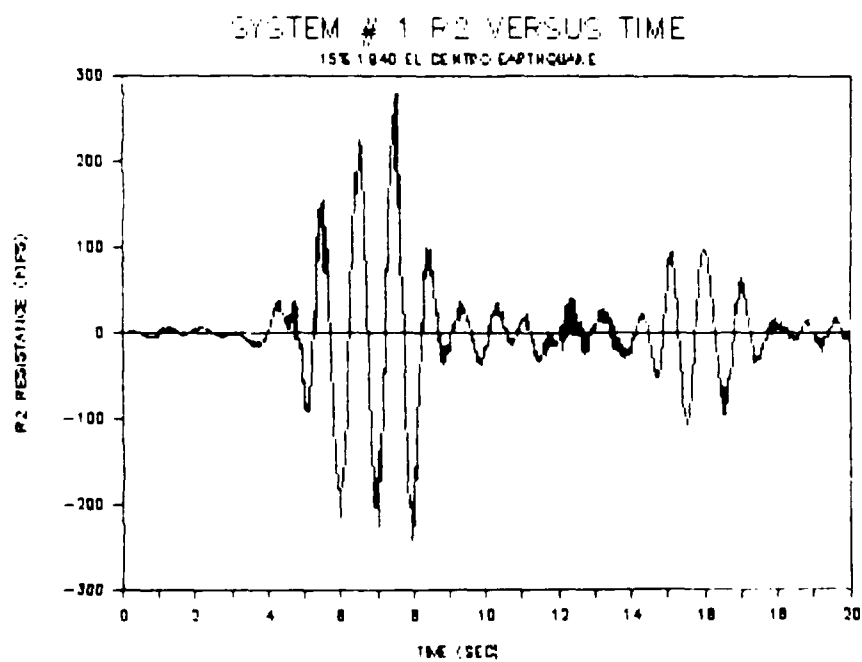
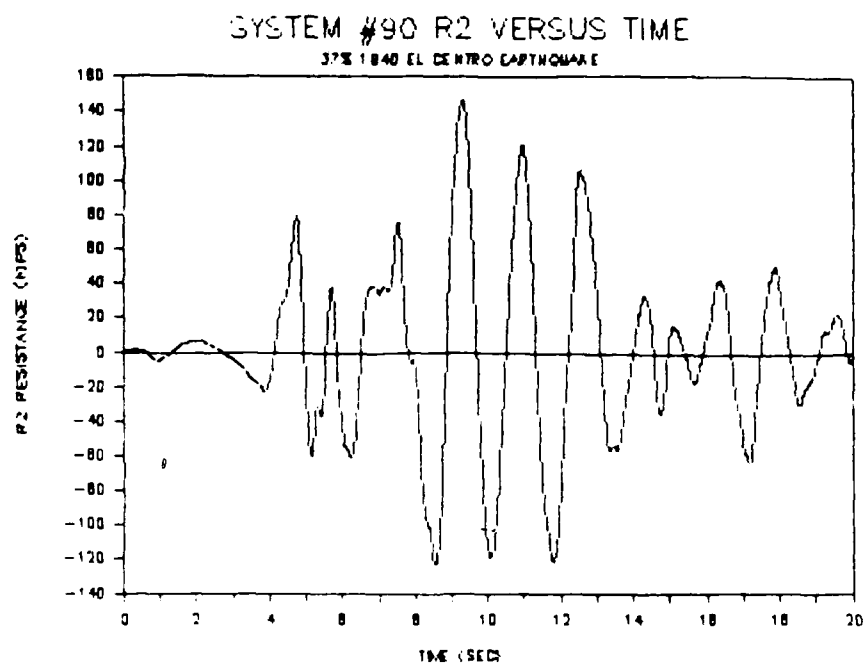


FIGURE 7.3

Though system 1 survives less than half the earthquake percentage of system 90, it experiences twice the forces. System 90 also shows smoother and lower frequency force response. This shows how the isolator reduces the forces and accelerations seen by the internal equipment and personnel on the submarine.

Figure (7.4), a plot of force versus horizontal displacement, shows that the side blocks on both systems 1 and 90 behaves in a linear elastic fashion up to their respective earthquake magnitude of failure. As shown by run output in Appendix 5 system 90 fails once bilinear side block system response starts to occur. The large resulting deflections cause the submarine to lift off the side blocks. This shows that these particular isolators are not optimized (tuned) for this system.

Optimal isolators for this system would decrease the modal frequencies until they are no longer efficiently excited by the earthquake frequency spectrum. Presently, system 90's mode 2 frequency (2 HZ) corresponds to the fundamental frequency of the El Centro earthquake. Luchs [21] describes the effect of modal frequencies on system response.

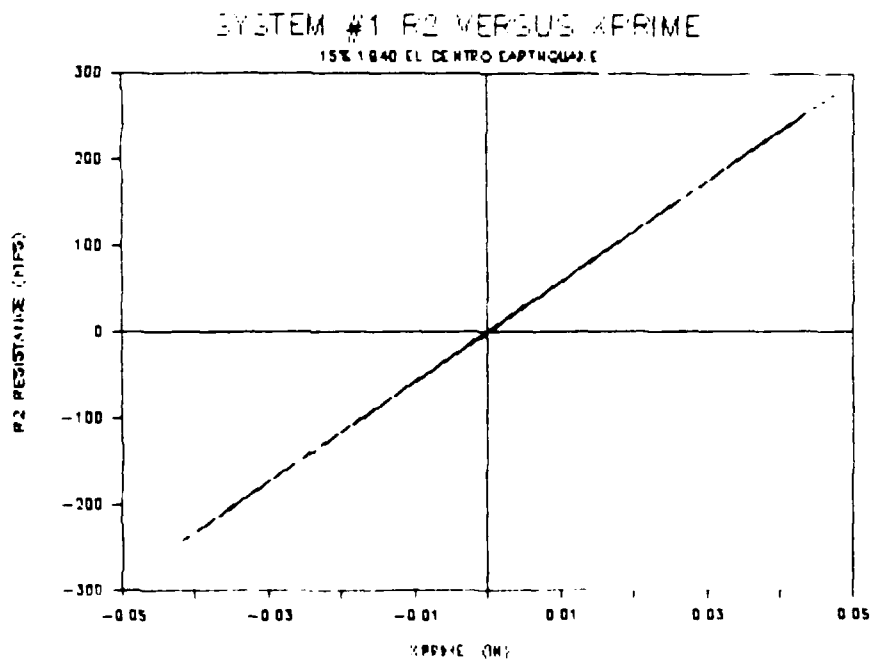
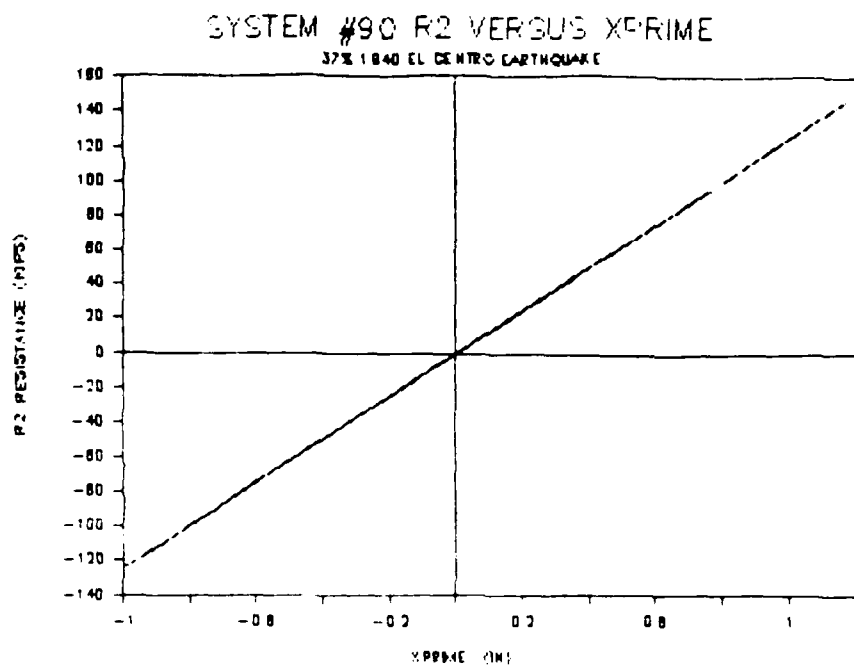


FIGURE 7.4

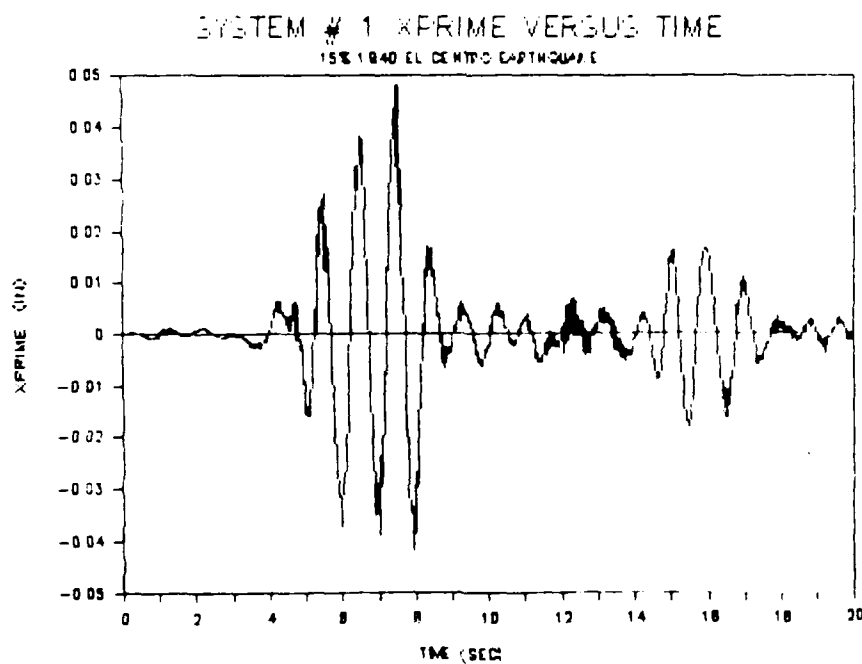
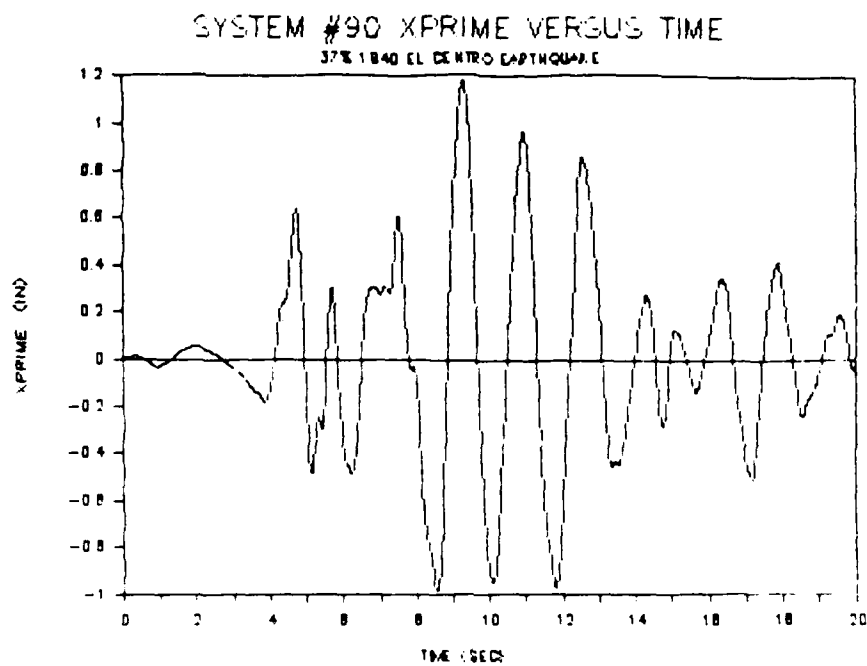


FIGURE 7.5

Horizontal displacement versus time is shown in figure (7.5) for the two systems. As expected system 90 shows very large displacements compared to system 1. Horizontal displacements are almost two orders of magnitude greater when isolators are used in this blocking system.

Forces and displacements correlate very strongly with rotation (θ), figure (7.6) for both systems. Again, this shows the dominance of the rotational degree of freedom in these systems. This is a large reason why the use of horizontal base isolation alone may not be the total answer to the lift off failure problem.

Figure (7.7) shows that the isolators have little effect on the vertical system displacements. Both systems 90 and 1 follow the earthquake's vertical excitation very closely in this direction. Displacements would be approximately the same if both systems experienced the same earthquake magnitude. Since the systems are much stiffer in the vertical direction, a much higher response frequency is seen.

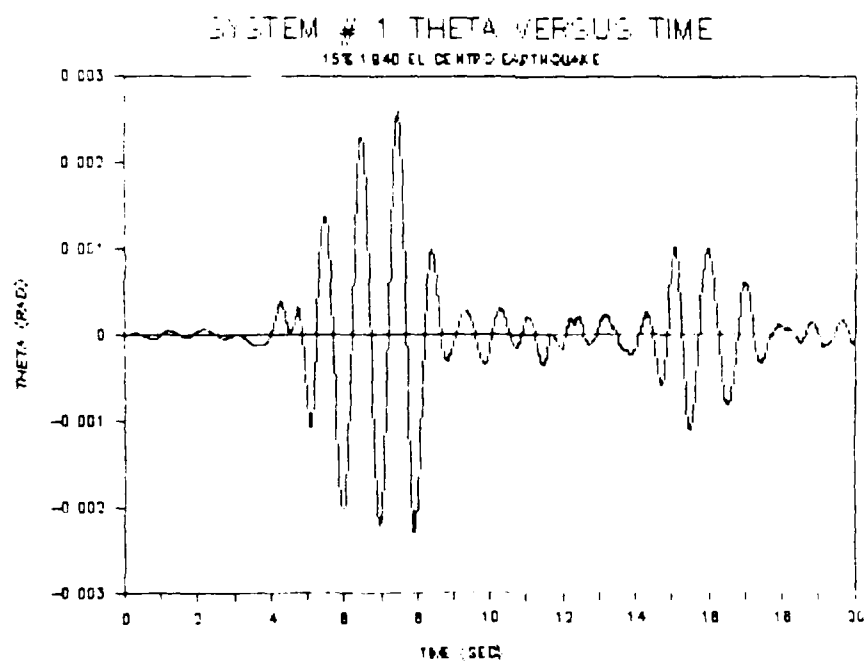
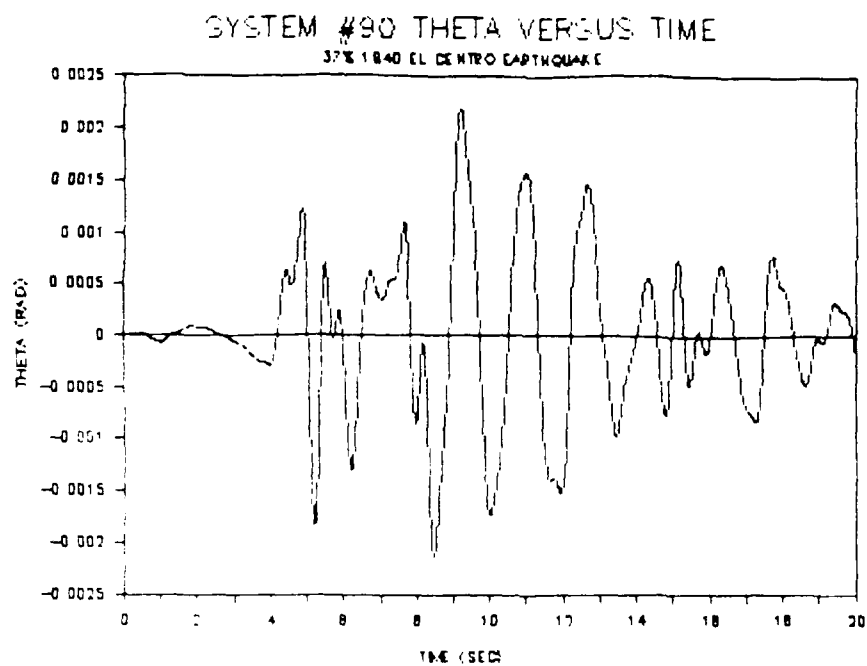


FIGURE 7.6

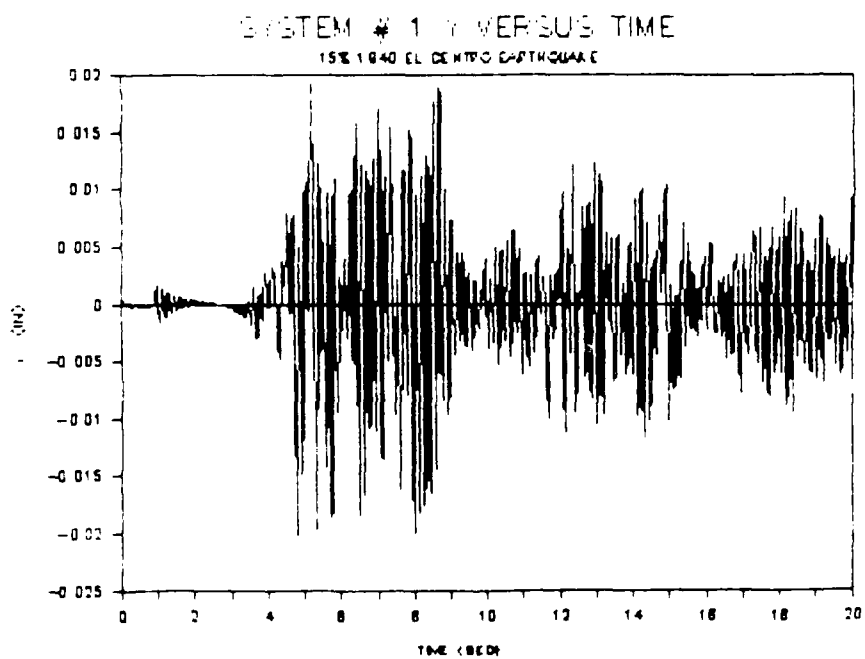
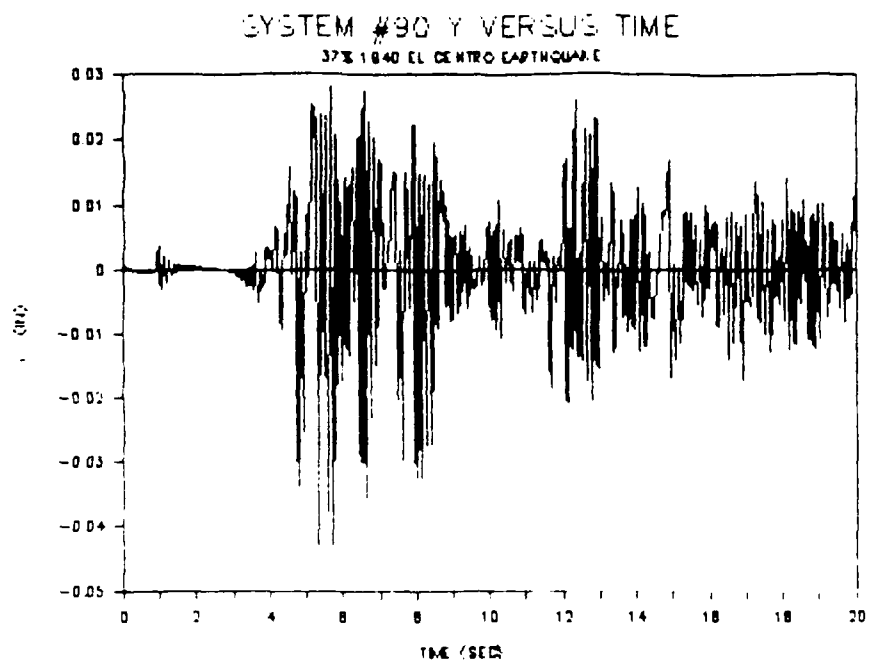


FIGURE 7.7

CHAPTER 8

COMPARISON OF SUBMARINE DRYDOCK BLOCKING SYSTEM MATERIALS

8.0 Submarine Drydock Blocking System Material Comparison

The eleven submarine drydock blocking systems previously analyzed by Sigman [16] are reexamined using the bilinear wood model and bilinear rubber model (using 1" rubber caps). Using the procedures described in sections 5.1 and 6.1 for wood and rubber respectively, stiffness and QD values are obtained for the eleven systems. A complete listing of these properties is included in Appendix 4.

These values are input into the "3DOFRUB" computer program for each of the eleven systems while all other submarine and dry dock parameters remain the same. The program is run for each system using the same 1940 El Centro earthquake acceleration time history as Sigman.

8.1 Bilinear Wood Versus Sigman's Drydock Blocking System Material Model

Sigman's results are discussed in section 3.2 and are shown in figure (3.2). The survival percentages for the eleven systems as determined by Sigman ranged from 13 to 39 % (mean 26%) of the 1940 El Centro earthquake acceleration time history (0.06 to 0.18 g's peak).

SUBMARINE BLOCKING SYSTEMS (1-11)

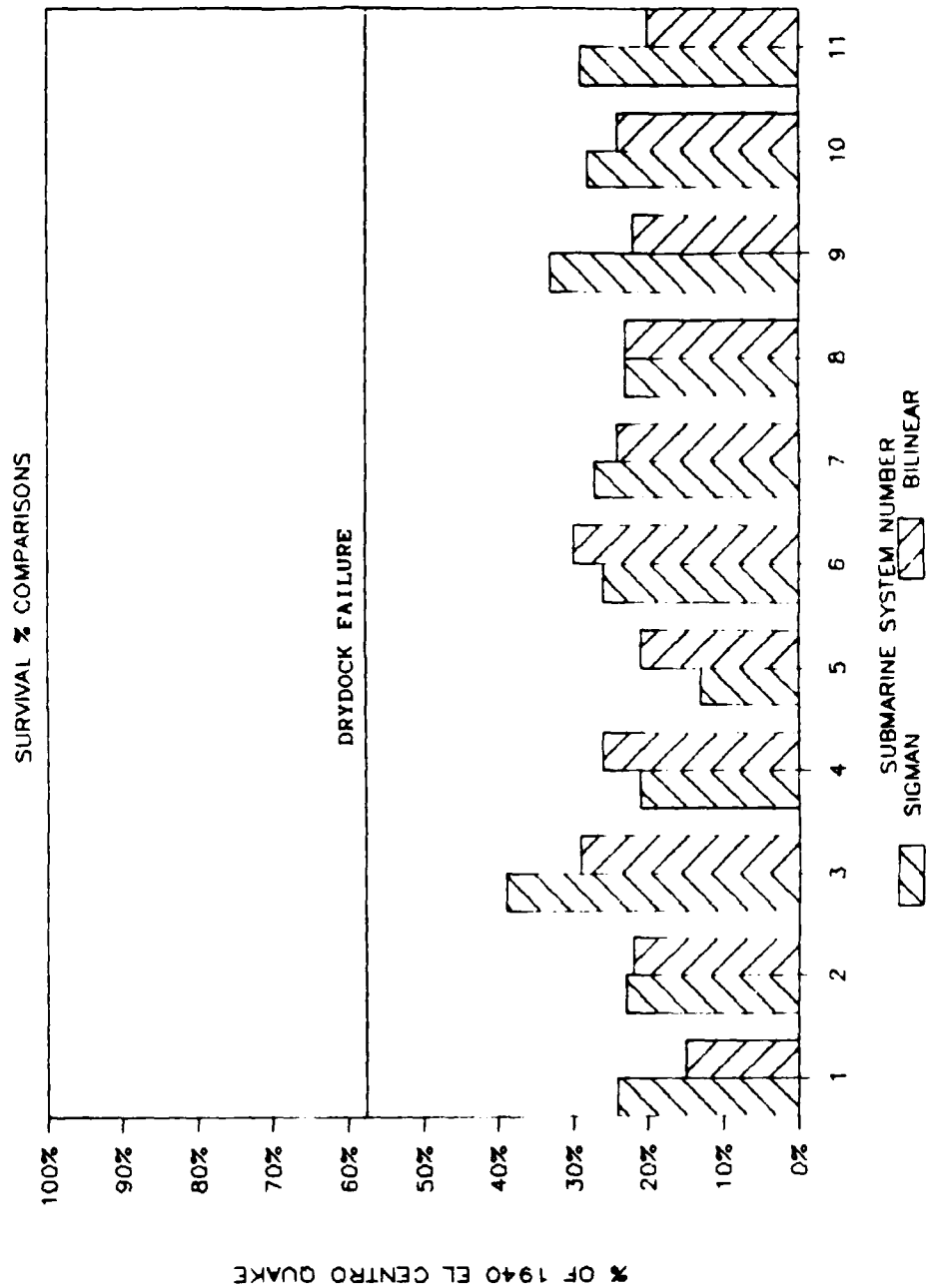


FIGURE 8.1

Figure (8.1) compares the bilinear wood model results with Sigman's. Survival percentages range from 15 to 30 % (mean 23 %) and in "g's" the range is 0.07 to 0.14 g's for the bilinear wood model.

Overall the bilinear wood model predicts failures at approximately 10 % lower acceleration values. In the case of systems 9 through 11 the bilinear wood model predicts failures at accelerations approximately 30 % lower than Sigman predicted.

8.2 Bilinear Rubber Versus Bilinear Wood Drydock Blocking System Material Model

Figure (8.2) compares the bilinear rubber model results with the bilinear wood model. Survival percentages range from 24 to 42 % (0.11 to 0.19 g's) with a mean of 30 % for the bilinear rubber model. Overall the bilinear rubber model predicts survival at approximately 30 % higher acceleration values than the bilinear wood model. In the case of systems 1 through 5 the bilinear rubber model predicts survival at accelerations approximately 50 % higher than what the bilinear wood model predicts.

SUBMARINE BLOCKING SYSTEMS (1-11)

SURVIVAL % COMPARISONS

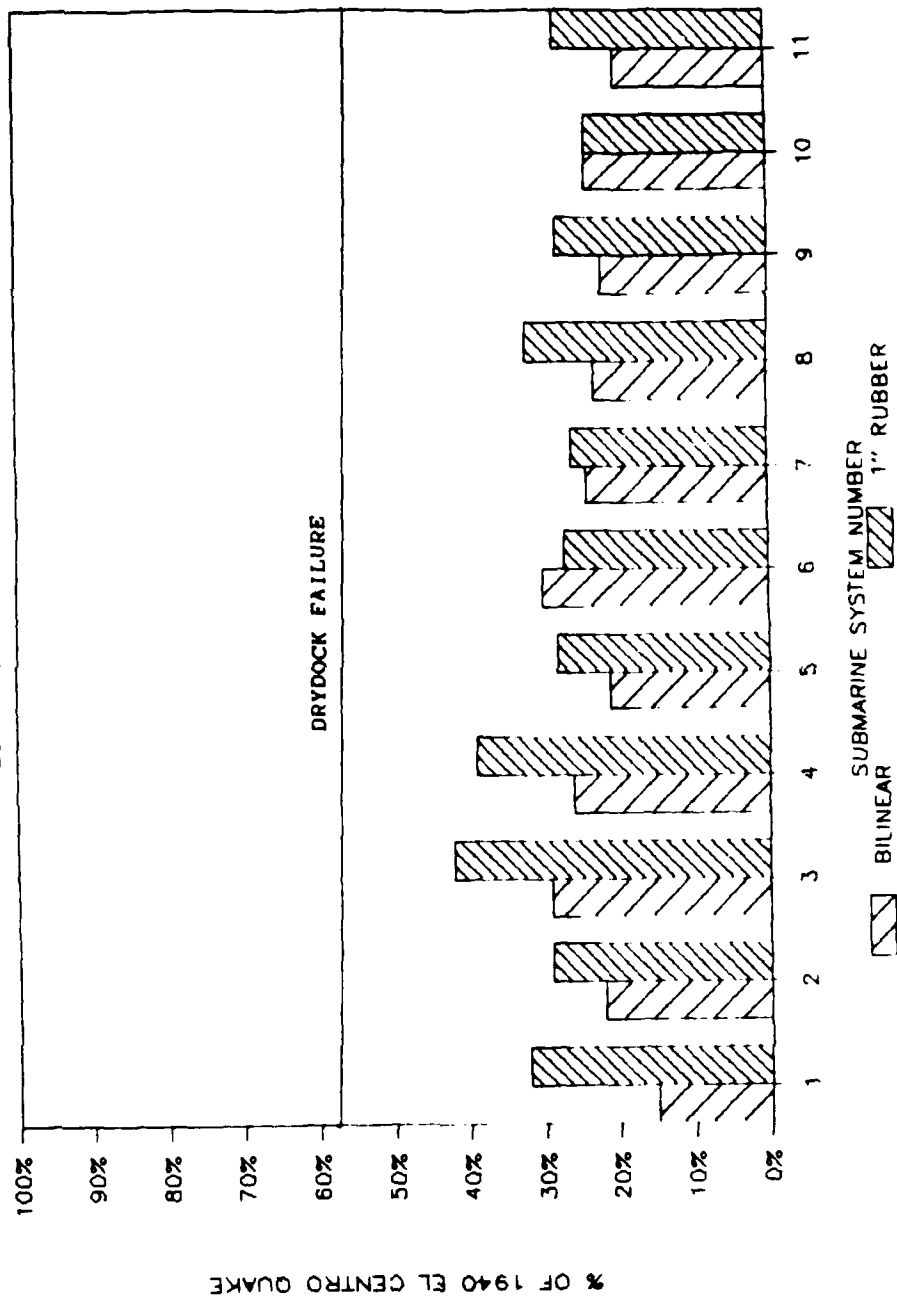


FIGURE 6.2

In one case, system 6, the bilinear rubber model predicts slightly lower survivability than the bilinear wood model. However, in every other case the bilinear rubber model predicts equal to significantly greater survivability.

8.3 Overall Comparison Among Bilinear Wood, Bilinear Rubber, Isolators, and Sigman Results.

Figure (8.3) combines the results for the eleven submarine drydock blocking systems using the various blocking material models. In every material model for all eleven systems failure is due to side block liftoff. Roughly, this figure shows that the use of rubber as a capping material increases the systems' survivability, and the use of the bilinear model decreases the survivability from the model used by Sigman. This is not always the case possibly due to system modal frequency effects. Since the behavior of system 1 is typical of the behavior of all eleven systems, it is chosen for further analysis.

Figure (8.4) is the comparison of the survival percentage of system 1 using the Sigman's model, the bilinear wood model, the bilinear rubber model, and the bilinear D.I.S. isolator model described in chapter 7. This figure clearly indicates the potential use of rubber caps and/or dynamic isolators in improving submarine drydock blocking system survivability.

SUBMARINE BLOCKING SYSTEMS (1-11)

SURVIVAL % COMPARISONS

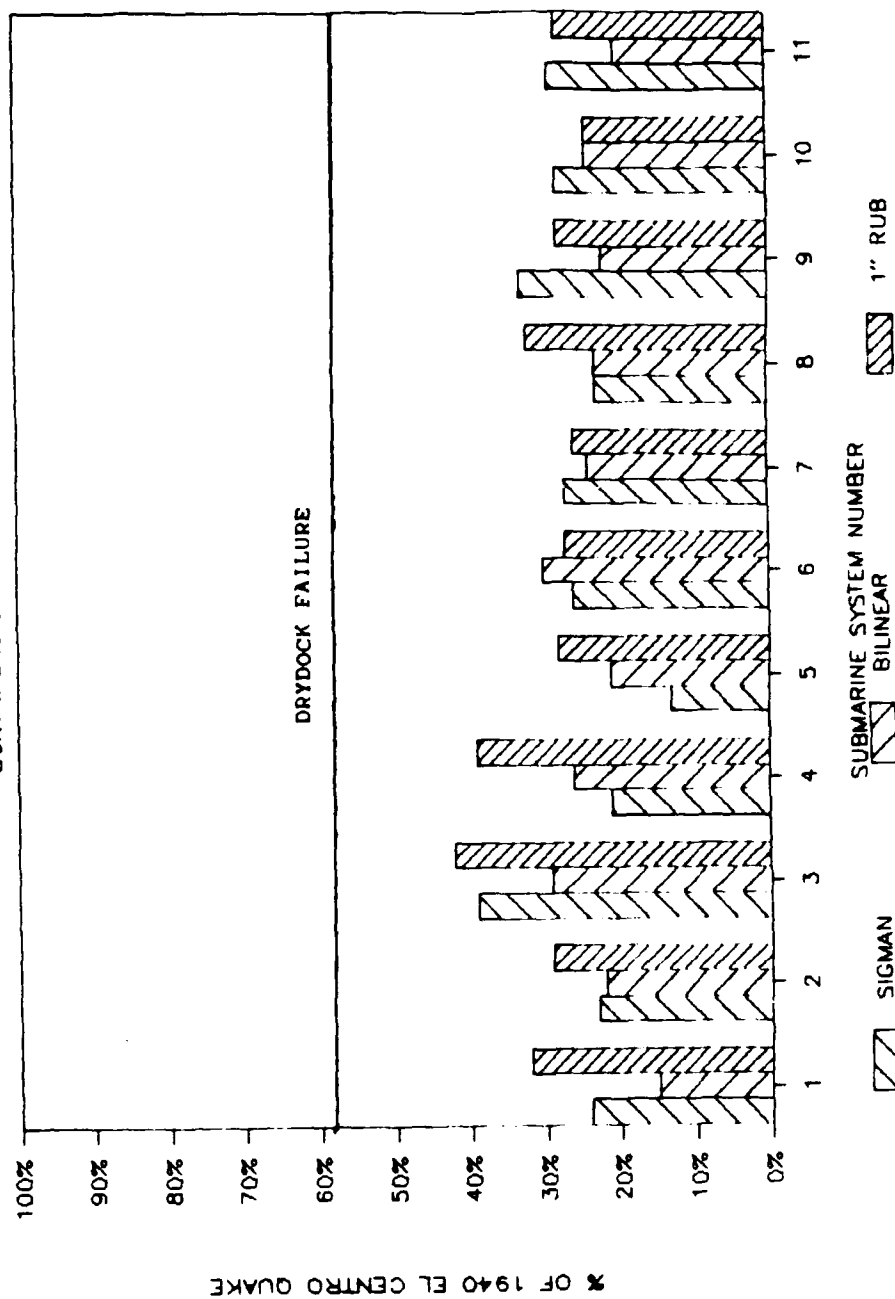


FIGURE 8.3

SUBMARINE DRYDOCK BLOCKING SYSTEM # 1

MATERIAL COMPARISON

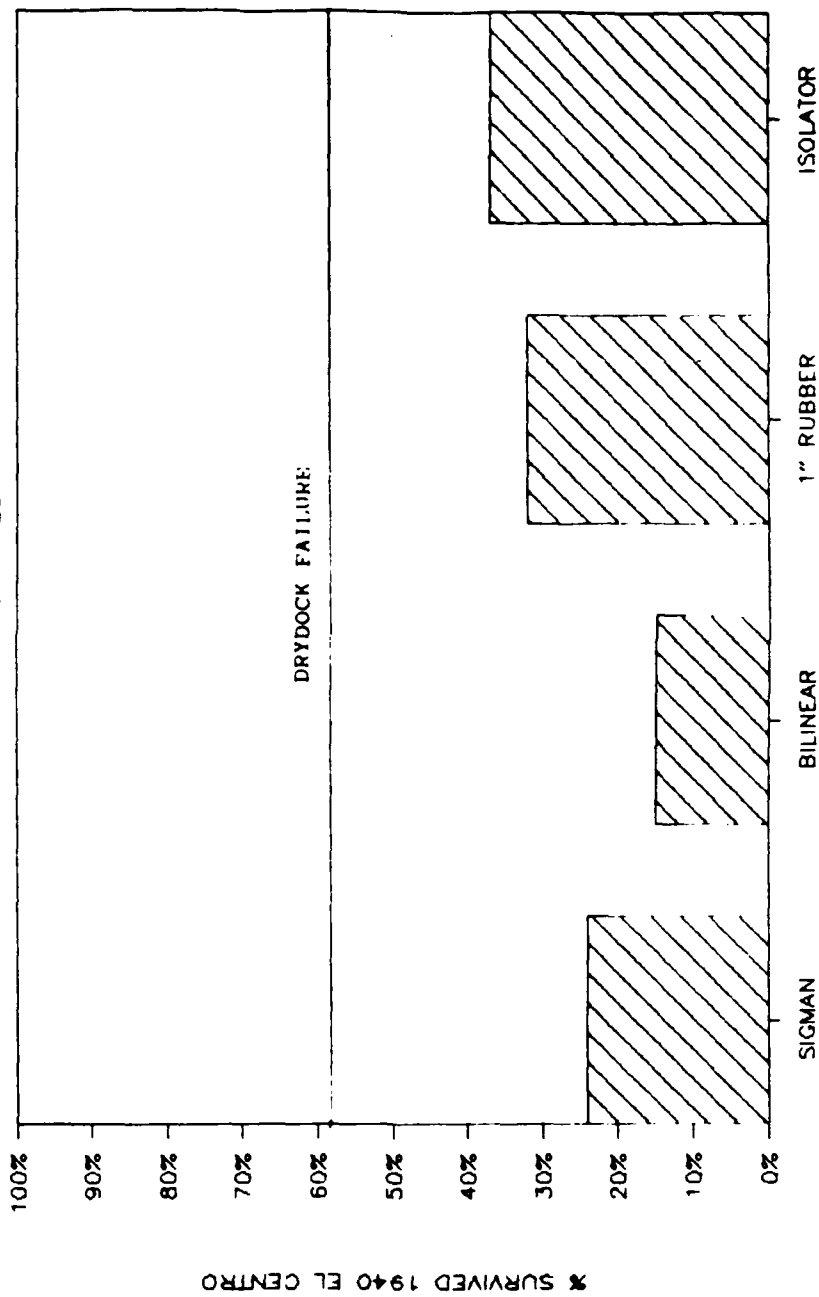


FIGURE B.4

The baseline condition in this thesis is considered to be the bilinear wood model. This best describes the condition of the submarine drydock blocking systems today. Compared to this baseline, the rubber caps and isolators each approximately double the system's survivability.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.0 Conclusions

U.S. Naval shipyards where submarines are drydocked are located in regions of the United States where significant earthquakes are known to occur. The graving dry docks at these shipyards are currently designed to withstand earthquake accelerations up to 0.26 g's. Previous research using linear elastic material models showed that submarine drydock blocking systems would fail due to side block liftoff at accelerations significantly lower than the 0.2 g level required by current Navy drydocking standards.

This thesis confirms these results using a material model for wood which more closely represents its actual behavior. Using this bilinear model, it is determined that the submarine drydock blocking systems would fail by side block liftoff at even lower accelerations due to plastic deformation of the Douglas fir capping material.

New materials are then analyzed in order to determine their potential for increasing system survivability. The materials analyzed are natural rubber and dynamic isolators. The rubber is used as a substitute for the Douglas fir soft

cap, and the dynamic isolators are used as a substitute for the oak (hard wood) layer of the blocking systems.

The response behavior of rubber and the dynamic isolators also allows them to be modeled as bilinear materials. It is determined that significant increases in survivability occur when these materials are incorporated in the blocking systems. Rubber caps and isolators either singly or in combination are very attractive potential solutions to the submarine drydock blocking systems' survivability problem.

Figures (8.3) and (8.4) show that all the systems examined in this thesis, including the systems where rubber caps or isolators are used, fail well before the dry dock itself fails (0.26 g's). They also fail well below the required 0.2 g level. It is clear that the current submarine drydock blocking systems provide inadequate protection of the submarines from accelerations caused by earthquakes that will probably be experienced in the near future.

9.1 Recommendations

Since the survivability of submarine drydock blocking systems is essential at least up to the point where the dry dock itself survives, a new blocking system for these submarines needs to be designed. The "3DOFRUB" computer

program with the bilinear models included should be used as a design tool in this effort.

In order to improve the design of the current blocking systems the following studies are recommended. First, determine the effect of side block cap angle, side block buildup height, and block on hull friction coefficients. Second, determine the effect of adding additional restraints to the submarine blocking system including the use of wale shores. Third, determine the effect of tuning dynamic isolators to enhance their performance. The use of rubber as a substitute capping material needs to be further analyzed including varying the thickness of the cap. Finally, combinations of use of isolators and rubber caps need to be studied.

Other design features need to be examined including increasing blocking stiffness, widening or restraining the keel and side blocks to prevent overturning, and changing the drydock blocking system modal frequencies. In addition, a study needs to be done examining the effects of using earthquake acceleration time histories representative of particular dry dock locations. If possible, experimental studies should be done to determine the validity of the "3DOFRUB" computer program and the bilinear subroutines.

Additional studies need to be done on the material properties of rubber, particularly the variation of shear modulus when subject to compressive loads. Even further studies need to be done on existing wood materials used in drydock blocks. These tests should include determining the modulus of elasticity of Douglas fir and oak when they are loaded at various grain angles. Biaxial loading should also be studied.

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APPENDIX 1

1. "3DOFRUB" Computer Program Listing
2. "BILINALL" and "RUBBER" Subroutine Listings
3. Sample Input Data File and Output File

"3DOFRUB" Computer Program Listing

Page 1

03-11-88

16:50:34

D Line# 1 7

Microsoft FORTRAN77 V3.20 02/84

```

1
2 $title: '3DOFRUB'
3 $nofloatcalls
4 $storage: 2
5
6 C-----
7
8 C      NON-LINEAR THREE DEGREE OF FREEDOM SYSTEM RESPONSE
9 C      USING FOURTH ORDER RUNGE-KUTTA METHOD
10 C      AND BILINEAR VERTICAL & HORIZONTAL STIFFNESSES
11 C      WITH HORZ/VERT ACCELERATION INPUT
12 C      AND DISPLACEMENT OUTPUT FILES
13 C      (INCLUDES WALE SHORE EFFECTS & HIGH BUILDUPS
14 C      AND THE USE OF RUBBER CAPS)
15
16 C-----
17
18
19      integer NN, l, mm, n, hull, nsys, flag10, l1
20      integer flag1, flag2, flag3, flag4, flag5, flag6, flag7, flag8
21      integer KY1, KY2, KY3, KY4, WWW1, YYY1, UUU1, WWW2, YYY2, UUU2, WWW3, YYY3
22      integer UUU3, WWW4, YYY4, UUU4, UUU5, WWW5, YYY5, decrr
23      real*8 beta, weight, h, lk, gravity, AAA, Ks, sidearea, keelarea, plside
24      real ac(2002), acv(2002), xx(2002), yy(2002), tt(2002), rrr(2002)
25      real*8 m(4,4), cx(4,4), k(4,4), ko(4,4), crit2, crit3
26      real*8 baseside, basekeel, htside, htkeel
27      real*8 dtau, maxx, maxt, maxy, timex, timet
28      real*8 rf1, rf2, rf3, hf1, hf2, hf3, ampacc, mass, ampacmax
29      real*8 kvs, kvk, kvkp, khs, khk, kshp, kkhp, kvsp, base, counter, time
30      real*8 time1, time2, time3, time4, time5, time6, time7, time8
31      real*8 x, t, y, xold, told, yold, XSCL(6)
32      real*8 bbb, ccc, w12, w1, w22, w2, w32, w3, model, mode3
33      real*8 mmx1, mmang1, mmx3, mmang3, crit4, alpha, LLL
34      real*8 timey, mmmmm1, mmmmm2, mmmmm3, mmmmm4
35      real*8 R, S, TAU, A(6), B(6), C(6), D(6), E(6), F(6), G(6), HH(6)
36      real*8 br, amp, plkeel, u1, u2, XPRIM, VEL
37      real*8 KU1, KD1, khkb, QD1, XEL1, XMAX1, XMIN1, RR1, ZZ1, WZ1, VEL1
38      real*8 KU2, KD2, khkb, QD2, XEL2, XMAX2, XMIN2, RR2, ZZ2, WZ2, YPRIM1
39      real*8 KU3, KD3, kvkb, QD3, YEL1, YMAX1, YMIN1, RR3, ZZ3, WZ3, DELTA
40      real*8 KU4, KD4, kvkb, QD4, YEL2, YMAX2, YMIN2, RR4, ZZ4, WZ4, YPRIM2, VEL2
41      real*8 KU5, KD5, kvkb, QD5, YEL3, YMAX3, YMIN3, RR5, ZZ5, WZ5, YPRIM3
42      CHARACTER*40 DEC, DECV, quakname, hname, vname
43      character*40 sbfname, acifname, outfname, vfname
44
45
46
47 C      READ IN VESSEL AND DRYDOCK DATA: VESSEL WEIGHT, KG, I(ABOUT KEEL),
48 C      TIME INCREMENT OF DATA POINTS, VERTICAL STIFFNESS OF SIDE AND
49 C      KEEL PIERS, HORIZONTAL STIFFNESS OF SIDE AND KEEL PIERS,
50 C      GAVITATIONAL CONSTANT, SIDE BLOCK BASE AND HEIGHT,
51 C      KEEL BLOCK BASE AND HEIGHT,
52 C      BLOCK-BLOCK AND BLOCK-HULL FRICTION COEFFICIENTS,
53 C      SIDE AND KEEL BLOCK'S PROPORTIONAL LIMIT,
54 C      SIDE PIER-VESSEL CONTACT AREA, KEEL PIER-VESSEL CONTACT AREA,
55 C      CAP BLOCK INCLINATION ANGLE.
56
57 C      OPEN INPUT FILES AND READ DATA
58
59      write(*, '(a)') ' ENTER SHIP/BUILDUP FILE NAME ... '

```

```

D Line# 1      7      Microsoft FORTRAN77 V3.20 02/84
60      read(*,'(a)') sbfname
61
62      open(4,file=sbfname,status='old',form='formatted')
63
64      read(4,*) weight,h,Ik,kvs,kvsp,kvk,AAA,Ks
65      read(4,*) khs,khk,kshp,kkhp,QD1,QD2,QD3,gravity
66      read(4,*) baseside, basekeel,htside,htkeel,u1,u2
67      read(4,*) br,plside,plkeel,sidearea,keelarea,zeta
68      read(4,*) hull,nsys,beta,QD4,kvvp
69      CLOSE (4)
70
71      write(*,*) 'DO YOU WANT RESPONSE OUTPUT FILES? (Y OR N)'
72      read(*,'(a)') dec
73      if (dec.eq.'Y'.or.dec.eq.'y') then
74      write(*,*) 'INPUT DESIRED RESISTANCE OUTPUT: (1,2,3,4,5)'
75      write(*,*) 'KEEL HORIZONTAL FORCE      = 1'
76      write(*,*) 'SIDE BLOCK HORIZONTAL FORCE = 2'
77      write(*,*) 'LEFT SIDE BLOCK VERT FORCE  = 3'
78      write(*,*) 'RIGHT SIDE BLOCK VERT FORCE = 4'
79      write(*,*) 'KEEL BLOCK VERTICAL FORCE   = 5'
80      read(*,*) decrr
81      endif
82
83      do 12,i=1,3
1 84      do 13,j=1,3
2 85      m(i,j)=0.0
2 86      k(i,j)=0.0
2 87      cx(i,j)=0.0
2 88      ko(i,j)=0.0
2 89      13 continue
1 90      12 continue
91
92
93 C      CALCULATE SYSTEM PARAMETERS
94
95      mass=weight/gravity
96      LLL=sqrt((htside-htkeel)**2D0+(br/2D0)**2D0)
97      alpha=asin((htside-htkeel)/LLL)
98
99      m(1,1)=mass
100      m(1,3)=h*mass
101      m(2,2)=mass
102      m(3,1)=mass*h
103      m(3,3)=Ik
104
105      k(1,1)=(2D0*Ks+2D0*khs+khk)
106      k(1,3)=(2D0*Ks*AAA+2D0*khs*LLL*sin(alpha))
107      k(3,1)=k(1,3)
108      k(2,2)=(2D0*kvs+kvk)
109      k(3,3)=(2D0*Ks*AAA**2D0+2D0*khs*((LLL*sin(alpha))**2D0)+
110      + (2D0*kvs*((LLL*cos(alpha))**2D0)-(weight*h)))
111      ko(1,1)=k(1,1)
112      ko(1,3)=k(1,3)
113      ko(3,1)=k(3,1)
114      ko(2,2)=k(2,2)
115      ko(3,3)=k(3,3)
116
117 C      DETERMINE NATURAL FREQUENCIES OF SYSTEM
118      bbb=-(m(1,1)*k(3,3)+m(3,3)*k(1,1)-m(1,3)*k(3,1)-m(3,1)*k(1,3))

```

```

D Line# 1      7      Microsoft FORTRAN77 V3.20 02/84
119      + /(m(1,1)*m(3,3)-m(1,3)*m(3,1))
120      ccc=(k(1,1)*k(3,3)-k(1,3)*k(3,1))/(m(1,1)*m(3,3)-m(1,3)*m(3,1))
121 C
122
123 C      NATURAL FREQ. MODE #1
124
125      w12=(-bbb-qrt(bbb**2-4D0*ccc))/2D0
126      w1=sqrt(w12)
127
128 C      NATURAL FREQ. MODE #2
129
130      w22=k(2,2)/m(2,2)
131      w2=sqrt(w22)
132 C      NATURAL FREQ. MODE #3
133
134      w32=(-bbb+sqrt(bbb**2-4D0*ccc))/2D0
135      w3=sqrt(w32)
136
137 C      MODE SHAPE #1 & #3
138
139      model=(m(1,3)*w12-k(1,3))/(-m(1,1)*w12+k(1,1))
140      mode3=(m(1,3)*w32-k(1,3))/(-m(1,1)*w32+k(1,1))
141 C      DETERMINE C11,C13,C31,C33
142      mmx1=m(1,1)+m(1,3)/model
143      mmang1=model*m(3,1)+m(3,3)
144      mmx3=m(1,1)+m(1,3)/mode3
145      mmang3=mode3*m(3,1)+m(3,3)
146      mmmm1=2D0*zeta*mmx1*w1
147      mmmm2=2D0*zeta*mmx3*w3
148      mmmm3=2D0*zeta*mmang1*w1
149      mmmm4=2D0*zeta*mmang3*w3
150
151
152
153
154
155      cx(1,3)=(mmmm1-mmmm2)/(1/model-1/mode3)
156      cx(1,1)=mmmm1-(cx(1,3)/model)
157      cx(2,2)=2D0*zeta*m(2,2)*w2
158      cx(3,1)=(mmmm3-mmmm4)/(model-mode3)
159      cx(3,3)=mmmm3-(cx(3,1)*model)
160
161
162 C      READ IN ACCELERATION DATA
163
164      CALL ACCLINPT(amp,ac,acv,dtau,quakname,hname,vname)
165
166 C      ESTABLISH FAILURE CRITERIA AND FLAGS
167
168      crit2=min(u1,u2)
169      crit3=(6.6D-1*baseside-1.2D1)/htside
170      crit4=basekeel/(6D0*htkeel)
171      ampacc=1D0
172      counter=0.0
173      ampacmax=0.0
174 10000 continue
175      write(*,*) ampacc
176      flag1=0
177      flag2=0

```

```

D Line# 1      7
178      flag3=0
179      flag4=0
180      flag5=0
181      flag6=0
182      flag7=0
183      flag8=0
184      flag10=0
185      maxx=0.0
186      maxt=0.0
187      maxy=0.0
188      mm=0
189      x=0.0
190      y=0.0
191      t=0.0
192      xold=0.0
193      yold=0.0
194      told=0.0
195      R=0.0
196      S=0.0
197      TAU=0.0
199 C      INITIALIZING BILINEAR VARIABLES
200
201 C      INITIALIZING DELTA
202
203      if (kvs.eq.kvsp) then
204          YEL1=0.0
205      elseif (kvs.ne.kvsp) then
206          YEL1=QD3/(kvs-kvsp)
207      endif
208      if (kvk.eq.kvkp) then
209          YEL3=0.0
210      elseif (kvk.ne.kvkp) then
211          YEL3=QD4/(kvk-kvkp)
212      endif
213      DELTA=weight/(2D0*kvs+kvk)
214      if (QD3.ge.0.0.or.QD4.ge.0.0) then
215          kvsbl=kvs
216          kvkb=kvk
217          goto 100
218      endif
219      if (DELTA.lt.YEL3.and.DELTA.lt.YEL1) then
220          kvsbl=kvs
221          kvkb=kvk
222      elseif (DELTA.ge.YEL3.or.DELTA.ge.YEL1) then
223          kvsbl=kvsp
224          kvkb=kvkp
225          DELTA=YEL3+(weight-(YEL3*(2D0*kvs+kvk)))/(2D0*kvsp+kvkp)
226      endif
227
228 100      continue
229
230 C      INITIALIZING KEEL HORIZONTAL STIFFNESS
231
232      KU1=khk
233      KD1=kkhp
234      khkb=KU1
235      if (QD1.eq.0.0) goto 101
236      KY1=0

```

```

D Line# 1      7
237      XEL1=QD1/(KU1-KD1)
238      XMAX1=0.0
239      XMIN1=0.0
240      RR1=0.0
241      ZZ1=0.0
242      WZ1=0.0
243      WWW1=0.0
244      YYY1=0.0
245      UUU1=0.0
246
247 101      continue
248
249 C      INITIALIZING SIDE BLOCK HORIZONTAL STIFFNESS
250
251      KU2=khs
252      KD2=kshp
253      khsb=KU2
254      if (QD2 .eq. 0.0) goto 102
255      KY2=0
256      XEL2=QD2/(KU2-KD2)
257      XMAX2=0.0
258      XMIN2=0.0
259      RR2=0.0
260      ZZ2=0.0
261      WZ2=0.0
262      WWW2=0.0
263      YYY2=0.0
264      UUU2=0.0
265
266 102      continue
267
268 C      INITIALIZING LEFT SIDE BLOCK VERTICAL STIFFNESS
269
270      KU3=kvs
271      KD3=kvsp
272      if (QD3 .eq. 0.0) goto 103
273      KY3=0
274      YMAX1=0.0
275      YMIN1=0.0
276      RR3=kvsb1*DELTA
277      ZZ3=0.0
278      WZ3=0.0
279      WWW3=0.0
280      YYY3=0.0
281      UUU3=0.0
282
283 103      continue
284
285 C      INITIALIZING RIGHT SIDE BLOCK VERTICAL STIFFNESS
286
287      KU4=kvs
288      KD4=kvsp
289      kvsb2=kvsb1
290      if (QD3 .eq. 0.0) goto 104
291      KY4=0
292      YEL2=YEL1
293      YMAX2=0.0
294      YMIN2=0.0
295      RR4=kvsb2*DELTA
296      ZZ4=0.0

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```

D Line# 1      7
296      WZ4=0.0
297      WWW4=0.0
298      YYY4=0.0
299      UUU4=0.0
300
301 104      continue
302
303 C      INITIALIZING KEEL VERTICAL STIFFNESS
304
305      KU5=kvk
306      KD5=kvkp
307      if (QD4.eq.0.0) goto 105
308      KY5=0
309      YMAX3=0.0
310      YMIN3=0.0
311      RR5=kvkb*DELTA
312      ZZ5=0.0
313      WZ5=0.0
314      WWW5=0.0
315      YYY5=0.0
316      UUU5=0.0
317
318 105      continue
319
320 C      IMPLEMENTATION OF EQUATIONS OF MOTION INTO THE
321 C      RUNGE-KUTTA FORMULUS
322
323      do 301.1=1,2000
1 324
1 325 C      CALCULATE BILINEAR STIFFNESS AND RESISTANCE
1 326
1 327 C      CALCULATE KEEL HORIZONTAL BILINEAR STIFFNESS
1 328
1 329      if (QD1 .eq. 0.0) goto 106
1 330
1 331      CALL BILINALL(x,S,khkb,RR1,KD1,QD1,KU1,XEL1,XMAX1,XMIN1,
1 332      + KY1,ZZ1,WZ1,WWW1,YYY1,UUU1)
1 333
1 334 106      continue
1 335
1 336 C      CALCULATE SIDE BLOCK HORIZONTAL BILINEAR STIFFNESS
1 337
1 338      XPRIM=+x+LLL*t*sin(alpha)
1 339
1 340      if (QD2 .eq. 0.0) goto 107
1 341
1 342      VEL=+S+LLL*TAU*sin(alpha)
1 343
1 344      CALL BILINALL(XPRIM,VEL,khsb,RR2,KD2,QD2,KU2,XEL2,XMAX2,XMIN2,
1 345      + KY2,ZZ2,WZ2,WWW2,YYY2,UUU2)
1 346
1 347 107      continue
1 348
1 349 C      CALCULATE LEFT SIDE BLOCK VERTICAL BILINEAR STIFFNESS
1 350
1 351      YPRIM1=-y-t*LLL*cos(alpha)+DELTA
1 352
1 353      if (QD3 .eq. 0.0) goto 108
1 354      if (QD3 .gt. 0.0) then

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D Line# 1      7
1 355
1 356      VEL1=-R-TAU*LLL*cos(alpha)
1 357
1 358      CALL BILINALL(YPRIM1,VEL1,kvsb1,RR3,KD3,QD3,KU3,YEL1,YMAX1,
1 359      + YMIN1,KY3,ZZ3,WZ3,WWW3,YYY3,UUU3)
1 360
1 361      elseif (QD3 .lt. 0.0) then
1 362
1 363      CALL RUBBER(YPRIM1,kvsb1,RR3,KD3,QD3,KU3,YEL1)
1 364
1 365      endif
1 366
1 367 108      continue
1 368
1 369 C      CALCULATE RIGHT SIDE BLOCK VERTICAL BILINEAR STIFFNESS
1 370
1 371      YPRIM2=-y+t*LLL*cos(alpha)+DELTA
1 372
1 373      if (QD3 .eq. 0.0) goto 109
1 374      if (QD3 .gt. 0.0) then
1 375
1 376      VEL2=-R+TAU*LLL*cos(alpha)
1 377
1 378      CALL BILINALL(YPRIM2,VEL2,kvsb2,RR4,KD4,QD3,KU4,YEL2,YMAX2,
1 379      + YMIN2,KY4,ZZ4,WZ4,WWW4,YYY4,UUU4)
1 380
1 381      elseif (QD3 .lt. 0.0) then
1 382
1 383      CALL RUBBER(YPRIM2,kvsb2,RR4,KD4,QD3,KU4,YEL2)
1 384
1 385      endif
1 386
1 387 109      continue
1 388
1 389 C      CALCULATE KEEL VERTICAL STIFFNESS
1 390
1 391      YPRIM3=-y+DELTA
1 392
1 393      if (QD4 .eq. 0.0) goto 110
1 394      if (QD4 .gt. 0.0) then
1 395
1 396      CALL BILINALL(YPRIM3,-R,kvkb,RR5,KD5,QD4,KU5,YEL3,YMAX3,
1 397      + YMIN3,KY5,ZZ5,WZ5,WWW5,YYY5,UUU5)
1 398
1 399      elseif (QD4 .lt. 0.0) then
1 400
1 401      CALL RUBBER(YPRIM3,kvkb,RR5,KD5,QD4,KU5,YEL3)
1 402
1 403      endif
1 404
1 405 110      continue
1 406
1 407
1 408 C      RECALCULATION OF DELTA
1 409
1 410      if (QD3.ge.0.0.or.QD4.ge.0.0) then
1 411          DELTA=weight/(2D0*kvs+kvk)
1 412          goto 120
1 413      endif

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3DOFRUB

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D Line# 1      7
1 414          if (kvkb.eq.kvk) then
1 415              DELTA=weight/(2D0*kvs+kvk)
1 416          elseif (kvkb.gt.kvk) then
1 417              DELTA=YEL3+(weight-(YEL3*(2D0*kvs+kvk)))/(2D0*kvsp+kvkp)
1 418          endif
1 419
1 420 120        continue
1 421
1 422          if (QD1.eq.0.0.and.QD2.eq.0.0.and.QD3.eq.0.0.
1 423      + and.QD4.eq.0.0) goto 111
1 424
1 425 C          RECALCULATION OF STIFFNESS MATRIX VALUES
1 426
1 427          k(1,1)=(2D0*Ks+2D0*khsb+khkb)
1 428          k(1,3)=(2D0*Ks*AAA+2D0*khsb*LLL*sin(alpha))
1 429          k(3,1)=k(1,3)
1 430          k(2,2)=(kvsb1+kvsb2+kvkb)
1 431          k(3,3)=(2D0*Ks*AAA**2D0+2D0*khsb*((LLL*sin(alpha))**2D0)+
1 432      + ((kvsb1+kvsb2)*((LLL*cos(alpha))**2D0)-(weight*h)))
1 433
1 434 111        DO 3000.11=0.5
2 435            A(11)=0.0
2 436            B(11)=0.0
2 437            C(11)=0.0
2 438            D(11)=0.0
2 439            E(11)=0.0
2 440            F(11)=0.0
2 441            G(11)=0.0
2 442            HH(11)=0.0
2 443 3000      CONTINUE
1 444            mm=mm+1
1 445            DO 302. NN=1.4
2 446                IF(NN.EQ.1) THEN
2 447                    FF=0.0
2 448                ELSE IF (NN.EQ.2 .OR. NN.EQ.3) THEN
2 449                    FF=5D-1
2 450                ELSE IF (NN.EQ.4) THEN
2 451                    FF=1D0
2 452                ENDIF
2 453                A(NN)=dtau*(R+FF*D(NN-1))
2 454                B(NN)=dtau*(S+FF*E(NN-1))
2 455                C(NN)=dtau*(TAU+FF*F(NN-1))
2 456                D(NN)=dtau*((-cx(2,2)/m(2,2))*(R+FF*D(NN-1))-(k(2,2)/m(2,2))
2 457      +*(y+FF*A(NN-1))-amp*ampacc*acv(1)/2.54D0)
2 458                G(NN)=dtau*((-cx(1,1)/m(1,1))*(S+FF*E(NN-1))-(cx(1,3)/m(1,1))
2 459      +*(TAU+FF*F(NN-1))-(k(1,1)/m(1,1))*(x+FF*B(NN-1))
2 460      +-(k(1,3)/m(1,1))*(t+FF*C(NN-1))-ampacc*ac(1)/2.54D0)
2 461                HH(NN)=dtau*((-cx(3,3)/m(3,3))*(TAU+FF*F(NN-1))-(cx(3,1)/m(3,3))
2 462      +*(S+FF*E(NN-1))-(k(3,3)/m(3,3))*(t+FF*C(NN-1))+(m(3,1)/m(3,3))
2 463      +*((-cx(2,2)/m(2,2))*(R+FF*D(NN-1))-(k(2,2)/m(2,2))*(y+FF*A(NN-
2 464      +1)))*(t+FF*C(NN-1))
2 465      +-(k(3,1)/m(3,3))*(x+FF*B(NN-1))
2 466      +-(m(3,1)/m(3,3))*ampacc*ac(1)/2.54D0)
2 467
2 468                E(NN)=(m(1,1)*m(3,3)*G(NN)-m(1,3)*m(3,3)*HH(NN))/
2 469      +(m(3,3)*m(1,1)-m(1,3)*m(3,1))
2 470                F(NN)=(HH(NN)-(m(3,1)/m(3,3))*E(NN))
2 471 302        continue
1 472

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D Line# 1      7      Microsoft FORTRAN77 V3.20 02/84
1 473 C      DETERMINING SYSTEM RESPONSE
1 474
1 475      yold=y
1 476      y=yold+(A(1)+2D0*A(2)+2D0*A(3)+A(4))/6D0
1 477
1 478      xold=x
1 479      x=xold+(B(1)+2D0*B(2)+2D0*B(3)+B(4))/6D0
1 480
1 481      told=t
1 482      t=told+(C(1)+2D0*C(2)+2D0*C(3)+C(4))/6D0
1 483
1 484      R=R+(D(1)+2D0*D(2)+2D0*D(3)+D(4))/6D0
1 485
1 486      S=S+(E(1)+2D0*E(2)+2D0*E(3)+E(4))/6D0
1 487
1 488      TAU=TAU+(F(1)+2D0*F(2)+2D0*F(3)+F(4))/6D0
1 489
1 490 C      MAXIMUM VALUES FOR TRANSLATIONS AND ROTATION
1 491
1 492      if (abs(xold).gt.abs(maxx)) then
1 493          timex=dtau*(1-1)
1 494          maxx=xold
1 495      endif
1 496      if (abs(told).gt.abs(maxt)) then
1 497          timet=dtau*(1-1)
1 498          maxt=told
1 499      endif
1 500      if (abs(yold).gt.abs(maxv)) then
1 501          timey=dtau*(1-1)
1 502          maxy=yold
1 503      endif
1 504
1 505 C      CALCULATE VERTICAL AND HORIZONTAL FORCES CAUSED BY VESSEL.
1 506 C      TEST FOR FAILURE
1 507
1 508 C      CALCULATE FORCES ON SIDE/KEEL BLOCKS
1 509      if (QD3.eq.0.0) then
1 510          rf1=kvs*((weight/k(2,2))-yold-(LLL*cos(alpha))*told)
1 511          rf2=kvs*((weight/k(2,2))-yold+(LLL*cos(alpha))*told)
1 512      elseif (QD3.ne.0.0) then
1 513          rf1=RR3
1 514          rf2=RR4
1 515      endif
1 516
1 517      if (QD4.eq.0.0) then
1 518          rf3=kvk*((weight/k(2,2))-yold)
1 519      elseif (QD4.ne.0.0) then
1 520          rf3=RR5
1 521      endif
1 522
1 523      if (QD2.eq.0.0) then
1 524          hf1=kns*(xold+LLL*told*sin(alpha))
1 525          hf2=khs*(xold+LLL*told*sin(alpha))
1 526      elseif (QD2.gt.0.0) then
1 527          hf1=RR2
1 528          hf2=RR2
1 529      endif
1 530
1 531      if (QD1.eq.0.0) then

```

```

D Line# 1      7
1 532      hf3=khk*(xold)
1 533      elseif (QD1.gt.0.0) then
1 534          hf3=RR1
1 535      endif
1 536
1 537 C      TEST FOR SIDE BLOCK SLIDING
1 538
1 539      if (flag1.eq.1) then
1 540          go to 400
1 541      else if (hf1.lt.0.0.and.rf1.gt.0.0
1 542      + .and. u1*rf1+hf1+u2*rf1*cos(beta)*sin(beta)
1 543      + -rf1*cos(beta)*sin(beta).lt.0.0) then
1 544          time1= dtau*(1-1)
1 545          flag1=1
1 546      else if (hf2.gt.0.0.and.rf2.gt.0.0
1 547      + .and. -u1*rf2+hf2-u2*rf2*(cos(beta)*sin(beta))
1 548      + +rf2*cos(beta)*sin(beta).gt.0.0) then
1 549          time1=dtau*(1-1)
1 550          flag1=1
1 551      endif
1 552      x1=xold
1 553      y1=yold
1 554      t1=told
1 555 400      continue
1 556
1 557 C      TEST FOR KEEL BLOCK SLIDING
1 558
1 559      if (flag2.eq.1) then
1 560          go to 410
1 561      else if (rf3.gt.0.0.and.abs(hf3/rf3).gt.crit2) then
1 562          time2=dtau*(1-1)
1 563          flag2=1
1 564      endif
1 565      x2=xold
1 566      y2=yold
1 567      t2=told
1 568 410      continue
1 569 C      TEST FOR SIDE BLOCK OVERTURNING
1 570
1 571      if (flag3.eq.1) then
1 572          go to 420
1 573      else if (hf1.lt.0.0.and.rf1.gt.0.0.and.abs(hf1/rf1).gt.crit3) then
1 574          time3= dtau*(1-1)
1 575          flag3=1
1 576      else if (hf2.gt.0.0.and.rf2.gt.0.0.and.abs(hf2/rf2).gt.crit3) then
1 577          time3=dtau*(1-1)
1 578          flag3=1
1 579      endif
1 580      x3=xold
1 581      y3=yold
1 582      t3=told
1 583 420      continue
1 584
1 585 C      TEST FOR KEEL BLOCK OVERTURNING
1 586
1 587      if (flag4.eq.1) then
1 588          go to 430
1 589      else if (rf3.gt.0.0.and.abs(hf3/rf3).gt.crit4) then
1 590          time4=dtau*(1-1)

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D Line# 1      7
1 591      flag4=1
1 592      endif
1 593      x4=xold
1 594      y4=yold
1 595      t4=told
1 596 430    continue
1 597
1 598 C      TEST FOR SIDE BLOCK LIFTOFF
1 599
1 600      if (flag5.eq.1) then
1 601      go to 440
1 602      else if (rf1.lt.0.0 .or. rf2.lt.0.0) then
1 603      time5=dtau*(1-1)
1 604      flag5=1
1 605      endif
1 606      x5=xold
1 607      y5=yold
1 608      t5=told
1 609 440    continue
1 610
1 611 C      TEST FOR KEEL BLOCK LIFTOFF
1 612
1 613      if (flag6.eq.1) then
1 614      go to 450
1 615      else if (rf3.lt.0.0) then
1 616      time6=dtau*(1-1)
1 617      flag6=1
1 618      endif
1 619      x6=xold
1 620      y6=yold
1 621      t6=told
1 622 450    continue
1 623
1 624 C      TEST FOR SIDE BLOCK CRUSHING
1 625
1 626      if (flag7.eq.1) then
1 627      go to 460
1 628      else if (rf1.gt.0.0 .and. (rf1/sidearea).gt.plside) then
1 629      flag7=1
1 630      time7=dtau*(1-1)
1 631
1 632      else if (rf2.gt.0.0 .and. (rf2/sidearea).gt.plside) then
1 633      flag7=1
1 634      time7=dtau*(1-1)
1 635      endif
1 636      x7=xold
1 637      y7=yold
1 638      t7=told
1 639 460    continue
1 640
1 641 C      TEST FOR KEEL BLOCK CRUSHING
1 642
1 643      if (flag8.eq.1) then
1 644      go to 470
1 645      else if (rf3.gt.0.0 .and. (rf3/keelarea).gt.pikeel) then
1 646      flag8=1
1 647      time8=dtau*(1-1)
1 648      endif
1 649      x8=xold

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D Line# 1      7
1      650      y8=yold
1      651      t8=told
1      652 470   continue
1      653
1      654 C     CAPTURE OF DISPLACEMENT, ROTATION & RESISTANCE OUTPUT:
1      655
1      656      if (dec.ne.'Y'.and.dec.ne.'y') goto 301
1      657      xx(mm)=xold
1      658      tt(mm)=told
1      659      goto (501,502,503,504,505),decr
1      660 501   if (QD1.eq.0.0) then
1      661      rrr(mm)=hf3
1      662      elseif (QD1.gt.0.0) then
1      663      rrr(mm)=RR1
1      664      endif
1      665      yy(mm)=yold
1      666      goto 506
1      667 502   if (QD2.eq.0.0) then
1      668      rrr(mm)=hf1
1      669      elseif (QD2.gt.0.0) then
1      670      rrr(mm)=RR2
1      671      xx(mm)=XPRIM
1      672      endif
1      673      yy(mm)=yold
1      674      goto 506
1      675 503   if (QD3.eq.0.0) then
1      676      rrr(mm)=rf1
1      677      elseif (QD3.ne.0.0) then
1      678      rrr(mm)=RR3
1      679      endif
1      680      yy(mm)=YPRIM1
1      681      goto 506
1      682 504   if (QD3.eq.0.0) then
1      683      rrr(mm)=rf2
1      684      elseif (QD3.ne.0.0) then
1      685      rrr(mm)=RR4
1      686      endif
1      687      yy(mm)=YPRIM2
1      688      goto 506
1      689 505   if (QD4.eq.0.0) then
1      690      rrr(mm)=rf3
1      691      elseif (QD4.ne.0.0) then
1      692      rrr(mm)=RR5
1      693      endif
1      694      yy(mm)=YPRIM3
1      695
1      696 506   continue
1      697
1      698 301   continue
1      699
1      700      go to 999
1      701
1      702 60000  continue
1      703      if(dec.ne.'Y'.and.dec.ne.'y') then
1      704      write(*, '(A)') ' I AM FINISHING. '
1      705      goto 20000
1      706      endif
1      707
1      708 C     CREATION OF DISPLACEMENT, ROTATION, & RESISTANCE OUTPUT FILES

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D Line# 1      7
709
710      CALL RESPALL(xx,yy,tt,rrr,dtau)
711
712 998      go to 20000
713
714 999      CONTINUE
715
716      if(ampacc.eq.1D0) then
717
718          write(*,'(a)') ' ENTER OUTPUT FILENAME ... '
719          read(*,'(a)') outfame
720          open(46,file=outfame,status='new',form='formatted')
721
722
723      write(46,4000) nsys
724 4000      format(1x,/,28x,'**** System ',I2,1x,'****')
725      write(46,4050) hull
726 4050      format(1x,/,30x,'** Hull ',I3,1x,'**')
727      write(46,4100)
728 4100      format(1x,/,28x,'* Ship Parameters *')
729      write(46,4150)
730 4150      format(1x,/,5x,'Weight',8x,'Moment of Inertia',9x,'K.G.')
731      write(46,4200) weight,Ik,h
732 4200      format(1x,f9.1,1x,'kips',1x,f11.1,1x,'kips-in-sec2',
733 +3x,f6.1,1x,'ins')
734      write(46,4250)
735 4250      format(1x,/,26x,'* Drydock Parameters *')
736      write(46,4300)
737 4300      format(1x,/,1x,'Side Block Height',3x,'Side Block Width',
738 +3x,'Keel Block Height',3x,'Keel Block Width')
739      write(46,4350) htside,baseside,htkeel,basekeel
740 4350      format(1x,f6.1,1x,'ins',11x,f6.1,1x,'ins',11x,f6.1,1x,'ins',
741 +9x,f6.1,1x,'ins')
742      write(46,4400)
743 4400      format(1x,/,1x,'Side-to-Side Pier Distance',3x,'Wale Shore Ht.',
744 +3x,'Wale Shore Stiffness',2x,'Cap Angle')
745      write(46,4450) br,AAA,Ks,beta
746 4450      format(1x,t7,f6.1,1x,'ins',17x,f6.1,1x,'ins',8x,f9.1,1x,
747 + 'kips/in',1x,f5.3,1x,'rad')
748      write(46,4470)
749 4470      format(1x,/,1x,'Side Side Pier Contact Area'
750 +3x,'Total Keel Pier Contact Area',6x,'kkhp')
751      write(46,4475) sidearea,keelarea,kkhp
752 4475      format(1x,8x,f11.1,1x,'in2',14x,f11.1,1x,'in2',10x,f7.1,1x,
753 + 'kips/in')
754      write(46,4500)
755 4500      format(1x,/,1x,'B/B Friction Coeff',3x,
756 + 'H/B Friction Coeff',5x,'kshp',10x,'kvsp')
757      write(46,4550) u1,u2,kshp,kvsp
758 4550      format(6x,f7.3,13x,f7.3,7x,f7.1,1x,'kips/in',1x,f7.1,1x,
759 + 'kips/in')
760      write(46,4600)
761 4600      format(1x,/,1x,'Side Pier Fail Stress Limit',4x,'Keel Pier'
762 + 'Fail Stress Limit',6x,'kvkp')
763      write(46,4650) plside,plkeel,kvkp
764 4650      format(1x,10x,f7.3,1x,'kips/in2',15x,f7.3,1x,'kips/in2',
765 + 6x,f7.1,1x,'kips/in')
766      write(46,4700)
767 4700      format(1x,/,1x,'Side Pier Vertical Stiffness',3x,'Side Pier',

```

```

D Line# 1      7
768      + ' Horizontal Stiffness' )
769      write(46,4750) kvs,khs
770 4750      format(1x,3x,f11.1,1x,'kips/in',11x,f11.1,1x,'kips/in')
771      write(46,4775)
772 4775      format(1x,/,1x,'Keel Pier Vertical Stiffness'.3x,
773      + 'Keel Pier Horizontal Stiffness')
774      write(46,4780) kvk,khk
775 4780      format(1x,3x,f11.1,1x,'kips/in',11x,f11.1,1x,'kips/in')
776      write(46,4782)
777 4782      format(1x,/,6x,'QD1',17x,'QD2',18x,'QD3',17x,'QD4')
778      write(46,4785) QD1,QD2,QD3,QD4
779 4785      format(2x,f8.1,1x,'kips',7x,f8.1,1x,'kips',8x,f8.1,1x,'kips',
780      + 7x,f8.1,1x,'kips')
781      write(46,4800)
782 4800      format(1x,/,20x,'* System Parameters and Inputs *')
783      write(46,4850) quakname
784 4850      format(1x,/,1x,'Earthquake Used is ',A40)
785      write(46,4852) hname
786 4852      format(1x,/,1x,'Horizontal acceleration input is ',A40)
787      write(46,4854) vname
788 4854      format(1x,/,1x,'Vertical acceleration input is ',A40)
789      write(46,4875)
790 4875      format(1x,20x,' Earthquake Acceleration Time History. ')
791
792      write(46,4995)
793 4995      format(1x,/,1x,'Vertical/Horizontal Ground Acceleration Ratio'
794      + '.3x,'Data Time Increment')
795      write(46,4990) amp,dttau
796 4990      format(1x,10x,f6.3,t55,f6.3,1X,'sec')
797      write(46,4900)
798 4900      format(1x,/,1x,'Gravitational Constant',3x,'% System Damping')
799      write(46,4950) gravity,zeta*100.
800 4950      format(1x,7x,f6.2,1x,'in/sec2',10x,f6.2,1x,'%')
801      write(46,5000)
802 5000      format(1x,/,25x,'Mass Matrix',/)
803      do 5100 i=1,3
1 804      write(46,5050) m(i,1),m(i,2),m(i,3)
1 805 5050      format(1x,f15.4,5x,f15.4,5x,f15.4)
1 806 5100      continue
807      write(46,5200)
808 5200      format(1x,/,25x,'Damping Matrix',/)
809      do 5300 i=1,3
1 810      write(46,5250) cx(i,1),cx(i,2),cx(i,3)
1 811 5250      format(1x,f15.4,5x,f15.4,5x,f15.4)
1 812 5300      continue
813      write(46,5400)
814 5400      format(1x,/,25x,'Stiffness Matrix',/)
815      do 5500 i=1,3
1 816      write(46,5450) ko(i,1),ko(i,2),ko(i,3)
1 817 5450      format(1x,f15.4,5x,f15.4,5x,f15.4)
1 818 5500      continue
819      write(46,5700)
820 5700      format(1x,/)
821      WRITE(46,6000)
822 6000      FORMAT(1X,'Undamped Natural Frequencies',t35,'Mode #1',t50,
823      + 'Mode #2',t65,'Mode #3')
824      write(46,6001) w1,w3,w2
825 6001      format(1x,t31,f7.3,1x,'rad/sec',t46,f7.3,1x,'rad/sec',t62,f7.3,
826      + ' rad/sec')

```

```

D Line# 1      7
827      WRITE(46,6002)
828 6002      FORMAT(1X,'Damped Natural Frequencies',t35,'Mode #1',t50,
829      +'Mode #2',t65,'Mode #3')
830      WRITE(46,6500) w1*sqrt(1-zeta**2),w3*sqrt(1-zeta**2),
831      +w2*sqrt(1-zeta**2)
832 6500      format(1x,t31,f7.3,1x,'rad/sec',t46,f7.3,1x,'rad/sec',t62,f7.3,
833      +'rad/sec')
834      endif
835
836      write(46,10500) ampacc*100,quakname
837 10500      format(1x,///,1x,'For Earthquake Acceleration of ',f6.2,' % '
838      +',of the ',A40,/)
839
840      write(46,25000)
841 25000      format(1x,'Maximums/Failures',t26,'X (ins)',t36,'Y (ins)',t51,
842      +'Theta (rads)',t65,'Time (sec)')
843      write(46,25001)
844 25001      format(1x,'-----',t25,'-----',t35,'-----',t50,
845      +'-----',t64,'-----')
846      write(46,310) maxx,timeX
847 310      format(1x,'Maximum X',t25,f9.6,t65,f5.2)
848      write(46,311) maxy,timeY
849 311      format(1x,'Maximum Y',t35,f9.6,t65,f5.2)
850      write(46,312) maxt,timeT
851 312      format(1x,'Maximum Rotation',t50,f9.6,t65,f5.2)
852
853      if (flag1.eq.1) then
854      flag10=flag10+1
855      write(46,313) x1,y1,t1,time1
856 313      format(1x,'Side block sliding',t25,f9.6,t35,f9.6,t50,f9.6,
857      +t65,f5.2)
858
859      endif
860
861      if (flag2.eq.1) then
862      flag10=flag10+1
863      write(46,314) x2,y2,t2,time2
864 314      format(1x,'Keel block sliding',t25,f9.6,t35,f9.6,t50,f9.6,
865      +t65,f5.2)
866      endif
867
868      if (flag3.eq.1) then
869      flag10=flag10+1
870      write(46,315) x3,y3,t3,time3
871 315      format(1x,'Side block overturning',t25,f9.6,t35,f9.6,t50,f9.6,
872      +t65,f5.2)
873      endif
874
875      if (flag4.eq.1) then
876      flag10=flag10+1
877      write(46,316) x4,y4,t4,time4
878 316      format(1x,'Keel block overturning',t25,f9.6,t35,f9.6,t50,f9.6,
879      +t65,f5.2)
880      endif
881
882      if (flag5.eq.1) then
883      flag10=flag10+1
884      write(46,317) x5,y5,t5,time5
885 317      format(1x,'Side block liftoff',t25,f9.6,t35,f9.6,t50,f9.6,

```

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```

D Line# 1      7
886      +t65,f5.2)
887      endif
888
889      if (flag6.eq.1) then
890      flag10=flag10+1
891      write (46,318) x6,y6,t6,time6
892 318      format (1x,'Keel block liftoff' ,t25,f9.6,t35,f9.6,t50,f9.6,
893      +t65,f5.2)
894      endif
895
896      if (flag7.eq.1) then
897      flag10=flag10+1
898      write (46,319) x7,y7,t7,time7
899 319      format (1x,'Side block crushing' ,t25,f9.6,t35,f9.6,t50,f9.6,
900      +t65,f5.2)
901      endif
902
903      if (flag8.eq.1) then
904      flag10=flag10+1
905      write (46,320) x8,y8,t8,time8
906 320      format (1x,'Keel block crushing' ,t25,f9.6,t35,f9.6,t50,f9.6,
907      +t65,f5.2)
908      endif
909
910      if(flag10.eq.0) then
911      write(46,11000)
912 11000      format(1x,/,1x,'No failures occurred.')
913      if(counter.eq.1.0 .and. flag10.eq.0) then
914      go to 60000
915      endif
916      if(counter.eq.0.0) then
917      ampacmax=ampacc
918      ampacc=ampacc+1D-1
919      counter=1.0
920      write(*,'(A)') ' In secondary looping stage. '
921      endif
922      endif
923      if(ampacc.le.ampacmax) go to 20000
924      if(counter.eq.1.0) then
925      ampacc=ampacc-1D-2
926      else if(counter.eq.0.0) then
927      ampacc=ampacc-1D-1
928      endif
929      go to 10000
930 20000      continue
931      stop
932      end

```

Name	Type	Offset	P Class
A	REAL*8	48946	
AAA	REAL*8	49082	
ABS			INTRINSIC
AC	REAL	32882	
ACLFNA	CHAR*40	*****	
ACV	REAL	40890	
ALPHA	REAL*8	49344	
AMP	REAL*8	49496	
AMPACC	REAL*8	49656	

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D Line# 1	7	
AMPACM	REAL*8	49672
ASIN		
B	REAL*8	48898
BASE	REAL*8	*****
BASEKE	REAL*8	49170
BASESI	REAL*8	49162
BBB	REAL*8	49352
BETA	REAL*8	49258
BR	REAL*8	49210
C	REAL*8	32834
CCC	REAL*8	49360
COS		
COUNTE	REAL*8	49664
CRIT2	REAL*8	49632
CRIT3	REAL*8	49640
CRIT4	REAL*8	49648
CX	REAL*8	32658
D	REAL*8	32786
DEC	CHAR*40	49282
DECRR	INTEGER*2	49322
DECV	CHAR*40	*****
DELTA	REAL*8	49812
DTAU	REAL*8	49504
E	REAL*8	32562
F	REAL*8	32610
FF	REAL	50266
FLAG1	INTEGER*2	49680
FLAG10	INTEGER*2	49696
FLAG2	INTEGER*2	49682
FLAG3	INTEGER*2	49684
FLAG4	INTEGER*2	49686
FLAG5	INTEGER*2	49688
FLAG6	INTEGER*2	49690
FLAG7	INTEGER*2	49692
FLAG8	INTEGER*2	49694
G	REAL*8	32514
GRAVIT	REAL*8	49154
H	REAL*8	49042
HF1	REAL*8	50318
HF2	REAL*8	50326
HF3	REAL*8	50334
HH	REAL*8	32466
HNAME	CHAR*40	49552
HTKEEL	REAL*8	49186
HTSIDE	REAL*8	49178
HULL	INTEGER*2	49254
I	INTEGER*2	49324
IK	REAL*8	49050
J	INTEGER*2	49326
K	REAL*8	32338
KD1	REAL*8	49844
KD2	REAL*8	49924
KD3	REAL*8	50004
KD4	REAL*8	50068
KD5	REAL*8	50148
KEELAR	REAL*8	49242
KHK	REAL*8	49106
KHKB	REAL*8	49852
KHS	REAL*8	49098

INTRINSIC

INTRINSIC

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```

D Line# 1      7
KHSB  REAL*8      49932
KKHP  REAL*8      49122
KO    REAL*8      32210
KS    REAL*8      49090
KSHP  REAL*8      49114
KU1   REAL*8      49836
KU2   REAL*8      49916
KU3   REAL*8      49996
KU4   REAL*8      50060
KU5   REAL*8      50140
KVK   REAL*8      49074
KVKB  REAL*8      49828
KVKP  REAL*8      49274
KVS   REAL*8      49058
KVSb1 REAL*8      49820
KVSb2 REAL*8      50076
KVSP  REAL*8      49066
KY1   INTEGER*2   49860
KY2   INTEGER*2   49940
KY3   INTEGER*2   50012
KY4   INTEGER*2   50084
KY5   INTEGER*2   50156
L     INTEGER*2   50204
LL    INTEGER*2   50262
LLL   REAL*8      49336
M     REAL*8      32082
MASS  REAL*8      49328
MAXT  REAL*8      49706
MAXX  REAL*8      49698
MAXY  REAL*8      49714
MIN
MM     INTEGER*2   49722
MMANG1 REAL*8      49440
MMANG3 REAL*8      49456
MMMMM1 REAL*8      49464
MMMMM2 REAL*8      49472
MMMMM3 REAL*8      49480
MMMMM4 REAL*8      49488
MMX1   REAL*8      49432
MMX3   REAL*8      49448
MODE1  REAL*8      49416
MODE3  REAL*8      49424
N      INTEGER*2   *****
NN     INTEGER*2   50264
NSYS   INTEGER*2   49256
OUTFNA CHAR*40     50502
PLKEEL REAL*8      49226
PLSIDE REAL*8      49218
QD1    REAL*8      49130
QD2    REAL*8      49138
QD3    REAL*8      49146
QD4    REAL*8      49266
QUAKNA CHAR*40     49512
R      REAL*8      49772
RF1    REAL*8      50294
RF2    REAL*8      50302
RF3    REAL*8      50310
RR1    REAL*8      49886
RR2    REAL*8      49866

```

INTRINSIC

3DOFRUB

D Line# 1	7	
RR3	REAL*8	50030
RR4	REAL*8	50110
RR5	REAL*8	50174
RRR	REAL	24074
S	REAL*8	49780
SBFNAM	CHAR*40	48994
SIDEAR	REAL*8	49234
SIN		INTRINSIC
SQRT		INTRINSIC
T	REAL*8	49740
T1	REAL	50358
T2	REAL	50378
T3	REAL	50398
T4	REAL	50418
T5	REAL	50438
T6	REAL	50458
T7	REAL	50478
T8	REAL	50498
TAU	REAL*8	49788
TIME	REAL*8	*****
TIME1	REAL*8	50342
TIME2	REAL*8	50362
TIME3	REAL*8	50382
TIME4	REAL*8	50402
TIME5	REAL*8	50422
TIME6	REAL*8	50442
TIME7	REAL*8	50462
TIME8	REAL*8	50482
TIMET	REAL*8	50278
TIMEX	REAL*8	50270
TIMEY	REAL*8	50286
TOLD	REAL*8	49764
TT	REAL	16066
U1	REAL*8	49194
U2	REAL*8	49202
UUU1	INTEGER*2	49914
UUU2	INTEGER*2	49994
UUU3	INTEGER*2	50058
UUU4	INTEGER*2	50138
UUU5	INTEGER*2	50202
VEL	REAL*8	50214
VEL1	REAL*8	50230
VEL2	REAL*8	50246
VFNAME	CHAR*40	*****
VNAME	CHAR*40	49592
W1	REAL*8	49376
W12	REAL*8	49368
W2	REAL*8	49392
W22	REAL*8	49384
W3	REAL*8	49408
W32	REAL*8	49400
WEIGHT	REAL*8	49034
WWW1	INTEGER*2	49910
WWW2	INTEGER*2	49990
WWW3	INTEGER*2	50054
WWW4	INTEGER*2	50134
WWW5	INTEGER*2	50198
WZ1	REAL*8	49902
WZ2	REAL*8	49982

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D Line# 1 7
WZ3 REAL*8 50046
WZ4 REAL*8 50126
WZ5 REAL*8 50190
X REAL*8 49724
X1 REAL 50350
X2 REAL 50370
X3 REAL 50390
X4 REAL 50410
X5 REAL 50430
X6 REAL 50450
X7 REAL 50470
X8 REAL 50490
XEL1 REAL*8 49862
XEL2 REAL*8 49942
XMAX1 REAL*8 49870
XMAX2 REAL*8 49950
XMIN1 REAL*8 49878
XMIN2 REAL*8 49958
XOLD REAL*8 49748
XPRIM REAL*8 50206
XSCL REAL*8 16018
XX REAL 2
Y REAL*8 49732
Y1 REAL 50354
Y2 REAL 50374
Y3 REAL 50394
Y4 REAL 50414
Y5 REAL 50434
Y6 REAL 50454
Y7 REAL 50474
Y8 REAL 50494
YEL1 REAL*8 49796
YEL2 REAL*8 50086
YEL3 REAL*8 49804
YMAX1 REAL*8 50014
YMAX2 REAL*8 50094
YMAX3 REAL*8 50158
YMIN1 REAL*8 50022
YMIN2 REAL*8 50102
YMIN3 REAL*8 50166
YOLD REAL*8 49756
YPRIM1 REAL*8 50222
YPRIM2 REAL*8 50238
YPRIM3 REAL*8 50254
YY REAL 8010
YYY1 INTEGER*2 49912
YYY2 INTEGER*2 49992
YYY3 INTEGER*2 50056
YYY4 INTEGER*2 50136
YYY5 INTEGER*2 50200
ZETA REAL 49250
ZZ1 REAL*8 49894
ZZ2 REAL*8 49974
ZZ3 REAL*8 50038
ZZ4 REAL*8 50118
ZZ5 REAL*8 50182

```

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D Line# 1 7

Name	Type	Size	Class
ACCLIN			SUBROUTINE
BILINA			SUBROUTINE
MAIN			PROGRAM
RESPAL			SUBROUTINE
RUBBER			SUBROUTINE

Pass One No Errors Detected
 932 Source Lines

"BILINALL" and "RUBBER" Subroutine
Listings.

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```

D Line# 1      7      Microsoft FORTRAN77 V3.20 02/84
1 $debug
2 $title: 'bilinall'
3 $storage: 2
4 $nofloatcalls
5
6
7 C-----
8
9 C      SUBROUTINE WHICH CALCULATES THE BILINEAR HORIZONTAL
10 C      OR VERTICAL STIFFNESS AND RESISTANCE
11
12 C-----
13
14      SUBROUTINE BILINALL(U,V,PK,RR,KD,QD,KU,UCL,UMAX,UMIN,KY,ZZ,WZ,
15      + WWW,YYY,UUD)
16
17      real*8 U,V,RR,KD,QD,KU,UCL,PK
18      real*8 UMAX,UMIN,ZZ,WZ
19      integer WWW,YYY,UUD,KY
20
21 C      BEGINNING OF BILINEAR LOGIC
22
23 C      CHECK IF RESPONSE STILL ON INITIAL ELASTIC LINE
24
25      if (KY .lt. 0) goto 4040
26      if (KY .gt. 0) goto 3460
27      RR=KU*U
28      PK=KU
29
30 C      CHECK IF THE RESPONSE HAS GONE PLASTIC
31
32      if (U .gt. -UCL .and. U .lt. UCL) goto 4720
33
34 C      RESPONSE IS NOW PLASTIC
35
36      if (U .lt. -UCL) goto 4040
37
38 C      RESPONSE IS ON THE TOP PLASTIC LINE
39
40 3220      KY=1
41           PK=KD
42           RR=KD*U+QD
43           WWW=0
44           YYY=0
45           ZZ=0.0
46           goto 4720
47

```

```

48 C    CHECK IF VELOCITY SHIFTS FROM POSITIVE TO NEGATIVE
49
50 3480  if (V .gt. 0) goto 3720
51
52 C    CHECK IF ON THE RIGHT ELASTIC LINE
53
54      if (YYY .gt. 0) goto 3630
55
56 C    CALCULATE VALUE OF UMAX
57
58      ZZ=U
59 3630  YYY=1
60      UMAX=ZZ
61
62 C    CHECK IF RESPONSE SHIFTS TO LOWER PLASTIC LINE
63
64 3720  if (U .lt. (UMAX-2*UEL)) goto 4040
65
66 C    CHECK IF RESPONSE SHIFTS TO TOP PLASTIC LINE
67
68      if (U .gt. UMAX) goto 3220
69
70 C    CHECK IF RESPONSE RETURNS TO TOP PLASTIC LINE
71
72      if (YYY .eq. 0) goto 3220
73
74 C    RESPONSE IS ON THE RIGHT ELASTIC LINE
75
76      KY=1
77      FX=KU
78      RR=KU*(U-(U-U)*UMAX+QD
79      goto 4720
80
81 C    CHECK IF VELOCITY SHIFTS TO POSITIVE
82
83 4040  if (V .gt. 0) goto 4350
84
85 C    CHECK IF RESPONSE REMAINS ELASTIC
86
87      if (WWW .eq. 1) goto 4350
88
89 C    RESPONSE IS ON THE BOTTOM PLASTIC LINE
90
91 4150  KY=-1
92      PY=KD
93      RR=KD*U-QD
94      UUU=0
95      WZ=0.0
96      goto 4720
97

```

```

98 C      CHECK IF RESPONSE IS ON THE LEFT ELASTIC LINE
99
100 4350   if (UUU .gt. 0) goto 4370
101       WZ=U
102 4370   UUU=1
103       UMIN=WZ
104
105 C      CHECK IF RESPONSE RETURNS TO TOP PLASTIC LINE
106
107       if (U .gt. (UMIN+2*UEL)) goto 3220
108
109 C      CHECK IF RESPONSE RETURNS TO BOTTOM PLASTIC LINE
110
111       if (U .lt. UMIN) goto 4150
112
113 C      RESPONSE IS ON THE LEFT ELASTIC LINE
114
115       WWW=1
116       KP=K0*U+KAD-KU*UMIN-QD
117       PK=KU
118
119 4720   continue
120       RETURN
121       END

```

Name	Type	Offset	P Class
------	------	--------	---------

KD	REAL*8	16 *
KU	REAL*8	24 *
KY	INTEGER*2	40 *
PK	REAL*8	8 *
QD	REAL*8	20 *
RR	REAL*8	12 *
U	REAL*8	0 *
UEL	REAL*8	28 *
UMAX	REAL*8	32 *
UMIN	REAL*8	76 *
UUU	INTEGER*2	60 *
V	REAL*8	4 *
WWW	INTEGER*2	52 *
WZ	REAL*8	48 *
YYY	INTEGER*2	56 *
ZZ	REAL*8	44 *

Name	Type	Size	Class
------	------	------	-------

BILINA			SUBROUTINE
--------	--	--	------------

Pass One No Errors Detected
 121 Source Lines

B Line# 1 7 Microsoft FORTRAN77 V3.20 02/84

```

1 $debug
2 $title: rubber
3 $nofloatcalls
4
5
6 C-----
7
8 C SUBROUTINE WHICH CALCULATES THE RUBBER CAP VERTICAL
9 C STIFFNESS AND RESISTANCE
10
11 C-----
12
13 SUBROUTINE RUBBER (X,P,RR,XD,GD,KU,UCL)
14
15 REAL*8 X,RR,XD,GD,KU,UCL,P
16
17 C BEGINNING OF RUBBER LOGIC
18
19 C CHECK IF RESPONSE STILL ON INITIAL ELASTIC LINE
20
21 IF (.NOT. UCL) goto 7220
22 PR=0.
23 PR=X
24 goto 4720
25
26 C RESPONSE IS ON THE 2ND ELASTIC LINE
27
28 7220 continue
29 PR=XD
30 PR=PR+GD
31
32 4720 continue
33 RETURN
34 END

```

Name	Type	Offset	P	Class
XD	REAL*8	12	*	
KU	REAL*8	20	*	
P	REAL*8	4	*	
GD	REAL*8	16	*	
RR	REAL*8	8	*	
U	REAL*8	0	*	
UCL	REAL*8	24	*	

Sample Input Data File and Output File

SHIP/SUB DRYDOCK BLOCKING SYSTEM DATA FILE: A:SIORBILN.DAT

INPUT FILE DATA

SHIP NAME: LAFAYETTE SSBN 616
 DISCRPTION OF ISOLATORS IF USED: NO ISOLATOR ALL BILINEAR
 DISCRPTION OF BUILDUP: 8 SPACING COMPOSITE
 DISCRPTION OF MALE SHORES USED: NO MALE SHORES
 DISCRPTION OF DAMPING: 5 % DAMPING
 LOCATION OF DRYDOCK BEING STUDIED: NO SPECIFIC LOCATION
 NAVSEA DOCKING DRAWING NUMBER: 845-2006640
 REFERENCE SPREADSHEET STIFFNESS CALC FILE NAME: SIKHORIG.WK1 & SISHORIG.WK1
 MISC. COMMENTS: SIORBILN.DAT 1839 4 MAR 88

SHIP WEIGHT (KIPS)	W= 16769.9
HEIGHT OF KG (IN)	H= 193
MOMENT OF INERTIA (KIPS*IN*SEC^2)	Ik= 2416451
SIDE PIER VERTICAL STIFFNESS (KIPS/IN)	Kvs= 10113.39
SIDE PIER VERTICAL PLASTIC STIFFNESS (KIPS/IN)	Kvsp= 4025.64
KEEL PIER VERTICAL STIFFNESS (KIPS/IN)	KVK= 46808.74
KEEL PIER VERTICAL PLASTIC STIFFNESS(KIPS/IN)	KVKP= 46808.74
HEIGHT OF MALE SHORES (IN)	AAA= 0
MALE SHORE STIFFNESS (KIPS/IN)	KS= 0
SIDE PIER HORIZONTAL STIFFNESS (KIPS/IN)	KHS= 5825.13
KEEL PIER HORIZONTAL STIFFNESS (KIPS/IN)	KHK= 59227.08
SIDE PIER HORIZONTAL PLASTIC STIFFNESS(KIPS/IN)	KSHp= 2212.17
KEEL PIER HORIZONTAL PLASTIC STIFFNESS(KIPS/IN)	KKHp= 38734.96
RESTORING FORCE AT 0 DEFLECT KEEL HORIZ (KIPS)	QD1= 18098.67
RESTORING FORCE AT 0 DEFLECT SIDE HORIZ (KIPS)	QD2= 4817.6
RESTORING FORCE AT 0 DEFLECT SIDE VERT (KIPS)	QD3= 2262.37
RESTORING FORCE AT 0 DEFLECT KEEL VERT (KIPS)	QD4= 0
GRAVITATIONAL CONSTANT (IN/SEC^2)	GRAV= 386.09

SIDE BLOCK WIDTH (IN)	SBW= 42
KEEL BLOCK WIDTH (IN)	KBW= 48
SIDE BLOCK HEIGHT (IN)	SBH= 74
KEEL BLOCK HEIGHT (IN)	KBH= 60
BLOCK ON BLOCK FRICTION COEFFICIENT	U1= .43
HULL ON BLOCK FRICTION COEFFICIENT	U2= .53
SIDE PIER TO SIDE PIER TRANSVERSE DISTANCE (IN)	BR= 144
SIDE PIER CAP PROPORTIONAL LIMIT	SCPL= .7
KEEL PIER CAP PROPORTIONAL LIMIT	KCPL= .45
TOTAL SIDE PIER CONTACT AREA (ONE SIDE) (IN^2)	SAREA= 9352
TOTAL KEEL PIER CONTACT AREA (IN^2)	KAREA= 55440
PERCENT CRITICAL DAMPING	ZETA= .05
HULL NUMBER (XXXX)	HULL= 616
SYSTEM NUMBER (XXX)	NSYS= 1
CAP ANGLE (RAD)	BETA= .377

16769.9 193.0 2410451 10113.39 4025.64 46808.74 0.0 0.0
 5825.13 59223.08 2212.17 38434.86 18098.07 4817.60 2262.37 386.09
 42.00 48.00 74.00 60.00 0.43 0.52
 144.00 0.70 0.45 9352.0 55440.0 0.050
 616 1 0.377 0.00 46808.74

LAFAYETTE SSBN 616
 NO ISOLATOR ALL BILINEAR
 8 SPACING COMPOSITE
 NO WALE SHORES
 5 % DAMPING
 NO SPECIFIC LOCATION
 845-2006640
 SISHORIG.WK1 & SISHOPIS.WK1
 SICHORLN.DAT 1879 4 MAR 88

**** System 1 ****

** Hull 616 **

* Ship Parameters *

Weight	Moment of Inertia	K.G.
16369.9 kips	2410451.0 kips-in-sec ²	193.0 ins

* Drydock Parameters *

Side Block Height	Side Block Width	Keel Block Height	Keel Block Width
74.0 ins	42.0 ins	60.0 ins	48.0 ins
Side-to-Side Pier Distance	Male Shore Ht.	Male Shore Stiffness	Cap Angle
144.0 ins	.0 ins	.0 kips/in	.377 rad
Side Side Pier Contact Area	Total Keel Pier Contact Area	kkhp	
9352.0 in ²	55440.0 in ²	36434.9 kips/in	
B/B Friction Coeff	H/E Friction Coeff	ksp	kvsp
.475	.530	2212.2 kips/in	4025.6 kips/in
Side Pier Fail Stress Limit	Keel Pier Fail Stress Limit	kvkp	
.700 kips/in ²	.450 kips/in ²	46808.7 kips/in	
Side Pier Vertical Stiffness	Side Pier Horizontal Stiffness		
10113.4 kips/in	5825.1 kips/in		
Keel Pier Vertical Stiffness	Keel Pier Horizontal Stiffness		
46808.7 kips/in	59223.1 kips/in		
Q01	Q02	Q03	Q04
18098.1 kips	4917.6 kips	2252.4 kips	.0 kips

* System Parameters and Inputs *

Earthquake Used is 1940 EL CENTRO

Horizontal acceleration input is HORIZONTAL

Vertical acceleration input is
Earthquake Acceleration Time History.

Vertical/Horizontal Ground Acceleration Ratio	Data Time Increment
1.000	.010 sec

Gravitational Constant	% System Damping
386.19 in/sec ²	5.00 %

Mass Matrix

42.3992	.0000	8183.0420
.0000	42.3992	.0000
8183.0420	.0000	2410451.0000

Damping Matrix

118.1018	.0000	5027.6454
.0000	118.5898	.0000
5027.6454	.0000	1549181.3597

Stiffness Matrix

70873.3400	.0000	163103.6400
.0000	67035.5200	.0000
163103.6400	.0000	99931610.6070

Undamped Natural Frequencies	Mode #1	Mode #2	Mode #3
	6.425 rad/sec	69.650 rad/sec	39.763 rad/sec
Damped Natural Frequencies	Mode #1	Mode #2	Mode #3
	6.416 rad/sec	69.563 rad/sec	39.713 rad/sec

For Earthquake Acceleration of 100.00 % of the 1940 EL CENTRO

Maximaes/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-1.243397			11.22
Maximum Y		-1.202029		8.01
Maximum Rotation			.048797	14.44
Side block sliding	-1.103557	.037213	-.021226	6.24
Keel block sliding	-1.095723	.021787	-.021704	6.23
Side block overturning	.082442	-.061166	.011885	5.61
Keel block overturning	.020383	.052877	.001717	4.71
Side block liftoff	-.007883	-.103857	-.003915	4.96
Side block crushing	-.009432	.021336	.009388	5.46

For Earthquake Acceleration of 90.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-0.246421			16.51
Maximum Y		-0.181860		8.01
Maximum Rotation			-0.049806	13.83
Side block sliding	.000484	-0.055408	.002296	5.77
Keel block sliding	-0.087291	.019017	-0.019629	6.23
Side block overturning	.000484	-0.055408	.002296	5.77
Keel block overturning	-0.031319	-0.030563	.001947	4.75
Side block liftoff	-0.002232	-0.081113	-0.003868	4.97
Side block crushing	-0.011740	-0.012852	.009220	5.48

For Earthquake Acceleration of 80.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-0.250337			16.51
Maximum Y		-0.161793		8.01
Maximum Rotation			.049040	19.75
Side block sliding	.000027	-0.051407	.001472	5.77
Keel block sliding	-0.088423	.009133	-0.017334	6.22
Side block overturning	.000027	-0.051407	.001472	5.77
Keel block overturning	-0.021642	.058728	-0.005154	5.03
Side block liftoff	.001236	-0.051243	-0.003723	4.98
Side block crushing	.008197	-0.014721	.008773	5.50

For Earthquake Acceleration of 70.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-0.248603			13.79
Maximum Y		-0.145349		8.01
Maximum Rotation			.049499	14.38
Side block sliding	-0.026676	.040248	-0.009791	6.28
Keel block sliding	-0.083862	.039448	-0.019523	7.37
Side block overturning	-0.018619	.034936	-0.011260	6.26
Keel block overturning	-0.029241	-0.004233	.007959	5.54
Side block liftoff	-0.000110	-0.023437	-0.003463	4.99
Side block crushing	-0.011305	-0.039360	-0.008468	5.92

For Earthquake Acceleration of 60.00 % of the 1940 EL CENTRO

Maximaes/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.252173			13.78
Maximum Y		-.116732		8.00
Maximum Rotation			.049920	19.65
Side block sliding	-.007131	.021628	-.004153	6.30
Keel block sliding	.061008	.097166	.017490	7.93
Side block overturning	-.036460	.021380	-.007884	6.24
Keel block overturning	.022516	.054039	.004804	5.42
Side block liftoff	-.007482	.000282	-.003069	5.00
Side block crushing	.001256	-.018546	-.008745	5.96

For Earthquake Acceleration of 50.00 % of the 1940 EL CENTRO

Maximaes/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	.246529			19.66
Maximum Y		-.094418		8.00
Maximum Rotation			.049232	19.61
Side block sliding	-.015797	.008866	-.002023	6.31
Keel block sliding	-.093131	-.025568	-.026015	8.50
Side block overturning	-.015797	.008866	-.002023	6.31
Keel block overturning	.029000	.008726	.004993	5.52
Side block liftoff	-.014161	.022488	-.003067	5.97
Side block crushing	-.000804	-.062532	.008307	6.58

For Earthquake Acceleration of 40.00 % of the 1940 EL CENTRO

Maximaes/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	.241724			19.55
Maximum Y		-.071379		8.00
Maximum Rotation			.048794	19.50
Side block sliding	.032752	.002736	.006452	7.86
Keel block sliding	.084762	.009522	.023788	9.05
Side block overturning	.008986	.014682	-.001517	7.34
Keel block overturning	.027507	.013162	.007261	6.60
Side block liftoff	-.004824	.006973	.002657	5.38
Side block crushing	.000491	-.013329	.009022	7.53

For Earthquake Acceleration of 30.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.031730			8.07
Maximum Y		-.040973		8.00
Maximum Rotation			.005341	7.51
Keel block overturning	-.028676	.012919	-.003477	8.06
Side block liftoff	-.009727	.017853	-.002363	5.84

For Earthquake Acceleration of 20.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.018083			7.97
Maximum Y		-.026897		8.00
Maximum Rotation			.003646	7.50
Side block liftoff	.002507	.019660	.002589	6.42

For Earthquake Acceleration of 10.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.008056			7.98
Maximum Y		-.013437		4.79
Maximum Rotation			.001623	7.45

No failures occurred.

For Earthquake Acceleration of 19.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.017166			7.97
Maximum Y		-.025552		8.00
Maximum Rotation			.003456	7.50
Side block liftoff	.002767	.020286	.002591	6.43

For Earthquake Acceleration of 18.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-0.015413			7.97
Maximum Y		-0.024136		4.79
Maximum Rotation			.003294	7.49
Side block liftoff	.010977	-0.002288	.002979	6.54

For Earthquake Acceleration of 17.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-0.014521			7.97
Maximum Y		-0.022842		4.79
Maximum Rotation			.003091	7.49
Side block liftoff	-0.002400	-0.002636	-0.002636	6.99

For Earthquake Acceleration of 16.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-0.013572			7.97
Maximum Y		-0.021499		4.79
Maximum Rotation			.002858	7.49
Side block liftoff	-0.003316	.016301	-0.002449	7.90

For Earthquake Acceleration of 15.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	.013488			7.57
Maximum Y		-0.020155		4.79
Maximum Rotation			.002624	7.48

No failures occurred.

APPENDIX 2

1. Sample Vertical and Horizontal
Stiffness Spreadsheets

Sample Vertical and Horizontal Stiffness Spreadsheets.

VERTICAL STIFFNESS CALCULATIONS FOR DRYDOCK BLOCKS

HULL TYPE 616 DOCKING PLAN # = 845-2006640

SYSTEM # 30 KEEL BLOCKS 1" RUBBER CAP E1

BLOCK SPA 16.00 FEET

VERTICAL STIFFNESS:

LEVEL #	MATERIAL	E (PSI)	LENGTH (IN)	WIDTH (IN)	HEIGHT (IN)	K (KIPS/IN)	1/K	PIER TOTAL K (KIPS/IN)
			(DEPTH) (B)	(TRANSVERSE) (H)	(L)			
1	RUBBER	992.00	42.00	24.00	1.00	999.94	0.0010001	459.76
2	D.FUR	12539.19	42.00	24.00	4.00	3159.88	0.0003165	
3	OAK	23980.00	42.00	33.67	29.00	1169.35	0.0008552	
4	CONCRETE	4000000.00	42.00	48.00	27.00	298666.67	0.0000033	
					61.00			
		1845.83						
					0 BLOCKS	55		TOTAL STIFF OF BLOCK SY (KIPS/IN):
								25286.68

03-Feb-88

HORIZONTAL STIFFNESS MATRIX FOR 4 LAYERS 1" RUBBER CAP E1

SYSTEM 30

THIS IS A SIDE BLOCK SYSTEM FOR HULL 616 WITH 5 FT BUILDUP
16 FOOT CENTERS

ELEMENT # 1	CONCRETE			
E1	DEPTH	TRANSVERSE	I1	HEIGHT
(PSI)	B1	H1	I1	L1
(IN)	(IN)	(IN)	(IN ⁴)	(IN)
4000000	48	42	296352	48

12E111/L1*3	6E111/L1*2	4E111/L1	2E111/L1
128625000	3087100000	98794000000	49392000000

RIGIDITY	TOP	SHEAR	ELEMENT
G1	CONTACT	STRAIN	SHEAR
(PSI)	AREA	(IN/IN)	DEFLECTION
(IN ²)	(IN ²)	(IN)	(IN)
2400000	2016	0.0000002067	0.0000099206

ELEMENT # 2	DAF			
E2	DEPTH	TRANSVERSE	I2	HEIGHT
(PSI)	B2	H2	I2	L2
(IN)	(IN)	(IN)	(IN ⁴)	(IN)
335720	23.4	29.7	51086.24235	20

12E212/L2*3	6E212/L2*2	4E212/L2	2E212/L2
25726009.923	257260099.23	3430134656.3	1715067328.2

RIGIDITY	TOP	SHEAR	ELEMENT
G1	CONTACT	STRAIN	SHEAR
(PSI)	AREA	(IN/IN)	DEFLECTION
(IN ²)	(IN ²)	(IN)	(IN)

22980 486.486 0.0000857197 0.0017143933

ELEMENT # 3 DOUGLAS FIR

E3 (PSI)	DEPTH B3 (IN)	TRANSVERSE H3 (IN)	L3 (IN*4)	HEIGHT L3 (IN)
95297	12	24	13824	6

12E313/L3*3	6E313/L3*2	4E313/L3	2E313/L3
7.3168E+07	2.1956E+06	8.7826E+08	4.2913E+08

RIGIDITY B1 (PSI)	TOP CONTACT AREA (IN*2)	SHEAR STRAIN (IN/IN)	ELEMENT SHEAR DEFLECTION (IN)
6807	288	0.0005101012	0.003060607

ELEMENT # 4 RUBBER

E4 (PSI)	DEPTH B4 (IN)	TRANSVERSE H4 (IN)	L4 (IN*4)	HEIGHT L3 (IN)
942	12	24	13824	1

12E414/L4*3	6E414/L4*2	4E414/L4	2E414/L4
1.6456E+06	8.2280E+07	5.4854E+07	2.7427E+07

RIGIDITY B1 (PSI)	TOP CONTACT AREA (IN*2)	SHEAR STRAIN (IN/IN)	ELEMENT SHEAR DEFLECTION (IN)	TOTAL SHEAR DEFLECTION (IN)
335	288	0.0103556324	0.0103556324	1.5141E+02

STIFFNESS MATRIX

D

F
M

q1	1.2862E+08	3.0870E+09	-1.2862E+08	3.0870E+09	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	q1
th1	3.0870E+09	9.8794E+10	-3.0870E+09	4.9392E+10	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	th1
q2	-1.2862E+08	-3.0870E+09	1.5435E+08	-2.8297E+09	-2.5726E+07	2.5726E+08	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	q2
th2	3.0870E+09	4.9392E+10	-2.8297E+09	1.0221E+11	-2.5726E+08	1.7151E+09	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	th2
q3	0.0000E+00	0.0000E+00	-2.5726E+07	-2.5726E+08	9.8914E+07	-3.7636E+07	-7.3188E+07	2.1956E+08	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	q3
th3	0.0000E+00	0.0000E+00	2.5726E+08	1.7151E+09	-3.7636E+07	4.3084E+09	-2.1956E+08	4.3913E+08	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	th3
q4	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	-7.3188E+07	-2.1956E+08	2.3775E+08	-1.3728E+08	-1.64561E+08	8.22804E+07	q4		
th4	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	2.1956E+08	4.3913E+08	-1.3728E+08	9.3311E+08	-8.22804E+07	2.74268E+07	th4		
q5	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	-1.64561E+08	-8.22804E+07	1.64561E+08	-8.22804E+07	q5		
th5	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	8.22804E+07	2.74268E+07	-8.22804E+07	5.48536E+07	th5		

KNOWN VALUES:

Q1 = -1000 lbs
 M1 = Q1*(L1+L2+L3+L4) = -75000 IN*LB
 Q2 = Q3 = Q4 = Q5 = 0
 Q5 = 1000 lbs
 θ1 = θ2 = 0

OF SYSTEM BLOCKS =

15

SOLVED UNKNOWN:

q2 = 0.000573372 in
 θ2 = 0.000020651 rad

q3 = 0.0003357536 in
 θ3 = 0.0000218894 rad

-B1 -B2
 -3006.3287622 -486.541190475

q4 = 0.0005354071 in
 θ4 = 0.0000401072 rad

-30379.296282 -99944.020772

q5 = 0.000598215 in
 θ5 = 0.000076568 rad

-92407.123564 -47253.569633

K (BEND HORIZ) FOR 1 SIDE BLOCK = 1867737.5583 lbs/in

1867.7375583 KIPS/IN

K (BEND HORIZ) ALL SIDE BLOCKS = 28016063.374 lbs/in

28016.063274 KIPS/IN

TOTAL SIDE BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:
 SYSTEM 30 E1

Khs (SIDE BLOCK HORIZONTAL STIFFNESS) = P/(BENDING DISPL + SHEAR DISPLACEMENT)

Khs = 63.53 KIPS/IN (PER BLOCK)

Khs = 952.96 KIPS/IN (ENTIRE SIDE BLOCK SYSTEM)

APPENDIX 3

1. System 1-11 Stiffness Table
2. XEL, QD, KU, and KD Values for Bilinear Douglas Fir Caps
3. BASIC Bilinear Stiffness Program Listing
4. "3DOFRUB" System 1 Output File
5. "3DOFRUB" System 1 Input Data File

System 1-11 Stiffness Table

TOTAL AXEL AND SIDE PIER STIFFNESS KIPS/IN
BILINEAR SYSTEMS (1-11) PER DOCKING DRAWINGS

SYSTEM	KVK	KVS	KVSP	KUM	KDMP	KUS	KSDP
1	46808.74	10113.39	4025.64	59223.08	38434.86	5825.13	2212.17
2	46808.74	5231.06	2002.23	59223.08	38434.86	3013.00	1144.23
3	31919.89	6178.56	3211.52	28875.45	22849.71	4655.29	1897.66
4	31919.89	3195.81	1661.13	28875.45	22849.71	2097.56	981.55
5	46808.74	3195.81	1661.13	59223.08	38434.86	2097.56	981.55
6	83270.20	43011.07	22269.52	79683.44	53718.39	28797.14	13345.17
7	83270.20	28512.95	14762.94	79683.44	53718.39	19090.24	8846.80
8	83270.20	21747.17	11259.87	79683.44	53718.39	14560.35	6747.56
9	24375.19	8629.57	4065.53	22050.35	17448.87	5842.63	2409.17
10	19442.11	6808.09	3188.10	17587.78	13917.55	4625.36	1890.63
11	19442.11	5236.99	2452.39	17587.78	13917.55	3557.97	1454.33

XEL, QD, KU, and KD Values
for Bilinear Douglas Fir Caps

1 = AXEL HORIZONTAL STIFFNESS
2 = SIDE BLOCK HORIZONTAL STIFFNESS
3 = SIDE BLOCK VERTICAL STIFFNESS

QD VALUES:

SYSTEM	AXEL	COMT.	SHEAR DE	ONE	AXEL	KU1-KU1	QD1	SP CAP	SHEAR DE	KUS	AXEL	KU2-KU2	QD2	CAP AREA	D.FIR	KVS	TEL1	KU3-KU3	QD3
0	AREA	PROP LHM	(KIPS/IN)	(IN)	(IN)	(KIPS/IN)	(KIPS)	AREA	PROP LHM	(KIPS/IN)	(IN)	(KIPS/IN)	(KIPS)	(IN ²)	(PSI)	(KIPS/IN)	(IN)	(KIPS/IN)	(KIPS)
	(IN ²)	(PSI)						(IN ²)	(PSI)										
1	55440.00	930.0	59223.1	0.8706	20788.22	18098.07	8352.00	930.0	5825.13	1.3334	3612.96	4817.602	8352.00	450.0	10113.39	0.3716	6087.75	2262.366	1
2	55440.00	930.0	59223.1	0.8706	20788.22	18098.07	4320.00	930.0	3013.00	1.3334	1868.77	2491.858	4320.00	450.0	5231.06	0.3716	3148.83	1170.186	2
3	55440.00	930.0	28875.5	1.7856	6025.74	10759.39	8352.00	930.0	4055.29	1.9154	2157.63	4132.648	8352.00	450.0	6178.56	0.6083	2967.04	1804.841	3
4	55440.00	930.0	28875.5	1.7856	6025.74	10759.39	5220.00	930.0	2097.56	2.3144	1116.01	2582.897	5220.00	450.0	3195.81	0.7350	1534.68	1128.028	4
5	55440.00	930.0	59223.1	0.8706	20788.22	18098.07	5220.00	930.0	2097.56	2.3144	1116.01	2582.897	5220.00	450.0	3195.81	0.7350	1534.68	1128.028	5
6	108864.00	930.0	79683.4	1.2706	25965.05	32990.45	57672.00	930.0	28797.14	1.8625	15451.97	28779.44	57672.00	450.0	43011.07	0.6034	20741.55	12515.21	6
7	108864.00	930.0	79683.4	1.2706	25965.05	32990.45	38232.00	930.0	19090.24	1.8625	10243.44	19078.50	38232.00	450.0	28512.95	0.6034	13750.01	8296.604	7
8	108864.00	930.0	79683.4	1.2706	25965.05	32990.45	29160.00	930.0	14560.35	1.8625	7812.79	14551.40	29160.00	450.0	21747.17	0.6034	10487.3	6327.919	8
9	42336.00	930.0	22050.4	1.7856	4601.48	8216.272	9600.00	930.0	5842.63	1.5281	3433.46	5246.598	9600.00	450.0	8629.57	0.5006	4564.04	2284.778	9
10	17768.00	930.0	17587.8	1.7856	3670.23	6553.458	7488.00	930.0	4625.36	1.5056	2734.73	4117.349	7488.00	450.0	6808.09	0.4949	3619.99	1791.679	10
11	37768.00	930.0	17587.8	1.7856	3670.23	6553.458	5760.00	930.0	3557.97	1.5056	2103.64	3167.193	5760.00	450.0	5236.99	0.4949	2784.6	1378.212	11

BASIC Bilinear Stiffness Program
Listing

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10 SCREEN 0: WIDTH 80
20 CLS
30 PRINT "*****"
40 '
50 PRINT:PRINT "          ****SHIP DRYDOCK BLOCKING SYSTEM***"
60 PRINT:PRINT "    ****TRANSVERSE RESPONSE ASSUMING BILINEAR BEHAVIOR****"
70 PRINT:PRINT "    ****USING TIME AND ACCELERATION INPUT DATA****":PRINT
80 '
90 PRINT "*****"
100 '
110 '           *INITIALIZATION*
120 '
130 DIM F(4001),UDP(4001)
140 C$=" ***.*** ***.*****"
150 A$=" ***.*** *****.##"
160 D$="*****.### *****.#### *****.#### *****.#### *****"
170 PRINT "      ***DATA FILE INFORMATION***":PRINT
180 PRINT "  1. PREPARE NEW DATA FILE":PRINT
190 PRINT "  2. MODIFY EXISTING DATA FILE":PRINT
200 PRINT "  3. USE EXISTING DATA FILE":PRINT
210 INPUT "      SELECT NUMBER":NN
220 PRINT:INPUT "      DRIVE USED FOR DATA FILES (A:,B:,C:,D:,E:,F:)":ABC$
230 INPUT "              FILE NAME ( OMIT DRIVE LETTER )":F4$
240 F4$=ABC$+F4$
250 INPUT "      DOES YOUR COMPUTER HAVE A GRAPHICS BOARD (Y/N) ":GR$
260 CLS
270 ON NN GOTO 290,370,480
280 '
290 GOSUB 580:' CALL SUBROUTINE "INPUT DATA"
300 GOSUB 890:' CALL SUBROUTINE "PRINT DATA"
310 GOSUB 1090:' CALL SUBROUTINE "STORE DATA"
320 GOSUB 1220:' CALL SUBROUTINE "CALCULATE RESPONSE"
330 IF GR$="N" OR GR$="n" THEN GOTO 520
340 GOSUB 5310:'CALL SUBROUTINE "PLOT"
350 GOTO 510
360 '
370 GOSUB 4960:' CALL SUBROUTINE "RECALL DATA"
380 GOSUB 5080:' CALL SUBROUTINE "MODIFY DATA"
390 GOSUB 890 : ' CALL SUBROUTINE "PRINT DATA"
400 GOSUB 1090 : ' CALL SUBROUTINE "STORE DATA"
410 GOSUB 1220 : ' CALL SUBROUTINE "CALCULATE RESPONSE"
420 IF GR$="N" OR GR$="n" THEN GOTO 520
430 GOSUB 5310:'CALL SUBROUTINE "PLOT"
440 GOTO 510
450 '
460 GOSUB 4960:' CALL SUBROUTINE "RECALL DATA"
470 GOSUB 890 : ' CALL SUBROUTINE "PRINT DATA"
480 GOSUB 1220 : ' CALL SUBROUTINE "CALCULATE RESPONSE"
490 IF GR$="N" OR GR$="n" THEN GOTO 520
500 GOSUB 5310:'CALL SUBROUTINE "PLOT"
510 LOCATE 23,2
520 PRINT "PRESS ANY KEY TO":PRINT "RETURN TO THE BILINEAR PROGRAM"
530 A$:INKEY$: IF A$="" THEN 530
540 CHAIN ABC$+"BILINEAR ",10
550 END
560 '*****'
570 '
580 CLS:' SUROUTINE "INPUT DATA"
590 PRINT "      INPUT THE FOLLOWING DATA":PRINT
600 INPUT "SHIP/SUB BLOCKING SYSTEM: ";SHIP$
610 INPUT "EARTHQUAKE ACCELERATION USED: ";QUAK$
620 INPUT "NUMBER OF POINTS DEFINING THE EXCITATION
630 INPUT "MASS (KIPS/IN^3-2)
640 INPUT "SPRING CONSTANT 1 (KIPS/IN)
650 INPUT "SPRING CONSTANT 2 (KIPS/IN)
660 INPUT "DAMPING COEFFICIENT

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670 INPUT "TIME STEP INTEGRATION (SEC) H=";H
680 INPUT "RESTORING FORCE AT 0 DEFLECT & POS. VELOCITY(KIPS) QD=";QD
690 INPUT "PROPORTIONAL LIMIT (KIPS/IN^2) P=";P
700 INPUT "AREA OF APPLIED FORCE (IN^2) A=";A
710 G=0
720 INPUT "X DISPLACEMENT PLOTTING MAX AMPLITUDE (IN) ";DD
730 INPUT "MAXIMUM RUN TIME OF EARTHQUAKE ACCELERATION INPUT: ";TT
740 INPUT "ARE THE ABOVE VALUES CORRECT Y/N";YN$
750 IF YN$="N" THEN GOTO 280
760 CLS :PRINT
770 PRINT:PRINT
780 INPUT "INPUT THE NAME OF ACCELERATION DATA FILE YOU WISH TO USE: ",ACCE$
790 OPEN ACCE$ FOR INPUT AS #1
800 PRINT "ACCELERATION FILE BEING READ ... "
810 FOR I=1 TO NE
820 INPUT #1,F(I)
830 NEXT I
840 CLOSE #1
850 PRINT "ACCELERATION DATA FILE INPUT COMPLETE "
860 RETURN
870 '*****
880 '
890 CLS: 'SUBROUTINE "PRINT DATA"
900 PRINT:PRINT " ***SHIP/SUB DRYDOCK BLOCKING SYSTEM*** DATA FILE: ";F4$
910 PRINT:PRINT " ***RESPONSE FOR BILINEAR BEHAVIOR***":PRINT
920 PRINT " INPUT DATA:":PRINT
930 PRINT " SHIP/SUB DRYDOCK BLOCKING SYSTEM: ",SHIP$
940 PRINT " EARTHQUAKE ACCELERATION TIME HISTORY USED: ";QUAK$
950 PRINT " NUMBER OF POINTS DEFINING THE EXCITATION NE=";NE
960 PRINT " MASS (KIPS/IN/S^2) M=";M
970 PRINT " SPRING CONSTANT 1 (KIPS) KU=";KU
980 PRINT " SPRING CONSTANT 2 (KIPS) KD=";KD
990 PRINT " DAMPING COEFFICIENT C=";C
1000 PRINT " TIME STEP INTEGRATION (SEC) H=";H
1010 PRINT " REST. FORCE AT 0 DEFL. W/POS. VEL (KIPS) QD=";QD
1020 PRINT " HORIZONTAL CONTACT AREA (IN^2) A=";A
1030 PRINT " SPRING PROPORTIONAL LIMIT (KIPS/IN^2) P=";P
1040 PRINT " THE DISPLACEMENT PLOT UPPER LIMIT (IN) DD=";DD
1050 PRINT " THE RUN TIME LIMIT (SEC) TT=";TT
1060 RETURN
1070 '*****
1080 '
1090 'SUBROUTINE "STORE DATA"
1100 IF NN<>2 THEN 1130
1110 INPUT "INPUT THE NAME OF THE MODIFIED DATA FILE: ",MD$
1120 F4$=ABC$+MD$
1130 OPEN F4$ FOR OUTPUT AS #1
1140 WRITE #1,SHIP$,QUAK$,NE,M,KU,KD,C,H,QD,P,A,DD,TT
1150 FOR I=1 TO NE
1160 WRITE #1,F(I)
1170 NEXT I
1180 CLOSE #1
1190 RETURN
1200 '*****
1210 '
1220 'SUBROUTINE "CALCULATE RESPONSE"
1230 '
1240 ' *INITIALIZATION*
1250 '
1260 'UD = TRANSVERSE RELATIVE SHIP CG DISPLACEMENT WITH DRY DOCK BOTTOM
1270 'UV = TRANSVERSE RELATIVE SHIP CG VELOCITY WITH DRY DOCK BOTTOM
1280 'UA = TRANSVERSE RELATIVE SHIP CG ACCELERATION WITH DRY DOCK BOTTOM
1290 '
1300 '
1310 UD=0 :UV=0 :UA=F(1)/M
1320 F(0)=0

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1330 '
1340 '
1350 '
1360 'THE TOTAL NUMBER OF DATA POINTS = NE
1370 '
1380 '
1390 NT=NE
1400 N1T=NT+1
1410 ANN=0
1420 NM1=NT-1
1430 '
1440 '
1450 'A1,A2,A3,A4 ARE COEFFICIENTS FOR THIS FORM OF NUMERICAL SOLUTION
1460 '
1470 '
1480 A1=3/H :A2=6/H :A3=H/2 :A4=6/H^2
1490 '
1500 '
1510 'XEL IS THE ELASTIC LIMIT (PROPORTIONAL LIMIT) FOR THE BLOCKING
1520 'SYSTEM IN INCHES.
1530 '
1540 '
1550 XEL=P*A/KU
1560 '
1570 '
1580 'KY IS A LOCATOR.
1590 '
1600 'WITH BILINEAR BEHAVIOR THERE ARE 5 POSSIBLE LINES THE RESISTANCE
1610 'VERSUS DISPLACEMENT RESPONSE CAN BE ON AS FOLLOWS:
1620 '
1630 'THE INITIAL SLOPE BEFORE ANY PLASTIC DEFORMATION,
1640 'THE TOP PLASTIC LINE,
1650 'THE RIGHT ELASTIC LINE,
1660 'THE BOTTOM PLASTIC LINE,
1670 'THE LEFT ELASTIC LINE,
1680 '
1690 'KY=0 INDICATES THAT THE RESPONSE IS STILL IN THE INITIAL
1700 'ELASTIC REGION AND HAS YET TO GO PLASTIC.
1710 '
1720 'KY=1 INDICATES THAT THE RESPONSE IS NOW ON THE TOP PLASTIC
1730 'LINE OR THE RIGHT ELASTIC LINE.
1740 '
1750 'KY=-1 INDICATES THAT THE RESPONSE IS NOW ON THE BOTTOM PLASTIC
1760 'LINE OR THE LEFT ELASTIC LINE.
1770 '
1780 '
1790 KY=0
1800 '
1810 '
1820 'PK IS THE CURRENT HORIZONTAL STIFFNESS AT TIME T
1830 '
1840 '
1850 PK=KU
1860 '
1870 '
1880 'XMAX IS THE HORIZONTAL DISPLACEMENT AT THE POINT VELOCITY
1890 'GOES FROM POSITIVE TO NEGATIVE AND SHIFTS FROM THE TOP
1900 'PLASTIC LINE TO THE RIGHT ELASTIC LINE.
1910 '
1920 'XMIN IS THE HORIZONTAL DISPLACEMENT AT THE POINT VELOCITY
1930 'GOES FROM NEGATIVE TO POSITIVE AND SHIFTS FROM THE BOTTOM
1940 'PLASTIC LINE TO THE LEFT ELASTIC LINE.
1950 '
1960 'THESE VALUES ARE INITIALLY SET TO ZERO
1970 '
1980 '

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2000 XMAX=0
2010
2020
2030 **TIME-DISPLACEMENT RESPONSE**
2040 II=1
2050
2060
2070
2080 'AN OUTPUT FILE IS NOW CREATED. THIS INCLUDES TIME, DISPLACEMENT,
2090 'VELOCITY, ACCELERATION, AND RESISTANCE OF THE SHIP IN THE
2100 'TRANSVERSE (HORIZONTAL) DIRECTION RELATIVE TO THE BOTTOM OF
2110 'THE DOCK. RESISTANCE IS THE RESISTANCE AGAINST DEFORMATION AND IS
2120 'DEPENDANT ON THE LOCATION ON THE RESISTANCE VERSUS DISPL. PLOT.
2130
2140
2150 PRINT:PRINT:PRINT
2160 INPUT " INPUT NAME OF OUTPUT FILE: ",ACNEW$
2170 OPEN ACNEW$ FOR OUTPUT AS #2
2180 PRINT "WAIT!!! OUTPUT FILE BEING CREATED ----- "
2190 T=0
2200
2210
2220 'RR IS THE VALUE FOR RESISTANCE AT TIME T (INITIALLY SET AT 0)
2230
2240
2250 RR=0
2260
2270
2280 'INITIAL VALUES ARE WRITTEN TO THE FILE BEFORE THE LOOP STARTS:
2290
2300 WRITE #2,T,UD,UV,UA,RR
2310
2320
2330 'ZY,ZZ,WY,WZ ARE LOCATORS SET TO ZERO HERE. THEY WILL BE
2340 'DESCRIBED WHEN THEY ARE USED LATER.
2350
2360 ZY=0
2370 ZZ=0
2380 WY=0
2390 WZ=0
2400
2410
2420 'THE BEGINNING OF THE NUMERICAL SOLUTION LOOP:
2430
2440
2450 FOR L=1 TO NT
2460
2470
2480 'TIME T = THE TIME STEP TIME THE LOOP #
2490
2500 T=H*L
2510
2520 'BK IS THE CURRENT EFFECTIVE STIFFNESS
2530
2540 BK=PK+A4*M+A1*C
2550
2560 'DFB IS THE DIFFERENTIAL FORCE AT TIME T
2570
2580 DFB=(F(L+1)-F(L))*M+(A2*M+3*C)*UV+(3*M+A3*C)*UA
2590
2600 'DUD IS THE DIFFERENTIAL DISPLACEMENT WHICH IS THE
2610 'DIFFERENTIAL FORCE DIVIDED BY THE CURRENT EFFECTIVE STIFFNESS.
2620
2630 DUD=DFB/BK
2640

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2660 '
2670 DVU=3*DUD/H-3*UV-UA*H/2
2680 '
2690 'THE NEW UD IS THE PREVIOUS DISPLACEMENT PLUS THE DIFFERENTIAL
2700 'DISPLACEMENT.
2710 '
2720 UD=UD+DUD
2730 '
2740 'THE NEW UV IS THE PREVIOUS VELOCITY PLUS THE DIFFERENTIAL
2750 'VELOCITY.
2760 '
2770 UV=UV+DVU
2780 '
2790 '
2800 '
2810 '*****
2820 '
2830 'THIS IS WHERE THE LOGIC OF HOW THE RESPONSE WORKS AROUND
2840 'THE RESISTANCE VERSUS DISPLACEMENT PLOT BEGINS*****
2850 '
2860 '*****
2870 '
2880 '
2890 'THE FIRST THING TO CHECK IS WHETHER OR NOT THE RESPONSE IS
2900 'STILL ON THE INITIAL ELASTIC LINE. IF NO PLASTIC DEFORMATION
2910 'HAS OCCURRED THEN KY=0. THE SLOPE OF THE RESISTANCE VERSUS
2920 'DISPLACEMENT CURVE SHOULD BE "KU" GOING THROUGH THE ORIGIN.
2930 '
2940 '
2950 IF KY<0 THEN 4040
2960 IF KY>0 THEN 3480
2970 RR=KU*UD
2980 PK=KU
2990 '
3000 '
3010 'THE NEXT CHECK IS TO SEE IF THE RESPONSE HAS GONE PLASTIC.
3020 'IF THIS OCCURS, USING BILINEAR BEHAVIOR, THE NEW RESISTANCE
3030 'VERSUS DISPLACEMENT CURVE WILL HAVE A SLOPE OF KD WITH A
3040 'RR INTERCEPT OF EITHER PLUS QD OR MINUS QD. QD IS AN INPUT
3050 'AND IS MATERIAL DEPENDENT.
3060 '
3070 '
3080 'IF THE DISPLACEMENT IS LESS THAN -XEL OR MORE THAN +XEL
3090 'THEN THE RESPONSE HAS GONE PLASTIC.
3100 'IF NOT, THE LOOP IS COMPLETED AND OUTPUTS FOR TIME T ARE WRITTEN
3110 'TO THE OUTPUT FILE.
3120 '
3130 IF UD>-XEL AND UD<XEL THEN GOTO 4720
3140 '
3150 'IF THE LOOP GOES HERE IT MEANS THAT THE RESPONSE IS NOW PLASTIC
3160 'ON THE TOP OR BOTTOM PLASTIC LINE.
3170 '
3180 IF UD<-XEL THEN GOTO 4040
3190 '
3200 'IF THE LOOP GOES HERE THEN THE RESPONSE IS ON THE TOP PLASTIC LINE.
3210 '
3220 KY=1
3230 PK=KD
3240 RR=KD*UD+QD
3250 '
3260 'WWW,YYY,ZZ ARE LOCATORS IN THE LOGIC. IT IDENTIFIES THE
3270 'RESPONSE SO IT KNOWS IT IS ON THE TOP PLASTIC LINE. AT THIS
3280 'POINT ALL OF THESE VALUES ARE SET TO ZERO.
3290 '
3300 WWW=0
3310 YYY=0

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3320 ZZ=0
3330 '
3340 'THE LOOP IS COMPLETED AT THIS POINT AND THE OUTPUT IS WRITTEN
3350 'TO THE OUTPUT FILE
3360 '
3370 GOTO 4720
3380 '
3390 '
3400 'THE LOGIC NOW SEES A KY=+1. ON THE NEXT LOOP THE LOGIC WILL
3410 'DO A VELOCITY CHECK. THAT IS THE NEXT STEP HERE. IF THE VELOCITY
3420 'SHIFTS FROM POSITIVE TO NEGATIVE THE RESPONSE SHIFTS FROM THE
3430 'TOP PLASTIC LINE TO THE RIGHT ELASTIC LINE.
3440 '
3450 'IF THE VELOCITY DID NOT GO NEGATIVE THEN THE LOOP RETURNS TO
3460 'THE TOP PLASTIC LINE EQUATION.
3470 '
3480 IF UV>0 THEN GOTO 3720
3490 '
3500 'IF THE RESPONSE JUST CAME FROM THE TOP PLASTIC LINE YYY=0.
3510 'OTHERWISE IT IS ALREADY ON THE RIGHT ELASTIC LINE. THIS YYY
3520 'CHECK IS USED TO DETERMINE THE VALUE OF XMAX. WHICH IS THE
3530 'THE MAXIMUM HORIZONTAL POSITIVE DISPLACEMENT WHEN THE VELOCITY
3540 'SHIFTS FROM POSITIVE TO NEGATIVE.
3550 '
3560 IF YYY>0 THEN GOTO 3630
3570 '
3580 'IF THE SHIFT FROM THE PLASTIC LINE TO THE ELASTIC LINE JUST OCCURRED,
3590 'THEN XMAX IS ASSIGNED THE VALUE OF THE CURRENT DISPLACEMENT.
3600 'OTHERWISE XMAX WILL RETAIN THE VALUE OF THE PREVIOUS MAXIMUM VALUE.
3610 '
3620 ZZ=UD
3630 YYY=1
3640 XMAX=ZZ
3650 '
3660 'THE NEXT CHECK IS TO DETERMINE WHEN THE RIGHT ELASTIC LINE SHIFTS
3670 'TO THE LOWER PLASTIC LINE. THIS OCCURS WHEN DISPLACEMENT
3680 'DECREASES TO THE POINT IT BECOMES LESS THAN THE XMAX VALUE BY
3690 'TWO TIMES THE VALUE OF XEL. THIS VALUE WAS DERIVED AND WAS
3700 'VERIFIED IN BIGGS BOOK ON STRUCTURAL DYNAMICS (1964).
3710 '
3720 IF UD<(XMAX-2*XEL) THEN GOTO 4040
3730 '
3740 'THE NEXT CHECK IS TO SEE IF THE RESPONSE SHIFTS BACK TO THE TOP
3750 'PLASTIC LINE IF THE VELOCITY SHIFTED WHILE STILL ON THE RIGHT
3760 'ELASTIC LINE AND WENT BACK UP THE LINE AND EXCEEDED THE VALUE
3770 'OF XMAX.
3780 '
3790 IF UD>XMAX THEN GOTO 3220
3800 '
3810 'THIS NEXT CHECK IS A LOCATOR. IF YYY=0 THEN THE LOGIC RETURNS
3820 'THE LOOP TO THE TOP PLASTIC LINE.
3830 '
3840 IF YYY=0 THEN GOTO 3220
3850 '
3860 'IF YYY IS NOT ZERO THEN THE LOGIC SEES THE RESPONSE AS ON THE
3870 'RIGHT ELASTIC LINE. IT ASSIGNS THE RESPONSE AGAIN TO KY=1.
3880 'ALL THE EQUATIONS OF "RR= " ARE THE VALUES OF THE RESISTANCE
3890 'AT THAT POINT ALONG THE RESPONSE PLOT.
3900 '
3910 KY=1
3920 PK=KU
3930 RR=KU*UD+(KD-KU)*XMAX+QD
3940 '
3950 'THE LOOP IS AGAIN ENDED AND THE OUTPUT RECORDED.
3960 '
3970 GOTO 4720

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3980
3990
4000 'THIS NEXT CHECK WAS ARRIVED AT WHEN THE DISPLACEMENT WAS LESS
4010 'THAN XMAX MINUS TWO TIMES XEL. IF THE VELOCITY SHIFTS POSITIVE
4020 'HERE A LATER CHECK WILL DETERMINE A VALUE FOR XMIN.
4030
4040 IF UV>0 THEN GOTO 4350
4050
4060 'THE ONLY WAY WWW=1 IS IF THE RESPONSE WAS LAST ON THE LEFT
4070 'ELASTIC LINE. THIS CHECK IS IN CASE THE RESPONSE STAYS ELASTIC
4080 'AND STAYED ON THE SAME LINE.
4090
4100 IF WWW=1 THEN GOTO 4350
4110
4120 'THE LOGIC NOW SEES THE RESPONSE AS ON THE BOTTOM PLASTIC LINE.
4130 'KY NOW BECOMES KY=-1.
4140
4150 KY=-1
4160 PK=KD
4170 RR=KD*UD-QD
4180
4190 'UUU AND WZ ARE SET TO ZERO TO IDENTIFY THE RESPONSE AS BEING
4200 'CURRENTLY ON THE BOTTOM PLASTIC LINE.
4210
4220 UUU=0
4230 WZ=0
4240
4250 'THE LOOP IS ENDED HERE AND THE OUTPUT RECORDED.
4260
4270 GOTO 4720
4280
4290
4300 'IF UUU IS NOW FOUND TO BE GREATER THAN ZERO, THE LOGIC KNOWS THAT
4310 'THAT THE RESPONSE IS ALREADY ON THE LEFT ELASTIC LINE AND XMIN
4320 'HAS ALREADY BEEN ASSIGNED A VALUE. IF UUU=0 THEN THE CURRENT
4330 'VALUE OF UD IS ASSIGNED TO XMIN.
4340
4350 IF UUU>0 THEN GOTO 4370
4360 WZ=UD
4370 UUU=1
4380 XMIN=WZ
4390
4400 'NOW WITH THE VALUE OF XMIN KNOWN THE VALUE OF DISPLACEMENT IS
4410 'CHECKED AGAINST THE UPPER LIMIT OF THE ELASTIC LINE WHICH IS
4420 'XMIN PLUS TWO TIMES XEL. IF IT IS GREATER THAN THE LOOP RETURNS
4430 'TO THE TOP PLASTIC LINE.
4440
4450 IF UD>(XMIN+2*XEL) THEN GOTO 3220
4460
4470 'IF THE VALUE OF UD IS LESS THAN XMIN THAT MEANS THAT THE VELOCITY
4480 'SHIFTED BACK TO NEGATIVE WHILE ON THE LEFT ELASTIC LINE.
4490 'ONCE IT GOES LESS THAN XMIN THAT THE RESPONSE SHIFTS TO THE BOTTOM
4500 'LINE AGAIN.
4510
4520 IF UD<XMIN THEN GOTO 4150
4530
4540 'THE LOGIC NOW RECOGNIZES THAT THE RESPONSE IS ON THE LEFT ELASTIC
4550 'LINE. WWW=1 IS A LOCATOR FOR THIS LINE.
4560 WWW=1
4570 RR=KU*UD+(KD-KU)*XMIN-QD
4580 PK=KU
4590
4600 'THE LOOP IS COMPLETE AND THE OUTPUT VALUES ARE RECORDED.
4610
4620 GOTO 4720
4630
4640

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```

4850
4860 *****
4870
4880 'NOW ACCELERATION IS CALCULATED FOR THE APPROPRIATE POINT ON THE
4890 'RESISTANCE VERSUS DISPLACEMENT PLOT, AND THE OUTPUTS ARE
4700 'WRITTEN TO THE OUTPUT FILE.
4710 '
4720 UA=(F(L+1)*M-C*UV-RR)/M
4730 '
4740 WRITE #2,T,UD,UV,UA,RR
4750 '
4760 *****
4770 '
4780 'UDP(L) ARE THE VALUES OF DISPLACEMENT AT EACH TIME T WHICH IS USED
4790 'IN THIS PROGRAMS PLOTTING ROUTINE.
4800 '
4810 UDP(L)=UD
4820 '
4830 'END OF THE LOOP*****
4840 '
4850 NEXT L
4860 CLOSE #2
4870 '
4880 '
4890 '
4900 PRINT "      PRESS ANY KEY TO CONTINUE"
4910 A$=INKEY$ : IF A$="" THEN 4910
4920 RETURN
4930 *****
4940 *****
4950 '
4960 CLS: 'SUBROUTINE "RECALL DATA"
4970 PRINT "WAIT!!! INPUTING PREVIOUS DATA FILE ----- "
4980 OPEN F4$ FOR INPUT AS #1
4990 INPUT #1,SHIP$,QUAK$,NE,M,KU,KD,C,H,QD,P,A,DD,TT
5000 FOR I=1 TO NE
5010 INPUT #1,F(I)
5020 NEXT I
5030 CLOSE #1
5040 RETURN
5050 '
5060 CLS: 'SUBROUTINE "MODIFY DATA"
5070 PRINT "NUM POINTS DEFINING THE EXCITATION      NE=";NE
5080 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*      NE=";I$: IF I$<>"" THEN NE=VAL(I$)
5090 PRINT "MASS                                     M=";M
5100 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*      M=";Q$: IF Q$<>"" THEN M=VAL(Q$)
5110 PRINT "SPRING CONSTANT 1                       KU=";KU
5120 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*      KU=";Q$: IF Q$<>"" THEN KU=VAL(Q$)
5130 PRINT "SPRING CONSTANT 2                       KD=";KD
5140 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*      KD=";Q$: IF Q$<>"" THEN KD=VAL(Q$)
5150 PRINT "SPRING CONSTANT 2                       KD=";KD
5160 PRINT "DAMPING COEFFICIENT                     C=";C
5170 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*      C=";Q$: IF Q$<>"" THEN C=VAL(Q$)
5180 PRINT "TIME STEP OF INTEGRATION                 H=";H
5190 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*      H=";Q$: IF Q$<>"" THEN H=VAL(Q$)
5200 PRINT "RESTORING FORCE                           QD=";QD
5210 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*      QD=";Q$: IF Q$<>"" THEN QD=VAL(Q$)
5220 PRINT "NEW HORIZONTAL CONTACT AREA              A=";A
5230 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*      A=";Q$: IF Q$<>"" THEN A=VAL(Q$)
5240 PRINT "X DISPLACEMENT PLOTTING MAX AMPLITUDE (IN) DD=";DD
5250 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*      DD=";Q$: IF Q$<>"" THEN DD=VAL(Q$)
5260 PRINT "MAXIMUM RUN TIME OF EARTHQUAKE (SEC)      TT=";TT
5270 INPUT "NEW VALUE *NO CHANGE PRESS ENTER*      TT=";Q$: IF Q$<>"" THEN TT=VAL(Q$)
5280 RETURN
5290 '

```

```

5300 '*****
5310 '
5320 ' SUBROUTINE "PLOT"
5330 'CLS :KEY OFF
5340 LOCATE 10,1
5350 PRINT PRINT:PRINT"TO OBTAIN A PRINT OF THE FOLLOWING GRAPH, SET PRINTER ON
AND PRESS SHIFT-PrtSc"
5360 PRINT "      PRESS ANY KEY TO CONTINUE "
5370 A$=INKEY$:IF A$="" THEN 5370
5380 SCREEN 1 : COLOR 0,1
5390 WINDOW SCREEN (0,-10)-(30,10)
5400 LINE (4,DD)-(4,-DD),1
5410 LINE (4,0)-(TT+4,0),1
5420 LOCATE 3,4
5430 PRINT "X"
5440 LOCATE 23,30
5450 PRINT "TIME"
5460 T$="TIME-DISPLACEMENT RESPONSE"
5470 LOCATE 2,(40-LEN(T$))/2+1
5480 PRINT T$
5490 LOCATE 3,1
5500 PSET (0,0),2
5510 FOR I=0 TO NE
5520 T=H*I
5530 LINE (T+4,UDP(I))-((T+H)+4,UDP(I+1)),2
5540 NEXT I
5550 RETURN
5560 '*****

```

"3DOFRUB" System 1 Output File. . .

===== System 1 =====

*** Hull Etc ***

* Ship Parameters *

Weight	Moment of Inertia	K.G.
16369.9 kips	2410451.0 kips-in-sec2	193.0 ins

* Drydock Parameters *

Side Block Height	Side Block Width	Keel Block Height	Keel Block Width
74.0 ins	42.0 ins	60.0 ins	48.0 ins
Side-to-Side Pier Distance	Wale Shore Ht.	Wale Shore Stiffness	Cap Angle
144.0 ins	.0 ins	.0 kips/in	.377 rad
1Side Side Pier Contact Area	Total Keel Pier Contact Area	kkhp	
8352.0 in2	55440.0 in2	38434.9 kips/in	
B/B Friction Coeff	H/B Friction Coeff	kshp	kvsp
.430	.530	2212.2 kips/in	4025.6 kips/in
Side Pier Fail Stress Limit	Keel Pier Fail Stress Limit	QD1	
.700 kips/in2	.450 kips/in2	18098.1 kips	
Side Pier Vertical Stiffness	Side Pier Horizontal Stiffness	QD2	
10113.4 kips/in	5825.1 kips/in	4817.6 kips	
Keel Pier Vertical Stiffness	Keel Pier Horizontal Stiffness	QD3	
46306.7 kips/in	53223.1 kips/in	2262.4 kips	

* System Parameters and Inputs *

Earthquake Used is 1940 EL CENTRO

Horizontal acceleration input is HORIZONTAL

Vertical acceleration input is

Earthquake Acceleration Time History.

Vertical/Horizontal Ground Acceleration Ratio	Data Time Increment
1.000	.010 sec

Gravitational Constant	% System Damping
386.04 in/sec2	5.00 %

Mass Matrix

42.3392	.0000	9133.0420
.0000	42.3392	.0000
9133.0420	.0000	2410451.0000

Damping Matrix

113.1019	.0000	5027.8454
.0000	113.1019	.0000
5027.8454	.0000	1549181.3597

Stiffness Matrix

70878.3400 1.0000 1.0000 1.0000
 1.0000 1.0000 1.0000 1.0000
 1.0000 1.0000 1.0000 1.0000
 1.0000 1.0000 1.0000 1.0000

Un-damped Natural Frequencies	Mode #1	Mode #2	Mode #3
	6.425 rad/sec	69.650 rad/sec	39.763 rad/sec
Damped Natural Frequencies	Mode #1	Mode #2	Mode #3
	6.416 rad/sec	69.563 rad/sec	39.713 rad/sec

For Earthquake Acceleration of 100.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	.209810			15.87
Maximum Y		-.197524		8.01
Maximum Rotation			-.049156	13.63
Side block sliding	.003405	.012522	-.001452	5.27
Keel block sliding	-.087838	-.003059	-.014561	6.32
Side block overturning	.010854	.042672	-.002265	5.26
Keel block overturning	.020363	.052677	.001717	4.71
Side block liftoff	-.007883	-.103357	-.003915	4.96
Side block crushing	-.018756	-.008475	.008794	5.47

For Earthquake Acceleration of 90.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.215306			13.89
Maximum Y		-.165358		8.01
Maximum Rotation			-.043429	13.84
Side block sliding	-.011928	-.025677	-.000336	5.28
Keel block sliding	.064047	.123538	.013743	7.91
Side block overturning	-.011928	-.025677	-.000336	5.28
Keel block overturning	-.031313	-.030563	.001947	4.75
Side block liftoff	-.001316	-.079103	-.003308	4.97
Side block crushing	-.011353	-.016663	.003267	5.48

For Earthquake Acceleration of 80.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	.230242			17.20
Maximum Y		-.164004		8.01
Maximum Rotation			.048575	13.79
Side block sliding	-.004720	-.030771	.001313	5.78
Keel block sliding	.060451	.124365	.013713	7.91
Side block overturning	-.004720	-.030771	.001313	5.78
Keel block overturning	-.022077	.057476	-.005186	5.03
Side block liftoff	.001802	-.043706	-.003757	4.38
Side block crushing	-.011827	-.010554	.008424	5.43

For Earthquake Acceleration of 30.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.022720			8.06
Maximum Y		-.042209		8.00
Maximum Rotation			.005146	7.49
Side block sliding	.003838	.003183	-.000124	7.24
Side block overturning	.006838	.003183	-.000124	7.24
Side block liftoff	.014433	.007283	.002863	5.52

For Earthquake Acceleration of 20.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.016896			7.98
Maximum Y		-.026873		4.79
Maximum Rotation			.003483	7.48
Side block liftoff	.006766	.014913	.002416	6.41

For Earthquake Acceleration of 10.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.008056			7.98
Maximum Y		-.013437		4.79
Maximum Rotation			.001622	7.45

No failures occurred.

For Earthquake Acceleration of 15.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.016033			7.98
Maximum Y		-.025530		4.74
Maximum Rotation			.002303	7.48
Side block liftoff	.008084	.013012	.002424	6.42

For Earthquake Acceleration of 15.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.015300			7.98
Maximum Y		-.024186		4.73
Maximum Rotation			.002223	7.45
Side block liftoff	.007653	-.017927	.002007	6.52

For Earthquake Acceleration of 17.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.014413			7.98
Maximum Y		-.022942		4.74
Maximum Rotation			.003024	7.48
Side block liftoff	.010248	.006283	.002757	6.55

For Earthquake Acceleration of 16.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.013510			7.98
Maximum Y		-.021499		4.73
Maximum Rotation			.002799	7.47
Side block liftoff	-.002631	.009920	-.002431	7.87

For Earthquake Acceleration of 15.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.012523			7.98
Maximum Y		-.020155		4.79
Maximum Rotation			.002561	7.47

No failures occurred.

"3DOFRUB" System 1 Input Data File.

16349.2 193.0 24183.7 10119.9 40858.1 46608.7 0.0 0.0 0.0
 5825.13 59243.08 2212.17 38434.8 18098.07 4817.60 2228.37 386.09
 42.00 48.00 74.00 60.00 0.43 0.53
 144.00 0.70 0.45 8352.0 55440.0 0.05
 616 1 0.377

LAFAYETTE SSBN 616
 NO ISOLATOR ALL BILINEAR
 8 SPACING COMPOSITE
 NO WALE SHORES
 5 % DAMPING
 NO SPECIFIC LOCATION
 845-2006640
 S1KHORIG.WK1 & S1SHORIG.WK1
 S1ORBILN.DAT 1532 21 JAN 88

APPENDIX 4

1. Rubber Cap Vertical Stiffness Spreadsheets
2. One Inch Rubber Cap Systems Stiffness Table
3. XEL, YEL, QD, KU, and KD Values for Once Inch Rubber Cap Systems
4. "3DOFRUB" System 12 Output File
5. "3DOFRUB" System 12 Input Data File

Rubber Cap Vertical Stiffness Spreadsheets.

VERTICAL STIFFNESS CALCULATIONS FOR DRYDOCK BLOCKS

HULL TYPE 616 DOCKING PLAN # = 845-2006640

SYSTEM # 12 KEEL BLOCKS ORIGINAL DOCKING DRAWING
RUBBER CAP E1

BLOCK SPA 8.00 FEET

VERTICAL STIFFNESS:

LEVEL #	MATERIAL	E (PSI)	LENGTH (IN)	WIDTH (IN)	HEIGHT (IN)	K (KIPS/IN)	1/K	PIER TOTAL K (KIPS/IN)
			(DEPTH) (B)	(TRANSVERSE) (H)	(L)			
1	RUBBER	992.00	42.00	24.00	1.00	995.94	0.001004	459.76
2	D.FUR	12539.19	42.00	24.00	4.00	3159.88	0.0003165	
3	DAK	23980.00	42.00	33.67	29.00	1169.35	0.0008552	
4	CONCRETE	4000000.00	42.00	48.00	27.00	298666.67	0.0000033	
		1845.83			61.00			
					# BLOCKS	55		TOTAL STIFF OF BLOCK SY (KIPS/IN):
								25286.68

VERTICAL STIFFNESS CALCULATIONS FOR DRYDOCK BLOCKS

HULL TYPE 616 DOCKING PLAN # = 845-2006640

SYSTEM # 12 KEEL BLOCKS ORIGINAL DOCKING DRAWING
RUBBER CAP E2

BLOCK SPA 8.00 FEET

VERTICAL STIFFNESS:

LEVEL #	MATERIAL	E (PSI)	LENGTH (IN)	WIDTH (IN)	HEIGHT (IN)	K (KIPS/IN)	1/K	PIER TOTAL K (KIPS/IN)
			(DEPTH) (B)	(TRANSVERSE) (H)	(L)			
1	RUBBER	3571.00	42.00	24.00	1.00	3599.57	0.0002778	688.32
2	D.FUR	12539.19	42.00	24.00	4.00	3159.88	0.0003165	
3	DAK	23980.00	42.00	33.67	29.00	1169.35	0.0008552	
4	CONCRETE	4000000.00	42.00	48.00	27.00	298666.67	0.0000033	
		1845.83			61.00			
					# BLOCKS	55		TOTAL STIFF OF BLOCK SY (KIPS/IN):
								37857.79

VERTICAL STIFFNESS CALCULATIONS

HULL TYPE 616 DOCKING PLAN # = 845-2006640

SYSTEM # 12 SIDE BLOCKS ORIGINAL DOCKING DRAWING
RUBBER CAP E1

BLOCK SPACING = 8.00 FEET

VERTICAL STIFFNESS:

LEVEL #	MATERIAL	E (PSI)	LENGTH (IN)	WIDTH (IN)	HEIGHT (IN)	K (KIPS/IN)	1/K	PIER TOTAL K (KIPS/IN)
			(DEPTH) (B)	(TRANSVERSE) (H)	(L)			
1	RUBBER	992.00	12.00	24.00	1.00	285.70	0.0035002	157.04
2	D.FIR	12539.19	12.00	24.00	6.00	601.88	0.0016615	
3	OAK	23980.00	23.40	29.70	20.00	833.28	0.0012001	
4	CONCRETE	4000000.00	48.00	42.00	48.00	168000.00	0.0000060	
					75.00			
		850.00			# BLOCKS	29		TOTAL STIFF OF BLOCK SY: (KIPS/IN):
								4554.23

VERTICAL STIFFNESS CALCULATIONS

HULL TYPE 616 DOCKING PLAN # = 845-2006640

SYSTEM # 12 SIDE BLOCKS ORIGINAL DOCKING DRAWING
RUBBER CAP E2

BLOCK SPACING = 8.00 FEET

VERTICAL STIFFNESS:

LEVEL #	MATERIAL	E (PSI)	LENGTH (IN)	WIDTH (IN)	HEIGHT (IN)	K (KIPS/IN)	1/K	PIER TOTAL K (KIPS/IN)
			(DEPTH) (B)	(TRANSVERSE) (H)	(L)			
1	RUBBER	3571.00	12.00	24.00	1.00	1026.45	0.0009723	260.43
2	D.FIR	12539.19	12.00	24.00	6.00	601.88	0.0016615	
3	OAK	23980.00	23.40	29.70	20.00	833.28	0.0012001	
4	CONCRETE	4000000.00	48.00	42.00	48.00	168000.00	0.0000060	
					75.00			
		850.00			# BLOCKS	29		TOTAL STIFF OF BLOCK SY (KIPS/IN):
								7552.43

TOTAL KEEL AND SIDE PIER STIFFNESS KIPS/IN
STANDARD & RUBBER-CAPPED BILINEAR SYSTEMS

SYSTEM	KVK	KVS	KVSP	KHK	KKMP	KHS	KSHP	KVKP
1	46808.74	10113.39	4025.64	59223.08	38434.86	5825.13	2212.17	46808.74
2	46808.74	5231.06	2082.23	59223.08	38434.86	3013.00	1144.23	46808.74
3	31919.89	6178.56	3211.52	28875.45	22849.71	4055.29	1897.66	31919.89
4	31919.89	3195.81	1661.13	28875.45	22849.71	2097.56	981.55	31919.89
5	46808.74	3195.81	1661.13	59223.08	38434.86	2097.56	981.55	46808.74
6	83270.20	43011.07	22269.52	79683.44	53718.39	28797.14	13345.17	83270.2
7	83270.20	28512.95	14762.94	79683.44	53718.39	19090.24	8846.80	83270.2
8	83270.20	21747.17	11259.87	79683.44	53718.39	14560.35	6747.56	83270.2
9	24375.19	8629.57	4065.53	22050.35	17448.87	5842.63	2409.17	24375.19
10	19442.11	6808.09	3188.10	17587.78	13917.55	4625.36	1890.63	19442.11
11	19442.11	5236.99	2452.39	17587.78	13917.55	3557.97	1454.33	19442.11
12	25286.68	4554.23	7552.43	18215.1	18215.1	1842.39	1842.39	37857.79
30	25286.68	2355.63	3906.43	18215.1	18215.1	952.96	952.96	37857.79
31	20197.36	3975.48	6083.7	13704.07	13704.07	1710.14	1710.14	27487.98
32	20197.36	2056.28	3146.74	13704.07	13704.07	884.55	884.55	27487.98
33	25286.68	2056.28	3146.74	18215.1	18215.1	884.55	884.55	37857.79
34	47016.9	25596.13	37814.68	28237.21	28237.21	11392.11	11392.11	68580.41
35	47016.9	16968.22	25068.16	28237.21	28237.21	7552.07	7552.07	68580.41
36	47016.9	12941.87	19119.78	28237.21	28237.21	5760.05	5760.05	68580.41
37	15423.44	5101.21	8319.8	10464.93	10464.93	2089.33	2089.33	20990.82
38	12302.03	3911.02	6310.69	8347.03	8347.03	1622.73	1622.73	16742.68
39	12302.03	3008.48	4854.38	8347.03	8347.03	1248.25	1248.25	16742.68

One Inch Rubber Cap Systems Stiffness
Table

QD VALUES:

- 1 = KEEL HORIZONTAL STIFFNESS
2 = SIDE BLOCK HORIZONTAL STIFFNESS
3 = SIDE BLOCK VERTICAL STIFFNESS

SYSTEM	KEEL CONT.	SHEAR DF	KW	XEL1	KU1-KD1	QD1	SB CAP	SHEAR DF	KWS	YEL2	KU2-KD2	QD2
0	AREA	PROP L/IN	(K/PS/IN)	(IN)	(KIPS/IN)	(KIPS)	AREA	PROP L/IN	(K/PS/IN)	(IN)	(KIPS/IN)	(KIPS)
	(IN ²)	(PSI)					(IN ²)	(PSI)				
1	55440.00	930.0	59223.1	0.8706	20788.22	18098.07	8352.00	930.0	5825.13	1.3334	3612.96	4817.602
2	55440.00	930.0	59223.1	0.8706	20788.22	18098.07	4320.00	930.0	3013.00	1.3334	1868.77	2491.858
3	55440.00	930.0	28875.5	1.7856	6025.74	10759.39	8352.00	930.0	4055.29	1.9154	2157.63	4132.648
4	55440.00	930.0	28875.5	1.7856	6025.74	10759.39	5220.00	930.0	2097.56	2.3144	1116.01	2582.897
5	55440.00	930.0	59223.1	0.8706	20788.22	18098.07	5220.00	930.0	2097.56	2.3144	1116.01	2582.897
6	108864.00	930.0	79683.4	1.2706	25965.05	32990.45	57672.00	930.0	28797.14	1.8625	15451.97	28779.44
7	108864.00	930.0	79683.4	1.2706	25965.05	32990.45	38232.00	930.0	19090.24	1.8625	10243.44	19078.50
8	108864.00	930.0	79683.4	1.2706	25965.05	32990.45	29160.00	930.0	14560.35	1.8625	7812.79	14551.40
9	42336.00	930.0	22050.4	1.7856	4601.48	8216.272	9600.00	930.0	5842.63	1.5281	3433.46	5246.598
10	33768.00	930.0	17587.8	1.7856	3670.23	6553.458	7488.00	930.0	4625.36	1.5056	2734.73	4117.349
11	33768.00	930.0	17587.8	1.7856	3670.23	6553.458	5760.00	930.0	3557.97	1.5056	2103.64	3167.193
12	55440.00	930.0	18215.1	2.8306	0	0	8352.00	930.0	1842.39	4.2159	0	0
30	55440.00	930.0	18215.1	2.8306	0	0	4320.00	930.0	952.96	4.2159	0	0
31	55440.00	930.0	13704.1	3.7623	0	0	8352.00	930.0	1710.14	4.5419	0	0
32	55440.00	930.0	13704.1	3.7623	0	0	5220.00	930.0	884.55	5.4882	0	0
33	55440.00	930.0	18215.1	2.8306	0	0	5220.00	930.0	884.55	5.4882	0	0
34	108864.00	930.0	28237.2	3.5855	0	0	57672.00	930.0	11392.11	4.7081	0	0
35	108864.00	930.0	28237.2	3.5855	0	0	38232.00	930.0	7552.07	4.7081	0	0
36	108864.00	930.0	28237.2	3.5855	0	0	29160.00	930.0	5760.05	4.7081	0	0
37	42336.00	930.0	10464.9	3.7623	0	0	9600.00	930.0	2089.33	4.2731	0	0
38	33768.00	930.0	8347.0	3.7623	0	0	7488.00	930.0	1622.73	4.2914	0	0
39	33768.00	930.0	8347.0	3.7623	0	0	5760.00	930.0	1248.25	4.2914	0	0

XEL, YEL, QD, KU, and KD Values
for Once Inch Rubber Cap Systems.

SCS	CAPAREA	CAP	KVS	YEL1	KU3-KD3	QD3	KEEL AREA	CAP	KVK	YEL3	KUS-KD5	QD4
	(IN^2)	PROP LIMI (KIPS/IN)	(PSI)	(IN)	(KIPS/IN)	(KIPS)	(IN^2)	PROP LIMI (KIPS/IN)	(PSI)	(IN)	(KIPS/IN)	(KIPS)
1	8352.00	450.0	10113.39	0.3716	6087.75	2262.366	55440.00	450.0	46808.74	0.5330	0	0
2	4320.00	450.0	5231.06	0.3716	3148.83	1170.188	55440.00	450.0	46808.74	0.5330	0	0
3	8352.00	450.0	6178.56	0.6083	2967.04	1804.841	55440.00	450.0	31919.89	0.7816	0	0
4	5220.00	450.0	3195.81	0.7350	1534.68	1128.028	55440.00	450.0	31919.89	0.7816	0	0
5	5220.00	450.0	3195.81	0.7350	1534.68	1128.028	55440.00	450.0	46808.74	0.5330	0	0
6	57672.00	450.0	43011.07	0.6034	20741.55	12515.21	108864.00	450.0	83270.2	0.5883	0	0
7	38232.00	450.0	28512.95	0.6034	13750.01	8296.604	108864.00	450.0	83270.2	0.5883	0	0
8	29160.00	450.0	21747.17	0.6034	10487.3	6327.919	108864.00	450.0	83270.2	0.5883	0	0
9	9600.00	450.0	8629.57	0.5006	4564.04	2284.778	42336.00	450.0	24375.19	0.7816	0	0
10	7488.00	450.0	6808.09	0.4949	3619.99	1791.679	33768.00	450.0	19442.11	0.7816	0	0
11	5760.00	450.0	5236.99	0.4949	2784.6	1378.212	33768.00	450.0	19442.11	0.7816	0	0
12	8352.00	99.2	4554.23	0.1819	-2998.2	-545.441	55440.00	99.2	25286.68	0.2175	-12571.1	-2734.11
30	4320.00	99.2	2355.63	0.1819	-1550.8	-282.126	55440.00	99.2	25286.68	0.2175	-12571.1	-2734.11
31	8352.00	99.2	3975.48	0.2084	-2108.22	-439.368	55440.00	99.2	20197.36	0.2723	-7290.62	-1985.20
32	5220.00	99.2	2056.28	0.2518	-1090.46	-274.605	55440.00	99.2	20197.36	0.2723	-7290.62	-1985.20
33	5220.00	99.2	2056.28	0.2518	-1090.46	-274.605	55440.00	99.2	25286.68	0.2175	-12571.1	-2734.11
34	57672.00	99.2	25596.13	0.2235	-12218.5	-2731.00	108864.00	99.2	47016.9	0.2297	-21563.5	-4952.92
35	38232.00	99.2	16968.22	0.2235	-8099.94	-1810.44	108864.00	99.2	47016.9	0.2297	-21563.5	-4952.92
36	29160.00	99.2	12941.87	0.2235	-6177.91	-1380.84	108864.00	99.2	47016.9	0.2297	-21563.5	-4952.92
37	9600.00	99.2	5101.21	0.1867	-3218.59	-600.862	42336.00	99.2	15423.44	0.2723	-5567.38	-1515.97
38	7488.00	99.2	3911.02	0.1899	-2399.67	-455.762	33768.00	99.2	12302.03	0.2723	-4440.65	-1209.16
39	5760.00	99.2	3008.48	0.1899	-1845.9	-350.586	33768.00	99.2	12302.03	0.2723	-4440.65	-1209.16

"3DOFRUB" System 12 Output File .

**** System 12 ****

** Hull 616 **

* Ship Parameters *

Weight	Moment of Inertia	K.G.
16369.9 kips	2410451.0 kips-in-sec2	193.0 ins

* Drydock Parameters *

Side Block Height	Side Block Width	Keel Block Height	Keel Block Width
75.0 ins	42.0 ins	61.0 ins	48.0 ins
Side-to-Side Pier Distance	Wale Shore Ht.	Wale Shore Stiffness	Cap Angle
144.0 ins	.0 ins	.0 kips/in	.377 rad
1Side Side Pier Contact Area	Total Keel Pier Contact Area	kkhp	
8352.0 in2	55440.0 in2	18215.1 kips/in	
B/B Friction Coeff	H/B Friction Coeff	ksbp	kvsp
.430	.750	4583.8 kips/in	7552.4 kips/in
Side Pier Fail Stress Limit	Keel Pier Fail Stress Limit	kvkp	
.700 kips/in2	.700 kips/in2	37857.8 kips/in	
Side Pier Vertical Stiffness	Side Pier Horizontal Stiffness		
4554.2 kips/in	4583.8 kips/in		
Keel Pier Vertical Stiffness	Keel Pier Horizontal Stiffness		
25288.7 kips/in	18215.1 kips/in		
QD1	QD2	QD3	QD4
.0 kips	.0 kips	-545.4 kips	-2734.1 kips

* System Parameters and Inputs *

Earthquake Used is 1940 EL CENTRO

Horizontal acceleration input is HORIZONTAL

Vertical acceleration input is
Earthquake Acceleration Time History.

Vertical/Horizontal Ground Acceleration Ratio	Data Time Increment
1.000	.010 sec

Gravitational Constant	% System Damping
386.09 in/sec2	5.00 %

Mass Matrix

42.3992	.0000	8183.0420
.0000	42.3992	.0000
8183.0420	.0000	2410451.0000

Damping Matrix

74.3450	.0000	3428.9487
.0000	120.7812	.0000
3428.9487	.0000	1021727.8065

Stiffness Matrix:

27382 6800	.0000	126346.1200
.0000	34395.1400	.0000
126346.1200	.0000	43319122.8111

Undamped Natural Frequencies	Mode #1	Mode #2	Mode #3
	4.239 rad/sec	42.984 rad/sec	28.482 rad/sec
Damped Natural Frequencies	Mode #1	Mode #2	Mode #3
	4.233 rad/sec	42.930 rad/sec	28.446 rad/sec

For Earthquake Acceleration of 100.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	.133628			6.70
Maximum Y		-.252150		5.34
Maximum Rotation			.014311	9.12
Side block sliding	.074181	.085959	-.002947	6.41
Side block overturning	.087029	.186782	.003970	5.42
Keel block overturning	-.085370	.031225	-.000848	4.91
Side block liftoff	.018785	-.025509	-.006513	5.02
Side block crushing	.018528	-.098058	-.005124	4.99

For Earthquake Acceleration of 90.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	.121682			6.70
Maximum Y		-.226920		5.34
Maximum Rotation			.012817	9.12
Side block overturning	.067669	.073081	-.002638	6.41
Keel block overturning	-.087898	.010883	-.001173	4.92
Side block liftoff	.017590	-.022420	-.005890	5.02
Side block crushing	-.005128	.101402	-.008079	5.10

For Earthquake Acceleration of 80.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	.110005			6.70
Maximum Y		-.202051		5.34
Maximum Rotation			.011419	9.12
Side block overturning	-.075537	.078222	.000599	6.12
Keel block overturning	.075679	.064484	.002542	5.40
Side block liftoff	.002582	.009507	-.005600	5.03
Side block crushing	.025392	.063556	-.007496	5.12

For Earthquake Acceleration of 70.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
-------------------	---------	---------	--------------	------------

Maximum X	.099249			8.70
Maximum Y		-.178057		5.34
Maximum Rotation			.010018	9.11
Keel block overturning	.070214	.101585	.002562	5.41
Side block liftoff	-.007956	.033827	-.005177	5.04
Side block crushing	.055384	-.070828	.005715	5.52

For Earthquake Acceleration of 60.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	.084043			8.70
Maximum Y		-.153034		5.34
Maximum Rotation			.008604	9.11
Keel block overturning	.082017	.087278	.002219	5.41
Side block liftoff	-.018024	.061380	-.004807	5.08
Side block crushing	.035903	-.084247	.005279	5.54

For Earthquake Acceleration of 50.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	.069098			8.70
Maximum Y		-.128438		5.34
Maximum Rotation			.007234	9.10
Side block liftoff	-.037360	.030443	-.005009	6.02
Side block crushing	.010838	-.009880	-.008408	6.09

For Earthquake Acceleration of 40.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.055481			8.43
Maximum Y		-.103239		5.34
Maximum Rotation			.005911	9.08
Side block liftoff	.014700	-.021988	.005709	9.02

For Earthquake Acceleration of 30.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.043904			8.43
Maximum Y		-.073915		5.34
Maximum Rotation			.004782	9.05

No failures occurred.

For Earthquake Acceleration of 39.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	- .054318			8.43
Maximum Y		- .100858		5.34
Maximum Rotation			.005843	9.08
Side block liftoff	.013999	- .021378	.005664	9.02

For Earthquake Acceleration of 38.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	- .054144			8.43
Maximum Y		- .098077		5.34
Maximum Rotation			.005714	9.08
Side block liftoff	.015857	- .016848	.005612	9.03

For Earthquake Acceleration of 37.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	- .052898			8.43
Maximum Y		- .095498		5.34
Maximum Rotation			.005584	9.07
Side block liftoff	.019130	- .010292	.005538	9.04

For Earthquake Acceleration of 36.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	- .051656			8.43
Maximum Y		- .092694		5.34
Maximum Rotation			.005448	9.07
Side block liftoff	.021071	- .002704	.005429	9.05

For Earthquake Acceleration of 35.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	- .050382			8.43
Maximum Y		- .089908		5.34
Maximum Rotation			.005338	9.07
Side block liftoff	.022892	.005154	.005337	9.06

For Earthquake Acceleration of 34.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	- .048970			8.43
Maximum Y		- .086829		5.34
Maximum Rotation			.005216	9.06
Side block liftoff	.022342	.012550	.005214	9.07

For Earthquake Acceleration of 33.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.047773			8.43
Maximum Y		-.083611		5.34
Maximum Rotation			.005105	9.06
Side block liftoff	.018046	.023179	.005087	9.09

For Earthquake Acceleration of 32.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	-.046433			8.43
Maximum Y		-.080243		5.34
Maximum Rotation			.004966	9.08

No failures occurred.

"3DOFRUB" System 12 Input Data File

```

-16389.9 193.0 2410451 4554.23 7552.43 25283.75 0.0 0.0
4583.79 18218.45 4583.79 18218.10 0.00 -545.44 386.09
42.00 48.00 78.00 41.00 0.43 0.78
144 00 0 70 0 70 8352 0 55440 0 0 050
616 12 0.377 -2734.11 37857.79

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LAFAYETTE SSBN 816
 RUBBER CAPS
 8 SPACING COMPOSITE
 NO WALE SHORES
 5 % DAMPING
 NO SPECIFIC LOCATION
 845-2006840
 S12KHE1.WK1 & S12SHE1.WK1 ETC.
 S12RUB.DAT 18:01 30 JAN 88

APPENDIX 5

1. Isolator Equivalent Elastic Moduli Spreadsheets
2. Isolator Blocking Pier Stiffness Spreadsheets,
3. "3DOFRUB" System 90 Output File,
4. "3DOFRUB" System 90 Input Data File

Isolator Equivalent Elastic Moduli Spreadsheets.

DIS E CALC
SIDE BLOCKS
K₀₂ = 780 KSI
B EQU = 786.5 PSI

11-Jan-88

HORIZONTAL STIFFNESS MATRIX FOR 4 LAYERS DIS E CALCULATOR FOR SIDE BLOCKS

THIS IS A SIDEBLOCK SYSTEM FOR HULL 616 WITH 5 FT BUILDUP
8 FOOT CENTERS

ELEMENT # 1 CONCRETE				
E1	DEPTH	TRANSVERSE		HEIGHT
PSI	B1	M1	I1	L1
(PSI)	(IN)	(IN)	(IN ⁴)	(IN)
1.000000E+50	48	42	296252	24

12E11/L1/3	6E111/L1/2	4E111/L1	2E111/L1	
2.5725000E+52	3.0870000E+52	4.9392000E+54	2.4696000E+54	

RIGIDITY	TOP	SHEAR	ELEMENT	
G1	CONTACT	STRAIN	SHEAR	
(PSI)	AREA	(IN/IN)	DEFLECTION	
	(IN ²)		(IN)	

***** 2016 8.2671958E-51 1.9841270E-49

ELEMENT # 2 DOW				
E2	DEPTH	TRANSVERSE		HEIGHT
PSI	B2	M2	I2	L2
(PSI)	(IN)	(IN)	(IN ⁴)	(IN)
1.000000E+50	48	42	296252	22

12E212/L2/3	6E212/L2/2	4E212/L2	2E212/L2	
3.3398047E+52	3.6737851E+53	5.3822182E+54	2.6941091E+54	

RIGIDITY	TOP	SHEAR	ELEMENT	
G1	CONTACT	STRAIN	SHEAR	
(PSI)	AREA	(IN/IN)	DEFLECTION	
	(IN ²)		(IN)	

***** 2016 6.9444444E-50 1.5277777E-48

ELEMENT # 3 DOUGLAS FIR				
ES	DEPTH	TRANSVERSE		HEIGHT
(PSI)	B3	KG	13	L3
	(IN)	(IN)	(IN ⁴)	(IN)
*****	12	24	13824	22
2E313/L313	6E313/L312	4E313/L3	2E313/L3	
1.5579E+51	1.7137E+52	2.5135E+53	1.2567E+53	
RIGIDITY	TOP	SHEAR	ELEMENT	
B1*	CONTACT	STRAIN	SHEAR	
(PSI)	AREA	(IN/IN)	DEFLECTION	
	(IN ²)		(IN)	
*****	238	4.9611111E-49	1.0694444E-47	

ELEMENT # 4 DIS ISOLATOR				
ES	DEPTH	TRANSVERSE		HEIGHT
(PSI)	B4	KG	14	L3
	(IN)	(IN)	(IN ⁴)	(IN)
786.50000	48	42	296352	22
2E414/L413	6E414/L412	4E414/L4	2E414/L4	
2.4263E+05	2.3894E+06	4.2378E+07	2.1189E+07	
RIGIDITY	TOP	SHEAR	ELEMENT	
B1*	CONTACT	STRAIN	SHEAR	TOTAL
(PSI)	AREA	(IN/IN)	DEFLECTION	SHEAR
	(IN ²)		(IN)	DEFLECTION (IN)
2E7	2016	0.0018610901	0.0409426626	4.0943E-02

F/ M	STIFFNESS MATRIX														D
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	
01	2.572E+52	3.087E+53	-2.572E+52	3.087E+53	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	01
02	3.087E+53	4.939E+54	-3.087E+53	2.469E+54	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	02
03	-2.572E+52	-3.087E+53	5.912E+52	5.867E+52	-3.338E+52	3.673E+53	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	03
04	3.087E+53	2.469E+54	5.867E+52	1.032E+55	-3.673E+53	2.634E+54	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	04
05	0.000E+00	0.000E+00	-3.338E+52	-3.673E+53	3.495E+52	-3.502E+53	-1.557E+51	1.713E+52	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	05
06	0.000E+00	0.000E+00	3.673E+53	2.634E+54	-3.502E+53	5.634E+54	-1.713E+52	1.250E+53	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	06
07	0.000E+00	0.000E+00	0.000E+00	0.000E+00	-1.557E+51	-1.713E+52	1.557E+51	-1.713E+52	-2.428E+05	2.889E+06	2.118E+07	2.889E+06	2.118E+07	2.889E+06	07
08	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.713E+52	1.250E+53	-1.713E+52	2.513E+53	-2.889E+06	2.118E+07	-2.889E+06	2.118E+07	-2.889E+06	2.118E+07	08
09	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	-2.628E+05	-2.889E+06	2.118E+07	-2.889E+06	2.118E+07	-2.889E+06	2.118E+07	-2.889E+06	09
10	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	2.889E+06	2.118E+07	-2.889E+06	2.118E+07	-2.889E+06	2.118E+07	-2.889E+06	2.118E+07	10
11	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	11
12	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	12
13	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	13
14	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	14

KNOWN VALUES:

Q1 = -1000 lbs
M1 = Q1*(L1+L2+L3+L4) = -90000 (IN*LB)
Q2 = Q3 = Q4 = Q5 = 0
Q5 = 1000 lbs
a1 = th1 = 0

OF SYSTEM BLOCKS =

29

SOLVED UNKNOWN:

a2 = 7.3629018E-49 in
th2 = 6.3168124E-50 rad

2.6656529E-48 in
th3 = 1.0399795E-49 rad
a4 = 1.1372402E-47 in
th4 = 8.2917156E-49 rad

a5 = 1.1152279E-4 in
th5 = 0.0010382663 rad

K (HORIZONTAL FOR 1 KEEL BLOCK) = 2.7932169E+49 lbs/in
8.7932169E+46 kips/in

K (HORIZONTAL) ALL KEEL BLOCKS = 2.5500329E+51 lbs/in
2.5500329E+48 kips/in

MATRIX CHECK:

Q1 = -1000.0000
M1 = -90000.0000
Q2 = -0.0000
Q3 = -0.0000
Q4 = -0.0000
Q5 = 1000.0000
M5 = 0.0000

TOTAL SIDE BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:

Khs (SIDE BLOCK HORIZONTAL STIFFNESS) = P/BENDING DISPL + SHEAR DISPLACEMENT

Khs = 17.80 kips/in (PER BLOCK)

Khs = 516.28 kips/in (ENTIRE SIDE BLOCK SYSTEM)

USE CONC
SIDE BLOCKS
K_u = 1.22
EQUINE = 805 PSI

11-Jan-88

HORIZONTAL STIFFNESS MATRIX FOR 4 LAYERS DIS E CALCULATOR FOR SIDE BLOCKS

THIS IS A SIDEBLOCK SYSTEM FOR HULL 616 WITH 5 FT BUILDUP
8 FOOT CENTERS

ELEMENT # 1 CONCRETE				
E1	DEPTH	TRANSVERSE		HEIGHT
(PSI)	B1	M1	I1	L1
	(IN)	(IN)	(IN ⁴)	(IN)
1.0000000E+50	48	42	296352	24
12E111/L1:3	6E111/L1:2	4E111/L1	2E111/L1	
2.5725000E+52	3.0670000E+53	4.7292000E+54	2.4636000E+54	
RIGIDITY	TOP	SHEAR	ELEMENT	
61*	CONTACT	STRAIN	SHEAR	
(PSI)	AREA	(IN/IN)	DEFLECTION	
	(IN ²)		(IN)	

***** 2015 8.2671958E-51 1.9641270E-49

ELEMENT # 2 04				
E2	DEPTH	TRANSVERSE		HEIGHT
(PSI)	B2	M2	I2	L2
	(IN)	(IN)	(IN ⁴)	(IN)
1.0000000E+50	48	42	296352	22
12E212/L2:3	6E212/L2:2	4E212/L2	2E212/L2	
5.3298047E+52	3.6737851E+53	5.3882182E+54	2.6941091E+54	
RIGIDITY	TOP	SHEAR	ELEMENT	
61*	CONTACT	STRAIN	SHEAR	
(PSI)	AREA	(IN/IN)	DEFLECTION	
	(IN ²)		(IN)	

***** 2016 6.9444444E-50 1.5277778E-46

ELEMENT # 3 DOUGLAS FIR				
E2	DEPTH	TRANSVERSE		HEIGHT
(PSI)	B3	H3	I3	L3
	(IN)	(IN)	(IN ⁴)	(IN)
*****	12	24	13824	22
12E313/L3:3	6E313/L3:2	4E313/L3	2E313/L3	
1.5579E+51	1.7157E+52	2.5135E+53	1.2567E+53	
RIGIDITY	TOP	SHEAR	ELEMENT	
GI*	CONTACT	STRAIN	SHEAR	
(PSI)	AREA	(IN/IN)	DEFLECTION	
	(IN ²)		(IN)	
*****	262	4.8E+1111E-43	1.0E+4444E-47	

ELEMENT # 4 DIS ISOLATOR				
E4	DEPTH	TRANSVERSE		HEIGHT
(PSI)	B4	H4	I4	L3
	(IN)	(IN)	(IN ⁴)	(IN)
80.50000	48	42	296352	22
12E414/L4:3	6E414/L4:2	4E414/L4	2E414/L4	
2.6885E+04	2.9574E+05	4.3375E+06	2.1688E+06	
RIGIDITY	TOP	SHEAR	ELEMENT	
GI*	CONTACT	STRAIN	SHEAR	
(PSI)	AREA	(IN/IN)	DEFLECTION	
	(IN ²)		(IN)	
27	2016	0.018182611	0.4000174422	4.0002E-01

F/ H	STIFFNESS MATRIX															D
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	
01	2.5725E+52	3.0870E+53	-2.5725E+52	3.0870E+53	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d1
02	3.0870E+53	4.3322E+54	-3.0870E+53	2.4636E+54	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d2
03	-2.5725E+52	-3.0870E+53	5.9123E+52	5.8679E+52	-3.3398E+53	3.6738E+53	2.6341E+54	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d3
04	3.0870E+53	2.4636E+54	5.8679E+52	1.0327E+55	-3.6738E+53	3.4756E+52	-3.5024E+53	5.8396E+54	-1.7137E+52	1.5579E+51	1.2587E+53	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d4
05	0.0000E+00	0.0000E+00	-3.3398E+53	-3.6738E+53	3.6738E+53	3.4756E+52	-3.5024E+53	5.8396E+54	-1.7137E+52	1.5579E+51	1.2587E+53	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d5
06	0.0000E+00	0.0000E+00	5.9123E+52	5.8679E+52	-3.3398E+53	3.6738E+53	2.6341E+54	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d6
07	0.0000E+00	0.0000E+00	3.0870E+53	3.0870E+53	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d7
08	0.0000E+00	0.0000E+00	-3.0870E+53	-3.0870E+53	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d8
09	0.0000E+00	0.0000E+00	5.8679E+52	5.8679E+52	-3.3398E+53	3.6738E+53	2.6341E+54	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d9
10	0.0000E+00	0.0000E+00	5.8679E+52	5.8679E+52	-3.3398E+53	3.6738E+53	2.6341E+54	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d10
11	0.0000E+00	0.0000E+00	-3.3398E+53	-3.6738E+53	3.6738E+53	3.4756E+52	-3.5024E+53	5.8396E+54	-1.7137E+52	1.5579E+51	1.2587E+53	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d11
12	0.0000E+00	0.0000E+00	3.6738E+53	3.6738E+53	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d12
13	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d13
14	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d14
15	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00 d15

KNOWN VALUES:

Q1 = -1000 lbs
M1 = Q1*(L1+L2+L3+L4) = -90000 IN*LB
Q2 = Q3 = Q4 = Q5 = 0
Q6 = 1000 lbs
Q1 = TH1 = 0

OF SYSTEM BLOCKS =

29

SOLVE: UNKNOWN:

Q2 = 7.9689018E-49 in
TH2 = 6.3168124E-50 rad

2.6656589E-48 in
TH3 = 1.0399795E-49 rad
TH4 = 6.2917156E-49 rad
Q5 = 0.1487794829 in
TH5 = 0.0101440557 rad

-B1 -B2
-50821.187077 -695123.96694
-6935.1320362 -115821.314122

K (HORIZONTAL) FOR 1 KEEL BLOCK = 5.7932169E+49 lbs/in
K (HORIZONTAL) ALL KEEL BLOCKS = 2.5500329E+51 lbs/in

-1000 -22000
5.7932169E+46 KIPS/IN
2.5500329E+48 KIPS/IN

MATRIX CHECK:

Q1 = -1000.0000
M1 = -90000.0000
Q2 = -0.0000
Q3 = -0.0000
Q4 = -0.0000
Q5 = 1000.0000
Q6 = -0.0000

TOTAL SIDE BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:

KHS (SIDE BLOCK HORIZONTAL STIFFNESS) = P/(BENDING DISPL + SHEAR DISPLACEMENT)

KHS = 1.82 KIPS/IN (PER BLOCK)
KHS = 52.84 KIPS/IN (ENTIRE SIDE BLOCK SYSTEM)

Copy available to DTIC does not
 permit fully legible reproduction

~~DIS E CALCULATOR
 FOR KEEL BLOCKS
 SUBSTITUTING THE
 3 CORNER IN FOR
 ELEMENT 4 AND
 MAKING ALL OTHER
 DATA THE SAME
 KU₂₅ = 31.31 KIPS~~

11-Jan-88

HORIZONTAL STIFFNESS MATRIX FOR 4 LAYERS DIS E CALCULATOR

THIS IS A KEEL SYSTEM FOR HULL 616 WITH 5 FT BUILDUP
 8 FOOT CENTERS

ELEMENT # 1	CONCRETE				
E1	DEPTH	TRANSVERSE	I1	HEIGHT	
(PSI)	B1	H1	(IN ⁴)	L1	
	(IN)	(IN)		(IN)	
1.0000000E+50	42	48	387072	27	

12E11/L1/3	6E11/L1/2	4E11/L1	2E11/L1
------------	-----------	---------	---------

2.3548354E+52	3.1357779E+53	5.7344000E+54	2.8672000E+54
---------------	---------------	---------------	---------------

RIGIDITY	TOP	SHEAR	ELEMENT
G1*	CONTACT	STRAIN	SHEAR
(PSI)	AREA	IN/IN	DEFLECTION
	(IN ²)		(IN)

*****	2016	8.2671950E-51	2.2321429E-49
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ELEMENT # 2	DA				
E2	DEPTH	TRANSVERSE	I2	HEIGHT	
(PSI)	B2	H2	(IN ⁴)	L2	
	(IN)	(IN)		(IN)	
1.0000000E+50	42	48	387072	29	

12E212/L2/3	6E212/L2/2	4E212/L2	2E212/L2
-------------	------------	----------	----------

1.3044914E+52	2.7615125E+53	5.3389241E+54	2.6644621E+54
---------------	---------------	---------------	---------------

RIGIDITY	TOP	SHEAR	ELEMENT
G1*	CONTACT	STRAIN	SHEAR
(PSI)	AREA	(IN/IN)	DEFLECTION
	(IN ²)		(IN)

*****	2016	6.9444444E-50	2.0138889E-48
-------	------	---------------	---------------

ELEMENT # 3 DOUGLAS FIR
 ES B3 TRANSVERSE HEIGHT
 (PSI) (IN) (IN) (IN) (IN)

 ***** 42 48 387072 4

12E313/L313 6E313 L3 13 4E313 L3 2E313/L3

 7.2576E+54 1.4515E+55 2.3707E+55 1.9354E+55

RIGIDITY TOP SHEAR ELEMENT
 611 CONTACT STRAIN SHEAR
 (PSI) AREA (IN IN) DEFLECTION
 (IN IN)

 ***** 2016 6.444444E+50 2.777777E+49

ELEMENT # 4 ~~12E414/L413 6E414 L413 4E414 L4 2E414/L4~~ OIS ISOLATORS

E4 B4 TRANSVERSE HEIGHT
 (PSI) (IN) (IN) (IN) (IN)

 1567.00000 42 48 387072 25

12E414/L413 6E414 L413 4E414 L4 2E414/L4

 4.6562E+55 5.3229E+56 9.7047E+57 4.8523E+57

RIGIDITY TOP SHEAR ELEMENT TOTAL
 611 CONTACT STRAIN SHEAR SHEAR
 (PSI) AREA (IN IN) DEFLECTION DEFLECTION
 (IN IN) (IN IN)

 531 2016 0.0000000000 0.0233513494 2.3252E+52

KNOWN VALUES:

Q1 = -1000 lbs
M1 = Q1(L1+L2+L3+L4) = -85000 IN*LB
Q2 = Q3 = Q4 = Q5 = 0
Q5 = 1000 lbs
Q1 = M1 = 0

OF SYSTEM BLOODS =

29

SOLVED UNKNOWN:

Q2 = 7.156806E-49 in
M2 = 4.967444E-50 rad

Q3 = 7.142E-48 in

-R1 -R2
-28402.968551 -5219.210951

M3 = 8.24E-50 rad

Q4 = 8.22E-48 in

-20700000 -42225000

M4 = 8.525545E-50 rad

Q5 = 0.000538421 in

-1000 -25000

M5 = 0.0005152159 rad

K HORIZONTAL FOR 1 KEEL BLOOD = 3.348307E+50 lbs/in 3.348307E+47 KIPS/IN

K HORIZONTAL ALL KEEL BLOODS = 9.5940923E+51 lbs/in 9.5940923E+48 KIPS/IN

MATRIX CHECK:

G1 = -1000.0000
M1 = -85000.0000
Q2 = -0.0000
M2 = -0.0000
Q3 = -0.0000
M3 = -0.0000
Q4 = -0.0052
M4 = -0.0654
Q5 = 1000.0052
M5 = -0.0654

TOTAL KEEL BLOOD HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:

Khs (KEEL BLOOD HORIZONTAL STIFFNESS) = P (BENDING DISPL + SHEAR DISPLACEMENT)

31.3100

Khs = 31.31 KIPS/IN (PER BLOOD)

Khs = 907.98 KIPS/IN (ENTIRE KEEL BLOOD SYSTEM)

11-Jan-98

HORIZONTAL STIFFNESS MATRIX FOR 4 LAYERS DIS E CALCULATOR

THIS IS A KEEL SYSTEM FOR HULL 616 WITH 5 FT BUILDUP
 8 FOOT CENTERS

ELEMENT # 1 CONCRETE				
E1 (PSI)	DEPTH B1 (IN)	TRANSVERSE M1 (IN)	I1 (IN ⁴)	HEIGHT L1 (IN)
1.0000000E+50	42	48	367072	27

12E111/L1/3	6E111/L1/2	4E111/L1	2E111/L1
2.0536554E+52	3.1857778E+53	5.7344000E+54	2.8672000E+54

RIGIDITY G1 (PSI)	TOP CONTACT AREA (IN ²)	SHEAR STRAIN (IN/IN)	ELEMENT SHEAR DEFLECTION (IN)
*****	2016	0.2671950E+51	2.0321429E+49

ELEMENT # 2 DW				
E2 (PSI)	DEPTH B2 (IN)	TRANSVERSE M2 (IN)	I2 (IN ⁴)	HEIGHT L2 (IN)
1.0000000E+50	42	48	367072	26

12E212/L2/3	6E212/L2/2	4E212/L2	2E212/L2
1.1044914E+52	2.7615125E+53	5.3389241E+54	2.6694621E+54

RIGIDITY G2 (PSI)	TOP CONTACT AREA (IN ²)	SHEAR STRAIN (IN/IN)	ELEMENT SHEAR DEFLECTION (IN)
*****	2016	6.9444444E-50	2.0138889E-48

STIFFNESS MATRIX

F/ N	D														
Q1	2.359E+52	3.185E+53	-2.359E+52	3.185E+53	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
M1	3.185E+53	5.734E+54	-3.185E+53	2.867E+54	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Q2	-2.359E+52	-3.185E+53	4.264E+52	-4.242E+52	-1.904E+52	2.761E+53	2.761E+53	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
M2	3.185E+53	2.867E+54	-4.242E+52	1.107E+55	-2.761E+53	2.669E+54	1.423E+55	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Q3	0.000E+00	0.000E+00	-1.904E+52	-2.761E+53	2.761E+54	1.423E+55	-7.257E+54	1.451E+55	1.451E+55	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
M3	0.000E+00	0.000E+00	2.761E+53	2.669E+54	1.423E+55	4.404E+55	-1.451E+55	-1.451E+55	1.451E+55	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Q4	0.000E+00	0.000E+00	0.000E+00	0.000E+00	-7.257E+54	-1.451E+55	7.257E+54	-1.451E+55	-1.451E+55	-5.529E+04	6.911E+05	6.911E+05	6.911E+05	6.911E+05	6.911E+05
M4	0.000E+00	0.000E+00	0.000E+00	0.000E+00	1.451E+55	1.959E+55	-1.451E+55	5.529E+04	5.529E+04	-6.911E+05	5.759E+06	5.759E+06	5.759E+06	5.759E+06	5.759E+06
Q5	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	-5.529E+04	-6.911E+05	-6.911E+05	5.529E+04	-6.911E+05	-6.911E+05	-6.911E+05	-6.911E+05	-6.911E+05
M5	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	6.911E+05	5.759E+06	5.759E+06	-6.911E+05	1.1519E+07	1.1519E+07	1.1519E+07	1.1519E+07	1.1519E+07

KNOWN VALUES:

Q1 = -1000 lbs
M1 = Q1(L1+L2+L3+L4) = -85000 IN-LBS
Q2 = Q3 = Q4 = Q5 = Q6 = Q7 = Q8 = Q9 = 0
Q5 = 1000 lbs
Q1 = Q11 = 0

OF SYSTEM BLOCKS =

25

SOLVED UNKNOWN:

Q2 = 7.1568080E-49 in

th2 4.9674442E-50 rad

2.6871142E-48 in

th3 6.2465279E-50 rad

Q4 3.3226135E-48 in

th4 8.5255456E-50 rad

Q5 0.0723425E-29 in

th5 0.004340555E rad

-B1 -B2
-28402.962551 -521912.00951

-20700000 -42225000

-1000 -25000

K (HORIZONTAL) FOR 1 KEEL BLOCK = 3.3083077E+50 lps/in 3.3083077E+47 KIPS/IN

K (HORIZONTAL) ALL KEEL BLOCKS = 9.5940923E+51 lps/in 9.5940923E+48 KIPS/IN

MATRIX CHECK:

Q1 = -1000.0000
M1 = -85000.0000
Q2 = -0.0000
Q3 = -0.0000
Q4 = -0.0000
Q5 = -0.0000
Q6 = -0.0000
Q7 = -0.0000
Q8 = -0.0000
Q9 = 1000.0000
Q10 = -0.0000

TOTAL KEEL BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:

Khs (KEEL BLOCK HORIZONTAL STIFFNESS) = P/(BENDING DISPL + SHEAR DISPLACEMENT)
3.7200
Khs = 3.72 KIPS/IN (PER BLOCK)
Khs = 107.78 KIPS/IN (ENTIRE KEEL BLOCK SYSTEM)

Isolator Blocking Pier Stiffness Spreadsheets.

VERTICAL STIFFNESS CALCULATIONS FOR DRYDOCK BLOCKS

HULL TYPE 616 DOCKING PLAN # 845-2006640

SYSTEM # 90 E1 KEEL BLOCKS ORIGINAL FOR 130 TON KEEL
 DAK REMOVED ISOLATORS INSTALLED

BLOCK SPA 8.00 FEET

VERTICAL STIFFNESS:

LEVEL #	MATERIAL	E (PSI)	LENGTH (IN)	WIDTH (IN)	HEIGHT (IN)	K (KIPS/IN)	1/K	PIER TOTAL K (KIPS/IN)
			(DEPTH) (B)	(TRANSVERSE) (H)	(L)			
1	D.FUR	12539.19	42.00	24.00	2.00	6319.75	0.0001582	1155.94
2	D.FUR	12539.19	42.00	24.00	2.00	6319.75	0.0001582	
3	DIS		42.00	48.00	25.00	1845.00	0.0000542	
4	CONCRETE	4000000.00	42.00	48.00	31.00	260129.03	0.0000038	
		1845.00						
					0 BLOCKS	35		TOTAL STIFFNESS OF BLOCK SY (KIPS/IN) :
								63799.62

VERTICAL STIFFNESS CALCULATIONS

HULL TYPE 616 DOCKING PLAN # 845-2006640

SYSTEM # 90 E1 SIDE BLOCKS ORIGINAL PER DOCKING DRAWING
OAK REMOVED ISOLATORS INSTALLED

BLOCK SPACING = 8.00 FEET

VERTICAL STIFFNESS:

LEVEL #	MATERIAL	E (PSI)	LENGTH (IN)	WIDTH (IN)	HEIGHT (IN)	K (KIPS/IN)	1/K	PIER TOTAL K (KIPS/IN)
			(DEPTH) (B)	(TRANSVERSE) (H)	(L)			
1	D.FIR	12539.19	12.00	24.00	3.00	1203.76	0.0008307	351.66
2	D.FIR	12539.19	12.00	24.00	3.00	1203.76	0.0008307	
3	DIS	850,000	48.00	42.00	22.00	850,000	0.0011765	
4	CONCRETE	4000000.00	48.00	42.00	46.00	175304.35	0.0000057	
		850,000			0 BLOCKS	29		TOTAL STIFFNESS OF BLOCK SYSTEM (KIPS/IN) 10198.22

VERTICAL STIFFNESS CALCULATIONS

HULL TYPE 616 DOCKING PLAN # 845-2006640

SYSTEM # 90 E2 SIDE BLOCKS ORIGINAL PER DOCKING DRAWING
OAK REMOVED ISOLATORS INSTALLED

BLOCK SPACING = 8.00 FEET

VERTICAL STIFFNESS:

LEVEL #	MATERIAL	E (PSI)	LENGTH (IN)	WIDTH (IN)	HEIGHT (IN)	K (KIPS/IN)	1/K	PIER TOTAL K (KIPS/IN)
			(DEPTH) (B)	(TRANSVERSE) (H)	(L)			
1	D.FIR	3473.50	12.00	24.00	3.00	333.46	0.0029989	129.02
2	D.FIR	3473.50	12.00	24.00	3.00	333.46	0.0029989	
3	DIS	850,000	48.00	42.00	22.00	850,000	0.0011765	
4	CONCRETE	4000000.00	48.00	42.00	46.00	175304.35	0.0000057	
		850,000			0 BLOCKS	29		TOTAL STIFFNESS OF BLOCK SYSTEM (KIPS/IN) 4039.02

TOTAL SIDE BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:
SYSTEM 90 E1

$$K_{ys} \text{ (SIDE BLOCK HORIZONTAL STIFFNESS)} = P / (\text{BENDING DISPL} + \text{SHEAR DISPLACEMENT})$$

$$K_{ys} = 4.30 \text{ KIPS/IN} \quad (\text{PER BLOCK})$$

$$K_{ys} = 124.71 \text{ KIPS/IN} \quad (\text{ENTIRE SIDE BLOCK SYSTEM})$$

TOTAL SIDE BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:
SYSTEM 90 E2

$$K_{ys} \text{ (SIDE BLOCK HORIZONTAL STIFFNESS)} = P / (\text{BENDING DISPL} + \text{SHEAR DISPLACEMENT})$$

$$K_{ys} = 0.45 \text{ KIPS/IN} \quad (\text{PER BLOCK})$$

$$K_{ys} = 12.93 \text{ KIPS/IN} \quad (\text{ENTIRE SIDE BLOCK SYSTEM})$$

TOTAL KEEL BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:
SYSTEM 90 E1

$$K_{hk} \text{ (KEEL BLOCK HORIZONTAL STIFFNESS)} = P / (\text{BENDING DISPL} + \text{SHEAR DISPLACEMENT})$$

$$K_{hk} = 10.78 \text{ KIPS/IN} \quad (\text{PER BLOCK})$$

$$K_{hk} = 593.02 \text{ KIPS/IN} \quad (\text{ENTIRE KEEL BLOCK SYSTEM})$$

TOTAL KEEL BLOCK HORIZONTAL STIFFNESS COEFFICIENT CALCULATION:
SYSTEM 90 E2

$$K_{hk} \text{ (KEEL BLOCK HORIZONTAL STIFFNESS)} = P / (\text{BENDING DISPL} + \text{SHEAR DISPLACEMENT})$$

$$K_{hk} = 1.28 \text{ KIPS/IN} \quad (\text{PER BLOCK})$$

$$K_{hk} = 70.55 \text{ KIPS/IN} \quad (\text{ENTIRE KEEL BLOCK SYSTEM})$$

"3DOFRUB" System 90 Output File . .

**** System 90 ****

** Hull 616 **

* Ship Parameters *

Weight	Moment of Inertia	K.G.
16369.9 kips	2410451.0 kips-in-sec ²	193.0 ins

* Drydock Parameters *

Side Block Height	Side Block Width	Keel Block Height	Keel Block Width
74.0 ins	999.0 ins	60.0 ins	999.0 ins
Side-to-Side Pier Distance	Wale Shore Ht.	Wale Shore Stiffness	Cap Angle
144.0 ins	.0 ins	.0 kips/in	.377 rad
1Side Side Pier Contact Area	Total keel Pier Contact Area	kkhp	
8352.0 in ²	55440.0 in ²	70.6 kips/in	
B/B Friction Coeff	H/B Friction Coeff	kskp	kvsp
9.000	.530	12.9 kips/in	4039.0 kips/in
Side Pier Fail Stress Limit	Keel Pier Fail Stress Limit	kvfp	
.700 kips/in ²	.700 kips/in ²	63799.6 kips/in	
Side Pier Vertical Stiffness	Side Pier Horizontal Stiffness		
10198.2 kips/in	124.7 kips/in		
Keel Pier Vertical Stiffness	Keel Pier Horizontal Stiffness		
63799.6 kips/in	593.0 kips/in		
QD1	QD2	QD3	QD4
606.4 kips	132.0 kips	2269.9 kips	.0 kips

* System Parameters and Inputs *

Earthquake Used is 1940 EL CENTRO

Horizontal acceleration input is HORIZONTAL

Vertical acceleration input is

Earthquake Acceleration Time History.

Vertical/Horizontal Ground Acceleration Ratio	Data Time Increment
1.000	.010 sec

Gravitational Constant	% System Damping
386.09 in/sec ²	8.00 %

Mass Matrix

42.3992	.0000	8183.0420
.0000	42.3992	.0000
8183.0420	.0000	2410451.0000

Damping Matrix

28.1828	.0000	3904.7339
.0000	302.3045	.0000
3904.7339	.0000	2110934.2033

Stiffness Matrix

842.4400	.0000	3491.8800
.0000	84196.0600	.0000
3491.8800	.0000	100635346.7016

Undamped Natural Frequencies	Mode #1	Mode #2	Mode #3
	3.850 rad/sec	12.738 rad/sec	44.562 rad/sec
Damped Natural Frequencies	Mode #1	Mode #2	Mode #3
	3.838 rad/sec	12.697 rad/sec	44.419 rad/sec

For Earthquake Acceleration of 100.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	15.016106			9.99
Maximum Y		-.116897		5.32
Maximum Rotation			.040585	19.89
Side block liftoff	.636733	-.007390	.003087	4.97
Side block crushing	4.559550	.028592	.010071	7.73

For Earthquake Acceleration of 90.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	13.527006			9.99
Maximum Y		-.107915		5.32
Maximum Rotation			.039428	19.95
Side block sliding	-5.560400	-.030395	.000234	8.40
Side block overturning	-5.560400	-.030395	.000234	8.40
Side block liftoff	.212407	.017846	.002485	4.99
Side block crushing	3.317758	.022864	.010455	7.76

For Earthquake Acceleration of 80.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	10.686809			12.17
Maximum Y		-.096222		5.32
Maximum Rotation			.041311	15.30
Side block sliding	.775303	-.012193	-.004976	17.89
Side block overturning	.775303	-.012193	-.004976	17.89
Side block liftoff	-.605223	.049976	-.002010	5.24
Side block crushing	1.506716	-.010418	.009568	7.83

For Earthquake Acceleration of 70.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	10.709546			15.88
Maximum Y		-.083638		5.32
Side block liftoff	-.846694	.048688	-.002108	5.15
Side block crushing	3.066522	.002094	.009600	9.87

For Earthquake Acceleration of 60.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	*****			18.08
Maximum Y		-.072901		5.32
Maximum Rotation			-.041717	18.43
Side block liftoff	-.740307	.038385	-.002281	5.13
Side block crushing	2.188692	-.003398	.009913	9.81

For Earthquake Acceleration of 50.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	10.189670			19.72
Maximum Y		-.058069		5.32
Maximum Rotation			-.041047	18.32
Side block sliding	.805700	.007265	-.002592	9.04
Side block overturning	.805700	.007265	-.002592	9.04
Side block liftoff	-.618767	.033610	-.002247	5.16
Side block crushing	.074574	.002589	.009661	9.84

For Earthquake Acceleration of 40.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	10.560604			18.35
Maximum Y		-.046455		5.32
Maximum Rotation			-.019585	19.51
Side block liftoff	-.974492	.021782	-.002440	8.50
Side block crushing	2.984180	-.010294	.009758	13.82

For Earthquake Acceleration of 30.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	.929978			9.29
Maximum Y		-.034841		5.32
Maximum Rotation			.001783	9.20

No failures occurred.

For Earthquake Acceleration of 39.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	11.118843			18.43
Maximum Rotation			.020881	18.67
Side block liftoff	.845572	-.002007	.002886	9.65
Side block crushing	-.824612	-.007999	-.009504	12.50

For Earthquake Acceleration of 38.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	10.650565			19.12
Maximum Y		-.044132		5.32
Maximum Rotation			.041563	19.46
Side block sliding	-2.550709	-.010928	-.004957	15.09
Side block overturning	-2.550709	-.010928	-.004957	15.09
Side block liftoff	.408778	-.000005	.002816	9.69
Side block crushing	1.821167	-.009694	.010243	13.82

For Earthquake Acceleration of 37.00 % of the 1940 EL CENTRO

Maximums/Failures	X (ins)	Y (ins)	Theta (rads)	Time (sec)
Maximum X	1.146910			9.29
Maximum Y		-.042971		5.32
Maximum Rotation			.002199	9.20

No failures occurred.

"3DOFRUB" System 90 Input Data File

SHIP/SUB DRYDOCK BLOCKING SYSTEM DATA FILE: B:S90ISO.DAT

INPUT FILE DATA

SHIP NAME: LAFAYETTE SSBN 616
 DISCRPTION OF ISOLATORS IF USED: BILINEAR WOOD W/ ISOLATORS
 DISCRPTION OF BUILDUP: 8 SPACING COMPOSITE
 DISCRPTION OF WALE SHORES USED: NO WALE SHORES
 DISCRPTION OF DAMPING: 8 % DAMPING
 LOCATION OF DRYDOCK BEING STUDIED: NO SPECIFIC LOCATION
 NAVSEA DOCKING DRAWING NUMBER: 845-2006640
 REFERENCE SPREADSHEET STIFFNESS CALC FILE NAME: S1KHORIG.WK1 & S1SHORIG.WK1
 MISC. COMMENTS: S90ISO.DAT 1356 4 MAR 88

SHIP WEIGHT (KIPS)	W= 16369.9
HEIGHT OF PG (IN)	H= 193
MOMENT OF INERTIA (KIPS*IN*SEC^2)	Ik= 2410451
SIDE PIER VERTICAL STIFFNESS (KIPS/IN)	Kvs= 10198.22
SIDE PIER VERTICAL PLASTIC STIFFNESS (KIPS/IN)	Kvsp= 4039.02
KEEL PIER VERTICAL STIFFNESS (KIPS/IN)	KVK= 63799.62
KEEL PIER VERTICAL PLASTIC STIFFNESS (KIPS/IN)	KVkf= 63799.62
HEIGHT OF WALE SHORES (IN)	AAA= 0
WALE SHORE STIFFNESS (KIPS/IN)	KS= 0
SIDE PIER HORIZONTAL STIFFNESS (KIPS/IN)	KHS= 124.71
KEEL PIER HORIZONTAL STIFFNESS (KIPS/IN)	KHK= 593.02
SIDE PIER HORIZONTAL PLASTIC STIFFNESS (KIPS/IN)	KSHP= 12.93
KEEL PIER HORIZONTAL PLASTIC STIFFNESS (KIPS/IN)	KKHF= 70.55
RESTORING FORCE AT 0 DEFLECT KEEL HORIZ (KIPS)	QD1= 606.41
RESTORING FORCE AT 0 DEFLECT SIDE HORIZ (KIPS)	QD2= 132
RESTORING FORCE AT 0 DEFLECT SIDE VERT (KIPS)	QD3= 2269.88
RESTORING FORCE AT 0 DEFLECT KEEL VERT (KIPS)	QD4= 0
GRAVITATIONAL CONSTANT (IN/SEC^2)	GRAV= 386.09
SIDE BLOCK WIDTH (IN)	SBW= 999
KEEL BLOCK WIDTH (IN)	KBW= 999
SIDE BLOCK HEIGHT (IN)	SBH= 74
KEEL BLOCK HEIGHT (IN)	KBH= 60
BLOCK ON BLOCK FRICTION COEFFICIENT	U1= 9
HULL ON BLOCK FRICTION COEFFICIENT	U2= .55
SIDE PIER TO SIDE PIER TRANSVERSE DISTANCE (IN)	BR= 144
SIDE PIER CAP PROPORTIONAL LIMIT	SCPL= .7
KEEL PIER CAP PROPORTIONAL LIMIT	KCPL= .7
TOTAL SIDE PIER CONTACT AREA (ONE SIDE) (IN^2)	SAF1= 144
TOTAL KEEL PIER CONTACT AREA (IN^2)	KAREA= 55440
PERCENT CRITICAL DAMPING	ZETA= .08
HULL NUMBER (XXXX)	HULL= 616
SYSTEM NUMBER (XXX)	NSYS= 90
CAP ANGLE (RAD)	BETA= .377