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EXPLOSION TEAR TEST STUDIES OF HIGH-STRENGTH Q&T STEELS

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ABSTRACT

Cleavage (brittle) fractures, the nominal mode of catastrophic failure for large welded structures of low-strength steels, have been investigated extensively. However, the potential problem of structural failure via shear (ductile) mode has generally received little attention by investigators, except for steels of very high strength. Proof-test failures involving "low energy shear" fractures have been encountered under conditions of near-yield-point loading for structures (rocket cases) which utilized high-strength materials. For service applications which anticipate the development of gross plastic overloads, the use of low energy shear materials may be considered potentially as dangerous as the case for materials capable of developing partially brittle fractures. This investigation was undertaken to develop a test method which would provide for the evaluation of tearing characteristics under explosive loadings for steels ranging in yield strength from 100 to 150 ksi.

A new test, the explosion tear test, was developed for this investigation. Preliminary results demonstrate that high-strength materials differ widely in tearing resistance. The relationship of Charpy V shelf level to tearing resistance has been examined. Shelf-level values significantly less than 40 to 50 ft-lb are shown to correlate with low energy shear characteristics in the explosion tear test. The quantitative correlation of Charpy V shelf level to tearing resistance of high-strength steels, however, is disclosed to be more complex than originally presumed. The complications, involving a yield-strength dependency and other factors, are discussed. It appears necessary to expand the investigation of various factors beyond the preliminary exploration represented by this report.

PROBLEM STATUS

This is a final report on one phase of this problem; other phases of the problem are continuing.

AUTHORIZATION

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EXPLOSION TEAR TEST STUDIES OF HIGH-STRENGTH Q&T STEELS

INTRODUCTION

Experience gained in conducting explosion tests has shown that some materials are ruptured, in a ductile mode, more readily than others. For example, nodular iron, malleable iron, and certain grades of "hard" ballistic armor have been shown to rupture relatively easily in explosion tests (1-3). Other materials, such as the presently used submarine hull steel, HY-80, * are extremely difficult to rupture in shear mode (3,4). To distinguish materials which ruptured readily from those which were difficult to rupture, the term "low energy shear" was coined (5). This term was meant to imply that the shear fracture propagation characteristics of some low energy shear materials might approximate the energy-absorption characteristics normally expected of cleavage (brittle) fractures.

With respect to service-load levels, materials may be classified according to their fracture-toughness (ductile-mode) characteristics into four general groups, as follows:

1. Materials of highest energy-absorption characteristics, such that extensive shear tearing could occur only at loads near the ultimate tensile strength of the material.
2. Materials of moderately reduced energy-absorption characteristics, such that extensive shear tearing could occur only at plastic overload levels, ranging between the yield strength (YS) and tensile strength (TS) of the material.
3. Materials of greatly reduced energy-absorption characteristics, such that extensive shear tearing could occur at or near yield-strength loads.
4. Materials of low-energy-absorption characteristics, such that extensive shear tearing could develop at load levels less than the YS of the material.

Explosion crack-starter tests have shown that the group 1 shear tearing characteristics, noted above, are invariably developed by HY-80 (4,5) and generally, by the medium carbon, structural mild steels (5). It should be noted, however, that the temperature range for shear fracture is above ambient temperatures for the mild steels. Materials of low energy shear characteristics, groups 3 and 4 above, are illustrated by service failures, which have been documented for rocket-casing materials heat treated to strength levels of 180 ksi YS and higher (6) and forged-steel retaining rings (7). These low energy shear service failures clearly indicate that the problem of low energy shear should be considered, and even anticipated, in design of highly stressed structures.

In relation to BuShips interest in steels within the HY-100 to HY-150 range, and for service performance involving loads in the YS and TS range (i.e., plastic overload region), the primary interest for this investigation resolves to group 2 energy-absorption characteristics, as described above. Within this strength-level range, it was considered probable that the problem of low energy shear ruptures might be encountered in a given steel,

*MIL-S-16216E - Denotes high yield, 80 ksi minimum. Although not presently covered by Navy specifications, a similar designation is used herein for higher strength level steels, e.g., HY-150 denotes high yield, 150 ksi minimum yield strength material.

depending on strength level. Accordingly, NRL was requested by BuShips to investigate the relative shear-energy characteristics of steels within the strength-level range of interest, and to develop test procedures and correlations of Charpy V (C_V) values for specifications. Because of their significance to submarine service, explosion tests were considered for first-step studies in this area. The conventional explosion bulge test specimens and procedures were modified to provide for evaluation of shear tearing characteristics of the materials under study.

TEST MATERIALS

A variety of materials (Table 1), which either are being used or have been proposed for use in submarine hull construction, were procured for this investigation. Except for one (to be described), these steels are representative of conventional mill-production material and were obtained from various shipyard stocks. The HY-80 steels of the lean-chemistry (L) and high-chemistry (H) range, the Navy special-treatment-steel (STS), the proprietary (Code Y) steel, and the British steel (QT-35) represent quenched-and-tempered (Q&T) steels normally supplied by the producers at strength levels ranging from approximately HY-80 to HY-110. In addition to tests of "as-received" (AR) plate, sections of the above steels were reheat-treated by NRL to permit the study of higher strength levels obtained by tempering at temperatures below those normally used in production. Table 2 lists the heat-treat conditions and the tensile test properties of the steels investigated.

Table 1
Chemical Compositions of Explosion Tear Test Steels (percent)

Element	HY-80 (L)	HY-80 (H)	STS	Code Y	QT-35	PHSS	MS
C	0.16	0.18	0.27	0.16	0.08	0.04	0.15
Mn	0.31	0.28	0.20	0.80	0.89	0.03	0.64
Si	0.21	0.26	0.22	0.23	0.10	0.08	0.19
S	0.016	0.010	0.025	0.014	0.021	0.004	0.019
P	0.015	0.015	0.010	0.015	0.011	0.001	0.009
Ni	2.16	2.76	3.16	0.79	1.07	18.3	
Cr	0.93	1.35	1.46	0.54	0.70	0.05	
Mo	0.29	0.44	0.20	0.50	0.43	5.3	
				0.21 Cu		7.4 Co	
				0.004 B*		0.24 Ti	

*0.003% to 0.005% B determined spectrographically.

An ultra-high-strength stainless steel, designated PHSS in Tables 1 and 2, represents an experimental composition of a new series of precipitation-hardened alloys developed by an industrial laboratory. This material was received in the solution-annealed condition to facilitate specimen preparation. The specimens were cut and aged by NRL, and tests were conducted only for the ultra-high-strength level (approximately HY-225) that the specific composition was designed to develop. The MS steel (Tables 1,2) represents a mild steel procured from shipyard stocks. The MS was used in exploratory investigations to establish the test conditions and explosion tear test specimen design.

Table 2
Heat-Treat Conditions and Mechanical Properties* of Explosion Tear Test Steels

Steel	Condition†	0.2% YS (ksi)	TS (ksi)	Reduction of Area (percent)	Elongation (percent)	1-in. Std NDT (°F)	Transverse Cv Shelf (ft-lb)	Explosion Tear Test Temperature (°F)
HY-80 (L)	AR	81.5	104.0	65.0	24.0	-150	80	+40
	Q&T 1050°F	113.0	125.3	52.0	17.0	-150	52	+40
	Q&T 900°F	150.0	159.7	45.0	13.0	-80	30	+80
HY-80 (H)	AR	83.5	102.2	63.8	23.0	-140	82	+40
	Q&T 1050°F	128.8	141.1	54.0	16.0	-130	52	+40
	Q&T 950°F	150.0	163.0	48.8	14.0	-40	39	+100
STS	AR	103.3	122.3	54.0	20.0	-180	52	+40
	Q&T 1050°F	123.5	139.0	56.2	20.0	-140	41	+40
	Q&T 875°F	156.2	170.8	45.6	13.0	-60	24	+100
Code Y	AR	115.8	122.4	47.2	16.5	-70	26	+100
	Q&T 1150°F	120.5	128.0	48.1	15.0	-60	27	+100
	Q&T 900°F	142.5	153.5	39.7	12.0	+10	18	+150
QT-35	AR	87.3	97.6	39.3	17.0	-50	30	+80
PHSS	Aged 900°F	221.8	234.5	41.2	9.0	---	22	+40
	AR	34.9	59.8	56.6	35.0	+20	45	+200

* Average of two 0.505-inch diameter specimens with axis of specimen oriented transverse to principal rolling direction.

† AR - As received.

Q&T - Water quenched from 1650°F plus temper 2+2 hr at temperature indicated.

Aged - Solution-annealed material aged 3 hr at 900°F.

CHARPY V AND NDT PROPERTIES OF TEST MATERIALS

Charpy V tests were conducted for each material over a range of temperatures to encompass the entire transition curve. In addition, 1-in.-thick, standard drop-weight specimens were used to establish the NDT temperatures of each material and heat-treat condition.* These data (Table 2) were used to establish the temperatures used for explosion tear tests of the various materials under study.

Although drop-weight specimens are insensitive to orientation, a great disparity between C_v shelf (100 percent shear) values has previously been shown to occur (9) in all materials which are not uniformly cross-rolled in the mill. All of the explosion tear test specimens covered by this report were oriented with the crack path parallel to the principal rolling direction (the path of least tear resistance). Consequently, for this investigation, all specimens (drop weight, Charpy V, and tension test) were oriented so that the tear propagation in each coincided with the fracture propagation direction chosen for the explosion tear test specimens.

The C_v energy-transition curves developed by the various steels are illustrated in Figs. 1 and 2. The heavy dot superimposed on each curve is the drop-weight NDT correlation temperature of each material. It is pertinent to note that the transverse orientation of all Charpy specimens shown in Figs. 1 and 2 differs from the conventional (longitudinal) orientation used in previous NRL investigations (5,10) to establish C_v energy "fix" values for NDT.

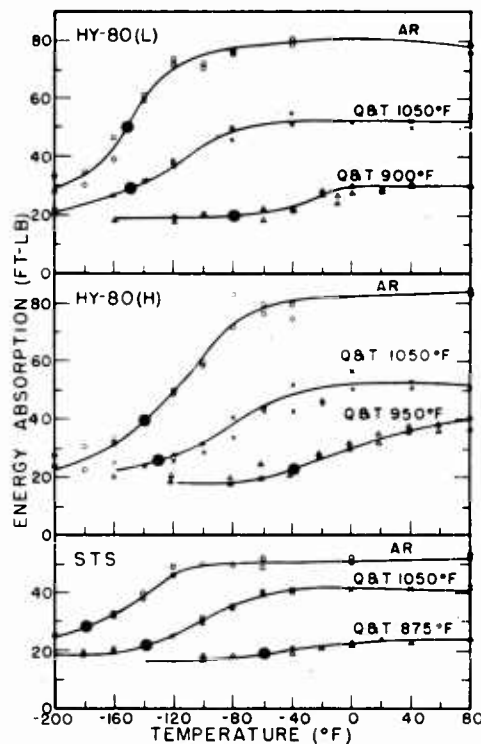


Fig. 1 - Charpy V energy-absorption curves and NDT temperatures (heavy dot) developed by various heat-treat conditions of the steels studied in the explosion tear test

*To avoid anomalous drop-weight behavior (8) resulting from the development of a ductile heat-affected zone (HAZ), the crack-starter weld was deposited on all drop-weight specimens before conducting the Q&T heat treatments given in Table 2. This precaution applies only to tests of high-strength (low-tempering temperatures) steels.

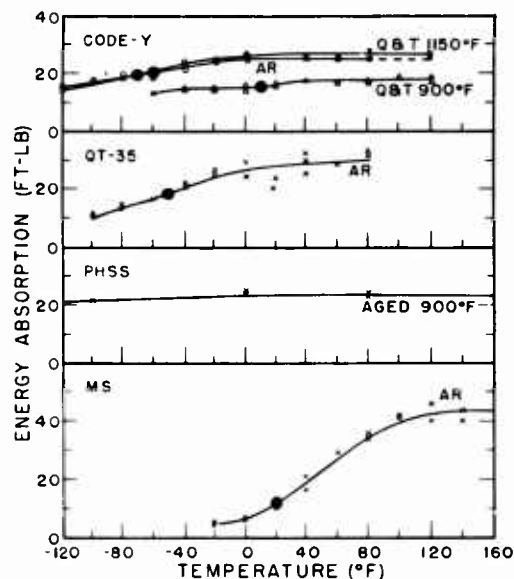


Fig. 2 - Charpy V energy-absorption curves and NDT temperatures (heavy dot) developed by various heat-treat conditions of the steels studied in explosion tear test

As indicated in Figs. 1 and 2, the C_V shelf values range from a high of 82 ft-lb to a low of approximately 20 ft-lb for the materials under study. The highest C_V shelf values, as well as the lowest NDT temperatures (Fig. 1) were developed by the HY-80 and STS materials, which are basically similar Ni-Cr-Mo alloys. The relatively low transverse C_V shelf value (26 ft-lb) indicated (Fig. 2) for the as-received condition of Code Y steel was as expected, because of the straightaway rolling process used for this particular steel plate.

A peculiar "flat C_V curve" was developed by the PHSS material. Charpy V tests of this material were conducted from -320°F to $+400^\circ\text{F}$. Throughout this temperature range, a very low slope, almost flat, straight-line relationship of C_V energy to test temperature was developed by the PHSS material. Such "flat Charpy curves" are inadequate for correlations with NDT and C_V energy-index values are impractical for estimation of a transition temperature. A significant NDT temperature could not be established and is not reported here for the PHSS material. In view of the explosion tear test results, to be described, further work with this PHSS alloy was not considered warranted at this time.

EXPLOSION TEAR TEST

A new type of explosion test has been developed* for the purpose of evaluating the shear tearing characteristics of intermediate and high-strength steels. The test specimen (Fig. 3) features a through-thickness crack, which in length is nominally twice the plate thickness ($2T$) and constitutes a gross flaw. The crack is developed by the weld deposited in the $1/2 \times 2$ inch through-thickness slot. The crack-starter electrode, Hardex N, is used for the weld, which is made without preheat, and with allowance for cooling between weld passes. The other features of the test sample illustrated in Fig. 3 are two side slits in the test plate and a rectangular supporting die. On explosion loading, the portion of the plate between the side slits "bulges" as a cylindrical surface, causing shear tearing from the ends of the centrally located flaw. The cylindrical bulge provides for propagating the tear

*The test concept and design are credited to W. S. Pellini, P. P. Puzak and E. P. Klier.

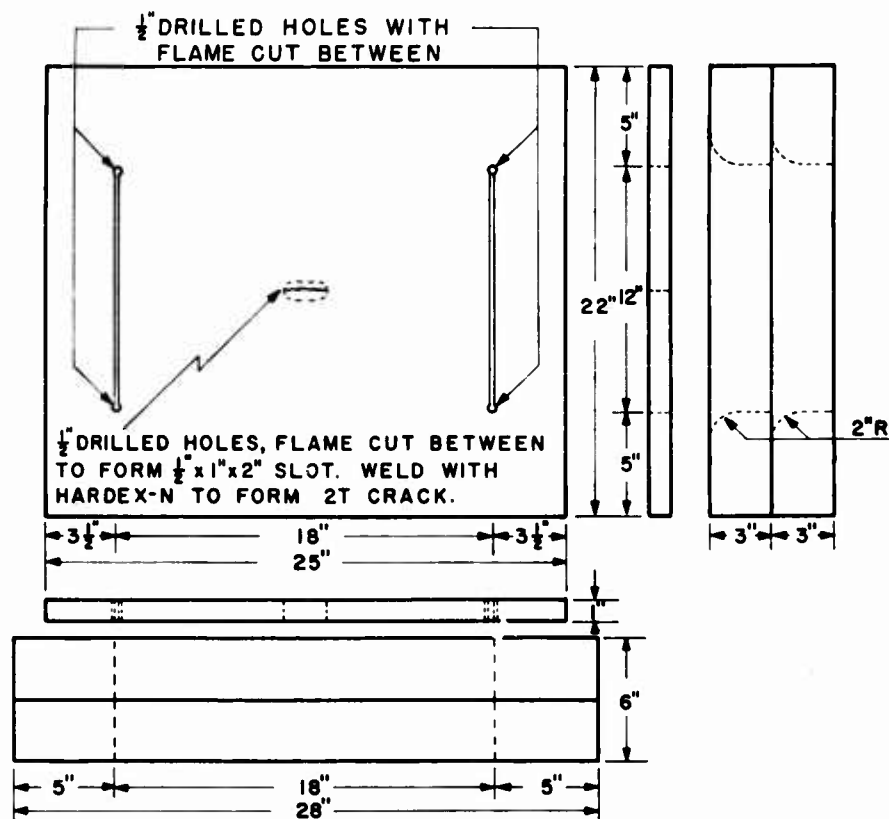


Fig. 3 - Explosion tear test plate with central 2T crack, and rectangular die. Duplicate dies are used for handling convenience.

in a stress field of essentially uniform plastic strain, as contrasted with the hemispherical bulge which results in propagation of the tear into a continually decreasing plastic strain, stress field, i.e., from the pole region down to the hold-down regions of the bulge.

All materials included in this investigation were explosion tear tested as 1-inch plates. The HY-80 (H) and the QT-35 steels were received as 1-1/2-inch-thick plates but were machined (from one side only) to a nominal thickness of 1 inch. The tests were conducted at temperatures (Table 2) which were more than 120° F above the NDT temperature of each respective material in order to insure the development of fracture by ductile (shear) mode. The sequence of testing involves the application of two successive shots to delineate the fracture toughness of the material. Surface-strain measurements were conducted initially for the purpose of evaluating the degree of local strain (near the tear) as compared with the general strain level of the bulge. These measurements were found to be excessively time consuming and did not add to the interpretability of the test results expressed in simple terms of tear length.

Test conditions which provided for discrimination among the materials of widely different shear tearing resistance characteristics involved the use of 7-lb explosive charges at standoff distances of 15, 19, or 23 inches. The approximate gradation of bulge levels developed with the first and second 7-lb shot is illustrated in Fig. 4. The test comparisons were based on the tearing exhibited for a given explosive-energy release; therefore the degree of bulging varied slightly within the range of strength levels investigated.

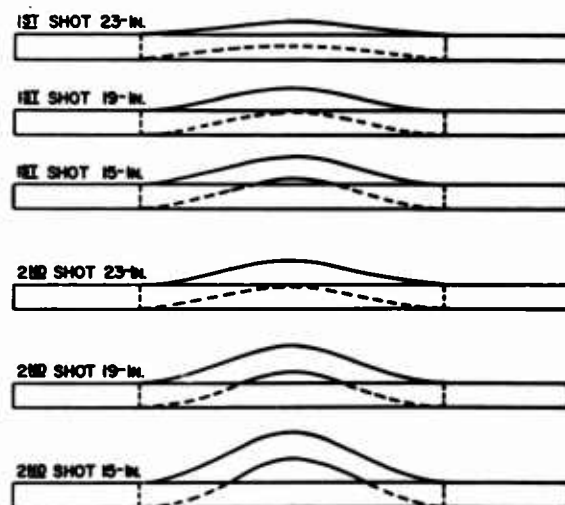


Fig. 4 - Relative bulge levels developed by energy release of 7-lb explosive charge at various standoff positions

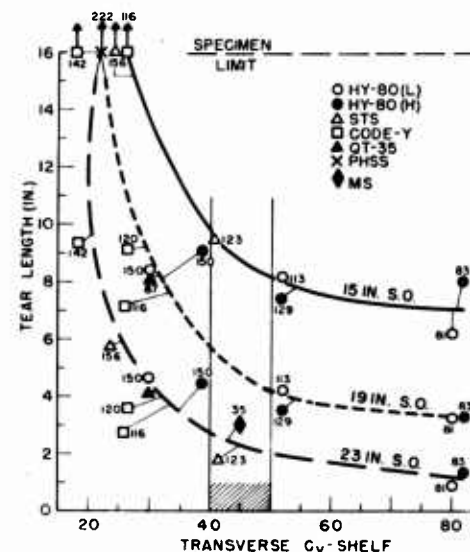


Fig. 5 - First-shot (7 lb) explosion tear test performance. YS levels are indicated by the numbers adjacent to each symbol.

The first-shot shear tear extensions developed for various steels, heat treated to various levels of yield strength, are presented in Fig. 5. The noted tear lengths represent extensions of the tear from the tip ends of the pre-existing flaw, i.e., the total of the tear extensions from both tips. The yield strengths (ksi) of the various steels (Table 2) are indicated by the numbers adjacent to the code symbols. The arrows at the top left of Fig. 5 indicate that the tear lengths exceeded the 16-inch dimension (specimen limit) of the test plate. The tear lengths are related to the Charpy V energy level obtained at temperatures of full shear fracture, i.e., the "upper shelf" values. These data indicate a transition in tearing resistance in the range of C_V 40 to 50 ft-lb shelf levels. In effect, the decrease in tearing resistance represented by a decrease in C_V level from 80 to 50 ft-lb is relatively minor compared with the drastic loss in tear resistance as the C_V levels decrease below the 40 ft-lb level. At levels of 20 ft-lb C_V , complete fracture occurs even with the mild loading conditions of 23-inch standoff; Fig. 6 illustrates the subject test sample. For comparison, tests of the C_V 80 ft-lb HY-80(L) material with the same conditions (7 lb, 23-inch standoff) developed a first-shot tear length of approximately 1 inch. The high tearing resistance of the C_V 80 material is illustrated (Fig. 7) by the application of five shots, which resulted in only a 10-1/2-inch tear length.

In an attempt to establish finer distinctions among the tearing characteristics of the various materials, additional tests were conducted with the application of two shots. The test conditions involved the relatively mild 23-inch standoff and the intermediate 19-inch standoff loadings. These results are presented in Fig. 8. As noted by the arrows, top left, tear lengths exceeding the specimen limit (16 inches) are developed on the second shot with 19-inch standoff loading for all steels of C_V 40 ft-lb or less. In general, the two-shot series (Fig. 8) confirms the "transition" aspects noted previously for the C_V 40 to 50 ft-lb range. It is apparent that these tests also delineate the high end of the range (50 ft-lb) as the critical point of the range. The additional feature of these tests is the apparent dependence of tearing resistance with yield strengths of the materials indicated within this range of C_V 40 to 50 ft-lb. This complication is illustrated by the second-shot 23-inch standoff loadings of the STS (condition HY-123) and the HY-80 (H) (condition HY-150) steels. In these reheat-treated conditions, both steels exhibit about 40 ft-lb C_V (39 and 41 ft-lb respectively) but differ widely in resistance to second-shot extension of the rupture.

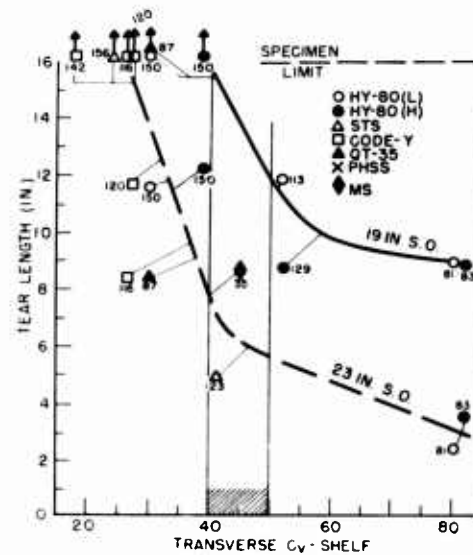


Fig. 6 - Low energy shear characteristics illustrated by first-shot complete rupture under mild (23-inch standoff) loading conditions for the Cy 22 ft-lb shelf PHSS material



Fig. 7 - High resistance to shear failure exhibited by Cy 80 ft-lb HY-80 (L) material. The illustration depicts 10-1/2-inch tear length developed after 5 shots with 23-inch standoff.

Fig. 8 - Second-shot (7 lb) explosion tear test performance. YS levels are indicated by the numbers adjacent to each symbol.



SUMMARY

It should be recognized that the information provided by this report represents the results of concurrent attempts to develop:

1. A new test method for evaluating shear tearing resistance
2. Preliminary data on tearing characteristics of a broad range of steels heat treated to a wide range of yield strengths
3. Explorations of possibilities for "calibration" of the C_v shelf levels for predictions of relative tearing toughness.

The explosion tear test method is reproducible and provides significant data on the tearing characteristics of steels under explosive-load conditions. It provides flexibility for the assessment of widely different "states" of tearing toughness. Although this investigation was limited to 1-inch-thick steels, no difficulty is envisioned for "scaling-up" to test thicker materials. All that will be required is a larger test plate and die, and the use of heavier explosive charges. The limitations of the new test are the same as those for the explosion bulge test, i.e., the requirement for testing at an established explosion test site. Conducted according to standard procedures (to be established), it should provide for BuShips requirements for "final" materials-qualification purposes, without additional test development.

The data presented on tearing characteristics justify the initial concept of the need to investigate this new aspect of fracture properties. Although limited to exploratory information at this time, it is obvious that the test results show that some materials are characterized by an alarming lack of tear resistance for use in critical naval structures. For service anticipating plastic overloads, low energy shear materials are considered to be potentially as dangerous as materials that are partially brittle at cold water temperature.

The question of "sufficiency" of tear resistance cannot be resolved from the available exploratory data at this time. The natural course should be to determine the highest toughness level that may be developed, at reasonable cost, for various strength levels of

future hull construction. The data presented suggest that tearing resistance is decreased with increasing strength level, and that for a given strength level widely different tearing resistance may be encountered. A "fine-structure" investigation, in detail, of various strength levels is an obvious next step.

The early estimate, based on a variety of NRL observations of tearing characteristics in explosion bulge tests, that the 50 ft-lb C_V marked a point of sharp "transition" in tearing resistance has been justified. Explosion tear tests have demonstrated that a major change in tearing characteristics is indicated for materials of the C_V 40 to 50 ft-lb range. However, the calibration of the C_V shelf level, as a reliable index of relative tearing characteristics, is disclosed by this investigation to be more complex than originally envisaged. The correlation of C_V shelf values to tearing resistance is complicated by a dependence on the YS level and possibly other factors not presently understood. One of these is most likely the relative degree of cross-rolling performed on the plates. At the present (imperfect) state of knowledge, it appears that C_V levels of significantly less than 50 ft-lb are definitely correlatable to low energy fracture. Accordingly, there is no justification to lower the C_V requirement (50 ft-lb) established by BuShips; to the contrary, this value is justified as a minimum requirement.

Since Charpy shelf correlation to tearing is more complicated than initially assumed, additional investigations are necessary for establishing the limits to which the Charpy test may be used in this manner, i.e., as something more than a critical transition level. It is not at all certain that this may in fact be accomplished. Complications of yield-strength levels, cross-rolling variables, and probably other factors may restrict the value of C_V data for this purpose.

All of the above findings point to the need for evolving a simple laboratory test suitable for rapid assessment of tearing toughness. This obvious need has resulted in a concurrent study aimed at developing a drop-weight tear test which is now under evaluation. The successful development of a suitable drop-weight tear test would reduce the requirement of explosion testing to "check" correlation and provide a means by which industrial laboratories would conduct independent materials developments of future Navy interest.

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<p style="text-align: center;">UNCLASSIFIED</p> <p>Naval Research Laboratory. Report 5836. EXPLOSION TEAR TEST STUDIES OF HIGH-STRENGTH Q&T STEELS, by P. P. Puzak and A. J. Babecki. 11 pp. & figs., September 6, 1962.</p> <p>Cleavage (brittle) fractures, the nominal mode of catastrophic failure for large welded structures of low-strength steels, have been investigated extensively. However, the potential problem of structural failure via shear (ductile) mode has generally received little attention by investigators, except for steels of very high strength. Proof-test failures involving "low energy shear" fractures have been encountered under conditions of near-yield-point loading for structures (rocket cases) which utilized high-strength materials. For service applications which anticipate the development of gross plastic overloads, the use of low energy shear</p> <p style="text-align: right;">UNCLASSIFIED (Over)</p>	<p style="text-align: center;">UNCLASSIFIED</p> <p>Naval Research Laboratory. Report 5836. EXPLOSION TEAR TEST STUDIES OF HIGH-STRENGTH Q&T STEELS, by P. P. Puzak and A. J. Babecki. 11 pp. & figs., September 6, 1962.</p> <p>Cleavage (brittle) fractures, the nominal mode of catastrophic failure for large welded structures of low-strength steels, have been investigated extensively. However, the potential problem of structural failure via shear (ductile) mode has generally received little attention by investigators, except for steels of very high strength. Proof-test failures involving "low energy shear" fractures have been encountered under conditions of near-yield-point loading for structures (rocket cases) which utilized high-strength materials. For service applications which anticipate the development of gross plastic overloads, the use of low energy shear</p> <p style="text-align: right;">UNCLASSIFIED (Over)</p>
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1. Steel - Rupture - Test methods
2. Steel - Shear stresses

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A new test, the explosion tear test, was developed for this investigation. Preliminary results demonstrate that high-strength materials differ widely in tearing resistance. The relationship of Charpy V shelf level to tearing resistance has been examined. Shelf-level values significantly less than 40 to 50 ft-lb are shown to correlate with low energy shear characteristics in the explosion tear test. The quantitative correlation of Charpy V shelf level to tearing resistance of high-strength steels, however, is disclosed to be more complex than originally presumed. The complications, involving a yield-strength dependency and other factors, are discussed. It appears necessary to expand the investigation of various factors beyond the preliminary exploration represented by this report.

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