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EXPEDIENT REPAIR OF STRUCTURAL FACILITIES (ERSF) - VOLUME II: ERSF SYSTEM REQUIREMENTS AND USERS GUIDE

D . L. READ, D. H. MERKLE

APPLIED RESEARCH ASSOCIATES, INC.
P. O. BOX 40128
TYNDALL AFB FL 32403

JULY 1991

FINAL REPORT

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Read, D.L., and Merkle, D.H.

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Applied Research Associates, Inc.
P.O. Box 40128
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The objective of this effort was to develop expedient systems to repair conventional weapon damage to mission-critical facilities at United States Air Forces in Europe (USAFE) and Pacific Air Forces (PACAF) forward operating bases (FOBs) in a postattack environment. Several of the developed Expedient Repair of Structural Facilities (ERSF) systems were demonstrated in the field to determine their effectiveness. Included in the development of each ERSF system was identification of the personnel, equipment, materials and procedures required to support it.

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EXECUTIVE SUMMARY

A. OBJECTIVE

The objective of this effort was to develop expedient systems to repair conventional weapon damage to mission-critical facilities at United States Air Forces in Europe (USAFE) and Pacific Air Forces (PACAF) forward-operating bases (FOBs) in a postattack environment. Included in the development of each repair system was identification of the personnel, equipment, materials, and procedures required to support it.

B. BACKGROUND

To fulfill its mission after an attack, an airbase must be able to quickly generate aircraft sorties, and then sustain them. To generate sorties, an airbase must have a usable and accessible runway surface. To sustain them, an airbase's mission-critical facilities must be operational.

During the SALTY DEMO air base survivability exercise in 1985, when damage assessment teams (DATs) in the field informed the Damage Control Center (DCC) of a damaged mission-critical facility, the DCC could give them little or no guidance on how to repair the facility. This highlighted the fact that the Air Force did not have systems in-place at FOBs to expediently repair mission-critical facilities. Without such a capability, airbase mission fulfillment is jeopardized. Consequently, the expedient repair of structural facilities (ERSF) development effort described here was undertaken by the Air Force Engineering and Services Center (AFESC) Engineering Research Division's Airbase Structures and Weapon Effects Branch (RDCS).

C. SCOPE

This technical report consists of two volumes. Volume I documents the development and screening of candidate ERSF systems for expected expediently repairable damage modes of mission-critical structures. This development and screening process allowed the most promising system(s) for each damage mode to be identified. Volume I also contains results from field demonstrations of several of the developed ERSF systems. Additionally, Volume I presents recommendations for further development and fielding of ERSF systems. Volume II describes ERSF system requirements with respect to the personnel, equipment, supplies, procedures, and training needed to support each recommended ERSF system.

D. EVALUATION METHODOLOGY

ERSF systems to repair expected damage modes of mission-critical structural facilities were developed, and underwent a preliminary, subjective screening process. Systems were modified, if possible, to improve their viability. Based on this screening and refinement process, the most viable candidate ERSF systems to repair each damage mode were identified. These candidate ERSF systems were then evaluated indepth for effectiveness, and ranked in order of merit using evaluation matrices. Each system was evaluated in operational, structural, and logistical categories for criteria such as manpower, simplicity, strength, durability, storage life, and cost. Each system was assigned a score for each criterion. Scores ranged from one (poor) to five (excellent). A system's criterion scores in each category were summed, and the sum multiplied by a weight factor to obtain the system's category score. The three category scores were then summed to obtain the system's total evaluation score. Based on this score, the system was ranked against other repair systems for the same damage mode.

E. RESULTS

Identified damage modes of structural facilities, and the candidate ERSF system(s) to repair each damage mode are presented below. Recommended systems and backup systems are denoted by the symbols (R) and (B), respectively.

Damage Mode	Repair Method
Damaged Steel Frame	Cutting And Welding (R)
Destroyed Column	Shoring Jack (R) Glued, Laminated Timber (Glulam) Column (R)

Damage Mode	Repair Method
Cracked Column	Column Splint (R)
Damaged Beam/Girder	Vertical Shoring (R)
	King Post (B)
Destroyed Wall	Plywood Backing (R)
	Earth Berm (B)
	Precast Slabs (B)
	Shotcrete[1] Repair
	Masonry Blocks
Wall Breach	Plywood Backing (R)
	Earth Berm (B)
	Precast Slabs (R)
	Shotcrete[1] Repair
	Masonry Blocks
Floor/Roof Breach	Plywood And Rolled Roofing (R)
	Rapid Set Concrete (R)
	Shotcrete[1] Repair
	Seal Stairs (B)
Damaged Overpressure Door	Canvas/Sheeting Covering (R)
	Third Door Insertion (B)
	Door Replacement (B)
	Seal Door Opening (B)
Stuck Blast Door	Pry Open Door (R)
Destroyed Window	Plastic Sheeting (R)
	Acrylic Panel Replacement (R)

1 - Shotcrete System is still under development by AFESC/RDCS.

Damage Mode	Repair Method
Fractured Aircraft Shelter Floor Slab	AM2 Panel Ramp (R) Rapid Set Concrete Ramp (B) Shotcrete[1] Ramp

1 - Shotcrete System is still under development by AFESC/RDCS.

F. CONCLUSIONS

Effective expedient repair systems can be fielded to repair a wide range of conventional weapon damage to mission-critical structural facilities. Most of the systems are simple, ease to use, and inexpensive. A shotcrete-based expedient repair system needs further development to identify suitable equipment and determine material storage requirements. However, an ERSF shotcrete system holds great promise, because of its wide range of uses, and the structural strength, durability, blast resistance, fragment penetration resistance, and airtightness of the resulting repairs.

G. RECOMMENDATIONS

Full-scale development of recommended ERSF systems should be undertaken. Engineering development of an ERSF shotcrete system should be continued to identify suitable equipment, procedures, and material storage requirements. If this engineering development effort is successful, full-scale development of the shotcrete system should be undertaken.

PREFACE

This report was prepared by Applied Research Associates, Inc. (ARA), under contract F08635-88-C-0067 for the Air Force Engineering and Services Center (AFESC), Engineering and Services Laboratory, Tyndall Air Force Base, Florida.

This report summarizes work done between 1 December 1987 and 30 October 1990. LT. William R. Burkett (USN) and Capt. Richard A. Reid were the AFESC/RDCS Project Officers for the subtasks under which this work was accomplished.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the public, including foreign nations.

This technical report has been reviewed and is approved for publication.

RICHARD A. REID, Capt, USAF
Project Officer

NEIL H. FRAVEL, Lt Col, USAF
Chief, Engineering Research Division

WILLIAM S. STRICKLAND
Chief, Airbase Structures and Weapon Effects Branch

FRANK. P. GALLAGHER, III, Colonel, USAF
Director, Engineering and Services Laboratory

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SECTION I

INTRODUCTION

A. OBJECTIVE

The objective of this research effort was to identify, test, evaluate, recommend, and develop construction materials, equipment, techniques, and training criteria for expedient repair of conventional weapon damage to mission-critical structural facilities at United States Air Forces in Europe (USAFE) and Pacific Air Forces (PACAF) forward operating bases (FOBs) in a postattack environment. This effort was undertaken because of lessons learned during the airbase survivability exercise SALTY DEMO in 1985 (see Section I-B, "Background").

This report consists of two volumes. Volume I describes the development and evaluation of ERSF systems to repair expected damage to mission-critical structures. Additionally, results from field demonstrations of ERSF systems to replace a destroyed column, splint a cracked column, replace a destroyed, non-load-bearing wall, and repair a wall breach are presented. Volume II describes ERSF system requirements with respect to personnel, equipment, supplies, and training.

B. BACKGROUND

Modern warfare grants no safe haven. In the past an airbase well behind the front line was considered immune from the threat of death and destruction characterizing an infantry battlefield. Now there is no front line, and the lethality of the battlefield threatens every major overseas airbase. This is because the range, accuracy, and destructive power of modern weapons pose the same threat to an airbase command post as to a tank. That situation mandates that Air Force civil engineers anticipate the nature, extent, and mission capability consequences of facility damage, and develop strategies to recover from it.

In 1985 at Spangdahlem air base (AB), Federal Republic of Germany (FRG) the NATO airbase survivability exercise SALTY DEMO dramatically underscored the need for reliable postattack communications and a facility recovery plan. The Airbase Operability (ABO) concept evolved from SALTY DEMO. Its five phases are defense, survival, recovery, aircraft sortie generation, and sortie support. This report deals with the recovery phase of ABO, called Base Recovery After Attack (BRAAT), and specifically with expedient repair of damaged mission-critical facilities, using preplanned methods and prepositioned resources.

Emergency repair is defined by AFR 93-2, Contingency Response Planning, as the least amount of immediate repair to damaged facilities necessary to accomplish the installation's primary mission. Emergency repair is designated an Air Force Base Civil Engineer (BCE) responsibility. However, follow-on repairs, which are repairs beyond those required during emergency repair operations, and which are intended to restore operational capability according to regulating construction standards, are designated an Army responsibility by AFR 93-2.

AFR 93-2 requires emergency facility repair to be expedient, and in this report the term "expedient repair" is used synonymously with the terms "emergency repair" and "rapid minimum emergency repair," which appear in AFR 93-2.

AFR 93-2 designates the Headquarters Air Force Engineering and Services Center Directorate of Readiness (HQ AFESC/DEO) as the focal point for the civil engineering contingency response program. It also holds each MAJCOM Deputy Chief of Staff (DCS) for Engineering and Services responsible for providing specific contingency response guidance and assistance to subordinate commands and installations; monitoring civil engineering contingency response programs at all subordinate levels; evaluating BCE contingency response capabilities; and reviewing contingency response training programs for compliance with applicable regulations.

Finally, AFR 93-2 tasks each BCE to establish a Contingency Response Program; maintain a Contingency Response Plan (CRP) consistent with the BRAAT operational concept; provide advice to the installation commander on all base facility recovery operations; and provide trained forces and use available equipment and materials to return the installation in minimum time after each attack to a condition in which the primary mission can be performed. In each

CRP are to be plans for rapid minimum emergency repairs to high-priority structural facilities, such as command posts, communication centers, and aircraft and weapon maintenance facilities; and provisions for procuring and storing necessary materials and equipment to accomplish emergency repairs.

Flexibility is cited by AFR 93-2 as a vital attribute of the plans and methods appearing in a CRP. This is particularly important for facility expedient repair methods, because facility damage modes are much more varied and much less predictable than the airfield pavement damage modes with which Rapid Runway Repair (RRR) crews must contend.

AFR 93-2 states that during wartime recovery operations, North Atlantic Treaty Organization (NATO) Standardization Agreement (STANAG) 2929, Airfield Damage Repair, must, as a minimum, govern and define preparation for and conduct of airfield damage repair at NATO airfields and airfields scheduled for deploying NATO aircraft. The goal, however, is to conduct airfield recovery operations to satisfy requirements identified in the Tactical Air Force Statement of Operational Need (TAFSON) 319-79 (SECRET), Post Attack Launch and Recovery. TAFSON 319-79 identifies more stringent wartime conditions expected at main operating bases in the European and Pacific theaters of operations. AFR 93-2 says nothing about operational requirements for airbase facility recovery. It is not obvious that airbase facility recovery operational requirements need to be the same as those given above for RRR, or even that they need to be classified. Unclassified airbase facility recovery operational requirements are developed and used in this report.

C. SCOPE

1. Definition of Expedient Repair

In the research effort documented here, ERSF was defined as simple, nonpermanent repairs to mission-critical facilities that can be accomplished within 4 hours. The 4 hour time limit is the maximum time an individual repair can take to be accomplished. The purpose of such repairs is to allow the damaged facility to continue to accomplish its mission without undue hazard to personnel within the facility, or at least allow critical resources to be safely removed from the facility.

2. Expedient Repair Logic

The reason for ERSF is to quickly recover the ability to generate aircraft sorties. In wartime, the mission of an airbase is to generate and sustain aircraft sorties against the enemy. To fulfill this mission, an airbase requires an accessible, usable runway surface, and facilities for aircraft sortie generation and sustainment. Expedient repair of mission-critical facilities supports the second and third requirements.

3. Types of Structures

ERSF is applicable to all mission-critical structural facilities on an airbase. This includes steel-framed, reinforced concrete, masonry block, and wood structures.

4. Available Technology

Simple, proven, off-the-shelf technology was stressed during development of the ERSF systems described in this report. However, when major benefits could be derived from a small amount of equipment and/or material development, it was undertaken.

5. Relation to Permanent Repair

Expedient repairs are temporary and do not attempt to return a facility to its original structural condition. Consequently, when time permits, expedient repairs should be replaced by permanent repairs, using standard construction techniques, and governed by standards and codes.

6. Interface with Postattack Damage Assessment

ERSF systems work in conjunction with the postattack damage assessment expert system (POST-DAM) under development by AFESC/RDCS. After an airbase has been attacked, damage assessment and response teams (DARTs) in the field will use POST-DAM to assess the extent of damage to mission-critical structural facilities, and recommend through the Survival Recovery Center

(SRC) to the Damage Control Center (DCC) which ERSF system(s) should be used to repair the damage. The DCC will then direct repair teams to the facilities, with the appropriate supplies and equipment to accomplish the repair(s).

D. APPROACH

1. ERSF System Guidelines

The first step in this development effort was a review of Air Force documents and directives that give guidance on expedient repair of airbase facilities in a postattack environment. During this review, it was determined that a Facility Recovery System Operational Requirements Document (SORD) was needed to provide the operational requirements needed to guide the development of ERSF systems.

2. Literature Review

A literature review was accomplished to determine what, if any, work had been accomplished to develop systems for rapidly repairing damaged structures. For example, had systems been developed for rapidly repairing structures damaged by earthquakes or other natural disasters? Based on this review, it was determined that little information applicable to the needs of the Air Force's ERSF development effort was available.

3. Mission-Critical Structural Facility Damage Modes

Review of mission-critical structural facilities on a FOB was accomplished to determine damage modes that could be expected from conventional weapon effects, and that would lend themselves to expedient repair. Bitburg AB, FRG was the airbase used for this process.

4. ERSF System Development and Screening

Once expected damage modes had been identified, possible systems for expediently repairing them were developed. These systems were then screened to determine their viability. Based on this screening, the most promising (candidate) ERSF systems were put through a more detailed evaluation.

5. Evaluation of Candidate ERSF Systems

Candidate ERSF systems were evaluated using a point system based on weighted operational, structural, and logistical criteria. Based on this evaluation, ERSF systems used to repair an individual damage mode were ranked. Based on this ranking, the best repair system(s) for each damage mode were identified.

6. Field Demonstrations

Several candidate ERSF systems were demonstrated in the field to determined if the ERSF system development, screening, and evaluation process described above actually produced effective systems. While some problems were encountered during the demonstrations, overall results showed that the process worked well.

7. ERSF System Requirements

The procedures, supplies, equipment, personnel, and training criteria required to support and use the developed ERSF systems were identified. That information is presented in Volume II of this report. The identified system requirements can be used as a starting point for developing an ERSF user's manual. When completed, the ERSF user's manual can be employed by a BCE at a FOB as a guide for developing and supporting an ERSF capability.

SECTION II

EXPEDIENT REPAIR OF STRUCTURAL FACILITIES (ERSF) SYSTEM GUIDELINES

A. AIR FORCE REQUIREMENTS AND GUIDELINES

AFR 57-1, Operational Needs, Requirements, and Concepts, outlines Air Force policies, procedures, and responsibilities for identifying, processing, and approving operational requirements which result in research, development, test, and evaluation (RDT&E), or procurement appropriations. Material, hardware, and equipment for expedient repair of structural facilities fall in this category. AFR 57-1 describes the criteria, content, format, and approval process for Statements of Operational Need (SONs), SORDs, and Depot Support Requirements Documents (DSRDs), all of which document Air Force system operational requirements.

The Air Force system operational requirements documentation process begins by identifying operational needs, and continues throughout the acquisition process and life-cycle of a system. SONs are mandatory for needs that cannot be met through changes in tactics, strategy, doctrine, or training, and for which solutions require a new development, new procurement, or existing system upgrade. Postattack facility recovery needs fall in this category. A SORD is mandatory to detail the operational requirements of a system supported by the Program Objective Memorandum (POM) process with funding. SONs and SORDs detail major command (MAJCOM) operational needs.

B. STATEMENT OF NEED (SON)

At the start of this research effort, Tactical Air Forces (TAF) SON 319-79(S), Postattack Launch and Recovery (PALR) (U), was thought to be broad enough in scope to cover facility recovery (postattack damage assessment of facilities (POSTDAM), and ERSF systems). However, there was no Facility Recovery SORD. Consequently, there was no detailed operational requirement which could be used to define criteria by which to evaluate ERSF systems. The evaluation criteria existed qualitatively, but not quantitatively.

C. FACILITY RECOVERY SORD

In early October 1989, representatives of HQ AFESC/RDCS visited HQ USAFE/DEM, and learned that HQ USAFE did not have a formal Facility Recovery Program, and that no Facility Recovery SORD was in preparation. That meant the HQ AFESC/RDCS facility expedient repair advanced development effort had no means of transitioning to HQ AFESC/YE, which performs engineering development of advanced development concepts produced by HQ AFESC/RD. However, HQ USAFE/DEM stated they would be pleased to receive a draft Facility Recovery SORD, and would then process it themselves and submit it to HQ TAC/DRP. Consequently, a draft SORD was prepared and sent to HQ USAFE/DEM (Reference 1). The detailed operational requirements listed in the draft SORD Requirements Correlation Matrix are, in some cases, less stringent than those stated in the ERSF System Specification discussed below.

D. ERSF SYSTEM SPECIFICATION

The above lack of documented facility expedient repair operational requirements was unacceptable, because it restricted the research to technology investigation with no means of quantitative evaluation. Consequently, before the SORD was drafted, a draft Expedient Repair of Structural Facilities (ERSF) System Specification was prepared (Reference 2). The provisions of the ERSF System Specification are based on, but not necessarily identical to those of the Air Force's Rapid Runway Repair (RRR) System Specification. The ERSF System Specification was an attempt to put the evaluation of facility expedient repair methods on a firm quantitative basis, prior to the existence of a SORD. When a Facility Recovery SORD is finally approved, the ERSF System Specification will be made consistent with the SORD.

SECTION III

LITERATURE REVIEW

A. INITIAL REVIEW

The initial technical literature review for the ERSF research reported herein was submitted on 1 April 1988 (Reference 3). It disclosed few references on the technical details of structural repair, and none on truly expedient structural repair. With one possible exception, that is still the case.

B. OTHER INFORMATION

1. Texas Report

The one possible exception cited above is ESL-TR-88-79, Expedient Repair of Structural Facilities (Reference 4), written by the University of Texas at Austin and the Southwest Research Institute. Although the report contains a thorough discussion of structural repair methods, few of the methods can be considered expedient because they cannot be completed within the time limits specified by either References 1 or 2. In fairness to the authors of the Texas report, it must be pointed out that neither reference was available when ESL-TR-88-79 was written, and even the TAF SON 319-79 operational criteria for RRR were not available to the authors, because their contract was unclassified. The Texas report drew heavily from an American Concrete Institute (ACI) Committee 546 draft report, Guide to Repair of Concrete (Reference 5), printed in October 1987 and obtained by AFESC/RDCS shortly after Reference 3 was submitted. See also the ACI Seminar Course Manual SCM-16(87), Repair and Rehabilitation of Concrete Structures, (Reference 6). The ACI committee report deals almost exclusively with permanent repair. Other structural repair reports written by the University of Texas at Austin's Ferguson Structural Engineering Laboratory for the National Science Foundation (References 7, 8, 9, 10, and 11) also provided information for the Texas report; and ESL-TR-82-14, Advanced Material Development for Repair of Bomb Damaged Runways, (Reference 12) contains information that may be useful for some types of facility expedient repair. The problem with most advanced materials, however, is that their use is too complex, their range of application is too narrow, their shelf-life is too short, and some pose hazards to the environment.

2. Facility Recovery Directives

Shortly after the initial technical literature review was submitted, a summary of Air Force facility recovery directives was compiled (Reference 13). This was done to define a facility recovery concept of operations, as a basis for preparing the ERSF System Specification.

3. NCEER Translation

Recently the National Center for Earthquake Engineering Research (NCEER) at the State University of New York at Buffalo published a translation of the Japanese Public Works Research Institute Ministry of Construction's Manual for Repair Methods of Civil Engineering Structures Damaged by Earthquakes (Reference 14). Unfortunately for the present investigation, the report says little about structures. It deals with river, shore protection, and erosion control facilities; road facilities; and sewerage facilities.

4. Expedient Hardening

Expedient repair and expedient hardening are different, but closely related. As a study of two recent expedient hardening reports (References 15 and 16) shows, expedient hardened structures are usually separate from or appendages to the primary structure, and rarely carry any of the primary structure's dead or vertical live load. Nevertheless, Reference 16 in particular is so closely related to this report that it should be viewed as a companion report.

SECTION IV

DEVELOPMENT OF CANDIDATE ERSF SYSTEMS

A. OVERVIEW

The development and screening of ERSF systems to identify which systems would become serious candidates and undergo in-depth evaluation consisted of the following steps. First, screening criteria were developed to supplement those specified in the contract Statement of Work (SOW). This was accomplished by determining the current organization, capabilities, resources, personnel, and training at FOBs, which can support expedient repair of structural facilities. Using this information, limitations imposed on ERSF systems, with respect to such factors as complexity, equipment, personnel requirements, and training levels were determined. Based on these limitations, screening criteria were developed. Next, expediently repairable damage modes for mission-critical structural facilities were identified, and ERSF systems to repair the damage were developed. These systems were then screened for viability using developed and SOW specified criteria. If possible, systems were modified to overcome shortfalls identified during the screening process. Systems that appeared viable, based on this screening process, then became candidate ERSF systems.

Using evaluation matrices, candidate ERSF systems were evaluated in-depth as described in Section V. Based on these evaluations, ERSF systems for a particular damage mode were ranked in order of merit. Additionally, several of the ERSF systems were field-demonstrated. Those results are presented in Section VI.

B. CURRENT ERSF METHODS

1. Definition And Scope

Expedient facility repair is defined in AFR 93-2, <u>Contingency Response Planning</u>, as the least amount of immediate repair to damaged facilities necessary to accomplish the installation's primary mission. AFR 93-2 also states that RRR kits R-1, R-2, and R-3 are designed to accomplish the repair of 3, 6, and 12 airfield pavement craters, respectively, in 4 hours. The R-4 RRR kit is designed to accomplish the repair of 12 craters in the classified time specified by TAF SON 319-79, presumably no longer than 4 hours. Thus, it seems reasonable to assume that ERSF must be accomplished in 4 hours or less. Since the 4 hour requirement for RRR does not apply when repair personnel are wearing chemical warfare gear, and/or under adverse environmental conditions, it also seems reasonable to apply the same time criterion relaxation to ERSF.

Many ERSF methods are simple and straightforward, and require no research. For example, AFR 93-2 speaks of covering holes with plywood, and the PRIME BEEF Wartime Task Standard lists standards for patching a 40-square-foot roof hole with plywood and tar paper, patching a 40-square-foot hole in a building exterior wall with two-by-fours and plywood, replacing a damaged exterior personnel door, replacing a single pane of 20- by 24-inch window glass, replacing ten linear feet of chain link fencing fabric, replacing rollers on an entry control point gate, making and installing a warning/identification sign on an unsafe facility, and buttressing a 150 square foot hole in a wall with sandbags. Such repairs are not the primary interest of this report because they require no engineering. Most of them would not be considered by an SRC commander for accomplishment in the first 4 hours after an attack, because they would produce little if any increase in mission capability. However, several of the above-mentioned repairs, such as repairing a breached roof or exterior wall to seal a building, do have relevance to ERSF and will be discussed in this section. Additionally, shoring a damaged structure, which is mentioned in both the above documents, may be relevant to have mission capability, does require engineering, and is discussed in detail in this report.

Many BCEs have had to accomplish expedient facility repair, e.g., at Elmendorf AFB after the 1964 Good Friday Earthquake, in Vietnam, at Ramstein AB after a terrorist bombing, at Kelly AFB after a tornado, and at Charleston AFB after Hurricane Hugo.

2. Planning And Training

Because of the possibility of attack, as well as natural disasters, both HQ AFESC and the Air Force Institute of Technology (AFIT) conduct training in expedient facility repair. However, that training generally involves only light carpentry. Herein lies a significant problem: structural damage significant enough to cause serious mission capability degradation will usually require more than light carpentry even for expedient repair. But an overseas BCE's "blue-suit" workforce, which is all he can count on during wartime, rarely does more than light carpentry. This generates a serious training challenge, and therefore places a high premium on system simplicity.

AFR 93-2 directs each overseas BCE to do contingency response planning, and the BCE delegates that job to his Readiness function. They must devise procedures and determine the associated resources needed to cope with a wide variety of natural and manmade disasters. However, a facilities recovery annex is not required in the Base Contingency Response Plan (CRP), so the depth of facility recovery planning reflected in a CRP is generally not great. There are several reasons: first, the cost of resources required to support an adequate facility recovery plan, embracing all base mission-critical facilities, will be considerable; second, the BCE workforce may not be large enough to even exercise an adequate facility recovery plan; third, the BCE probably lacks the time and experience to write an in-depth facility recovery plan; and forth, the BCE probably thinks he cannot afford the training time required to become proficient in expedient facility repair. Here again, simplicity becomes of paramount importance.

Adequate preparation for postattack facility recovery requires a BCE to: make a detailed survey of all base mission-critical facilities; anticipate expediently repairable damage each might suffer; determine at least one expedient repair strategy/system for each damage mode; determine the resources and time required to utilize each system; order and stock the required resources (or have them stocked as War Readiness Material (WRM)); train a sufficient number of on-base military personnel to utilize all the systems; exercise all the systems; document the systems in the CRP; and enter the damage modes and expedient repair systems into POST-DAM, the personal computer-based postattack facility damage assessment program being developed by AFESC/RDCS.

C. ERSF SCREENING CRITERIA

It was not the intent of the effort reported herein to tell each BCE what expedient facility repair methods to use, and what resources to stock. Only the BCE can make those decisions, after completing the base-wide mission-critical facility survey described above. Rather, it was the intent of this effort to identify, investigate, evaluate, and recommend ERSF systems applicable to many if not all overseas airbases, under most environmental conditions, but which are beyond the BCE's capability to evaluate locally.

To screen ERSF systems for expediency, the definition of expedient repair given above was amplified as follows:

1. Expedient repair is first aid for damaged, mission-critical structures.

2. Expedient repair is useful only for light to moderate damage.

3. Expedient repair is accomplished only to recover mission capability, safeguard human life, or allow extraction of mission-critical resources from a damaged structure.

4. Facility damage assessment using POST-DAM will be accomplished within one half to 2 hours after each attack.

5. Expedient repair will be accomplished within 4 hours to four days after attack. The 4 day figure arises because, although any one expedient repair operation may take only 4 hours, the Survival/Recovery Center (SRC) commander may elect to defer some expedient repairs because of lack of resources or personnel.

The basic ERSF evaluation criteria specified in Task 2 of the SOW for this research effort are: strength, availability, environmental conditions, ease of use, shelf-life, and cost. As previously mentioned, Section V of this report is devoted entirely to evaluation of candidate ERSF systems, and so not much will be said about evaluation at this point. However, the act of screening possible ERSF systems to determine which should be evaluated in detail in Section V was itself an evaluation, albeit subjective, and so it is important to explain the criteria used for preliminary screening. The criteria are shown in Table 1, where they are grouped under three major headings: Operational, Structural, and Logistic. The screening criteria include all the subtask criteria listed above, and criteria given in the draft ERSF system specification (Reference 2). Additionally, the screening criteria reflect the capabilities and limitations imposed on ERSF systems at FOBs.

D. DAMAGE MODES AND ERSF SYSTEMS

1. Advanced Materials

When developing ERSF systems, advanced materials, such as polymer concretes and epoxy resins, were investigated. However, several factors opposed their use. First, and most important was shelf-life. During development of the RRR fiberglass mat crater repair system an effort was undertaken to identify an advanced material to repair damaged mats. During this effort, AFESC/YE determined the minimum material shelf-life that could be logistically supported at FOBs was 3 years. A comprehensive search was undertaken by AFESC/YE to identify advanced materials that met this requirement. During this search, it was discovered that no long-term storage data was available for advanced materials, because it was uneconomical for companies to store them for more than 3 to 6 months. Experts in the field also stated that unless the storage environment is carefully controlled, which is unlikely at a FOB, a shelf-life greater than 1 year is unlikely for advanced polymers, epoxies, and other such materials.

Another factor opposing the use of advanced materials is environmental constraint. In most cases, rain, extreme cold or heat, or poor surface conditions in the repair area will severely degrade the performance of advanced materials. These conclusions are documented in a letter technical review, Fast-Setting Concrete fpr Spall and Small Crater Repair, developed by AFESC/YE (Reference 17).

The final opposing factor is the chemically hazardous nature of many advanced materials, such as the polymer concrete (PERCOL) developed for runway crater repair by AFESC/RD as part of the RRR program. Due to logistic factors pertaining to the cleanup and disposal of PERCOL during training

TABLE 1. EXPEDIENT REPAIR SYSTEM SCREENING CRITERIA.

Operational	Structural
simplicity	strength
versatility	stiffness
speed	toughness
set time (pot life)	durability
number of components	protection
environmental limitations	airtightness
bulk	
weight	Logistic
special equipment	availability
skill requirements	peacetime use
training	storage life
manpower	cost
safety	reliability
environmental reaction	maintainability
no hazardous waste	

activities at FOBs, and storage shelf-life considerations, PERCOL was not fielded, even though its operational and structural performance was good. During wartime, the hazardous nature of a material might not be a major factor, but during normal routine peacetime training, it would.

2. Steel Structures

In this report, discussions of structural damage modes and candidate ERSF systems emphasize repair of reinforced concrete structures. This is because the majority of mission-critical buildings at FOBs are of this type, as indicated by review of engineering drawings of mission-critical structures at Bitburg AB, FRG. Still, the majority of candidate ERSF systems can be used to repair steel framed structures. However, a large number of expedient repairs to a steel framed structure can be accomplished simply by cutting and welding. This type of repair would, in most cases, be chosen for steel framed structures, and will be the one evaluated in Section V.

3. Identified Structural Damage Modes And Candidate ERSF Systems

Identified structural damage modes and associated candidate ERSF systems are described below for particular structural members. These are the damage modes considered most likely for mission-critical structures, and which lend themselves to expedient repair. Portions of headings within parentheses indicated the general type of repair for the indicated damage mode.

a. Destroyed Reinforced Concrete Column (Column Replacement)

In this damage mode, a reinforced concrete column is damaged by blast and/or fragments, to the extent that it can no longer support its design load and must be replaced. An example of such a damaged column is shown in Figure 1. Candidate column replacement ERSF systems are described below.

Figure 1. Example of a Destroyed Column.

(1) Glulam Column

Figures 2 through 5 show a method for replacing a badly damaged reinforced concrete column. After clearing away debris and other interfering, non-load-bearing structural material from around the column, a shoring jack is placed beside the damaged column, then extended until its capacity is reached or repair personnel can no longer extend it, whichever occurs first. Then a glued, laminated timber (glulam) column, trimmed to the correct length, is positioned and wedged next to the jack. A 10-foot long, 12-inch square glulam column should provide sufficient capacity, while still being relatively easy to handle. The capacity of such a column is discussed in Section VI. The glulam column is braced laterally with lumber for stability, and the jack removed to be reused elsewhere, leaving the glulam column to carry the vertical load.

Figure 6 shows the simple engineering calculations performed to calculate the load transfer from jack to replacement column.

(2) Shoring Jack

Another possible column replacement repair method uses only a shoring jack, such as the one shown in Figure 7. Instead of replacing the jack with a glulam column as described above, the jack is left in place and braced laterally with lumber or steel members. The jack must be modified by attaching an angle iron with predrilled holes or nailing blocks, to allow bracing members to be attached to it. Both a glulam column and a shoring jack cost approximately 300 dollars, so the screw jack by itself is attractive, because the column replacement process involves one less step than using a glulam column. However, a glulam column requires little or no care during long-term storage, and is easier to brace laterally by simply nailing bracing lumber to it. These issues are addressed in Section V.

A glulam column replacement ERSF system was field-demonstrated during this project, and results are presented in Section VI.

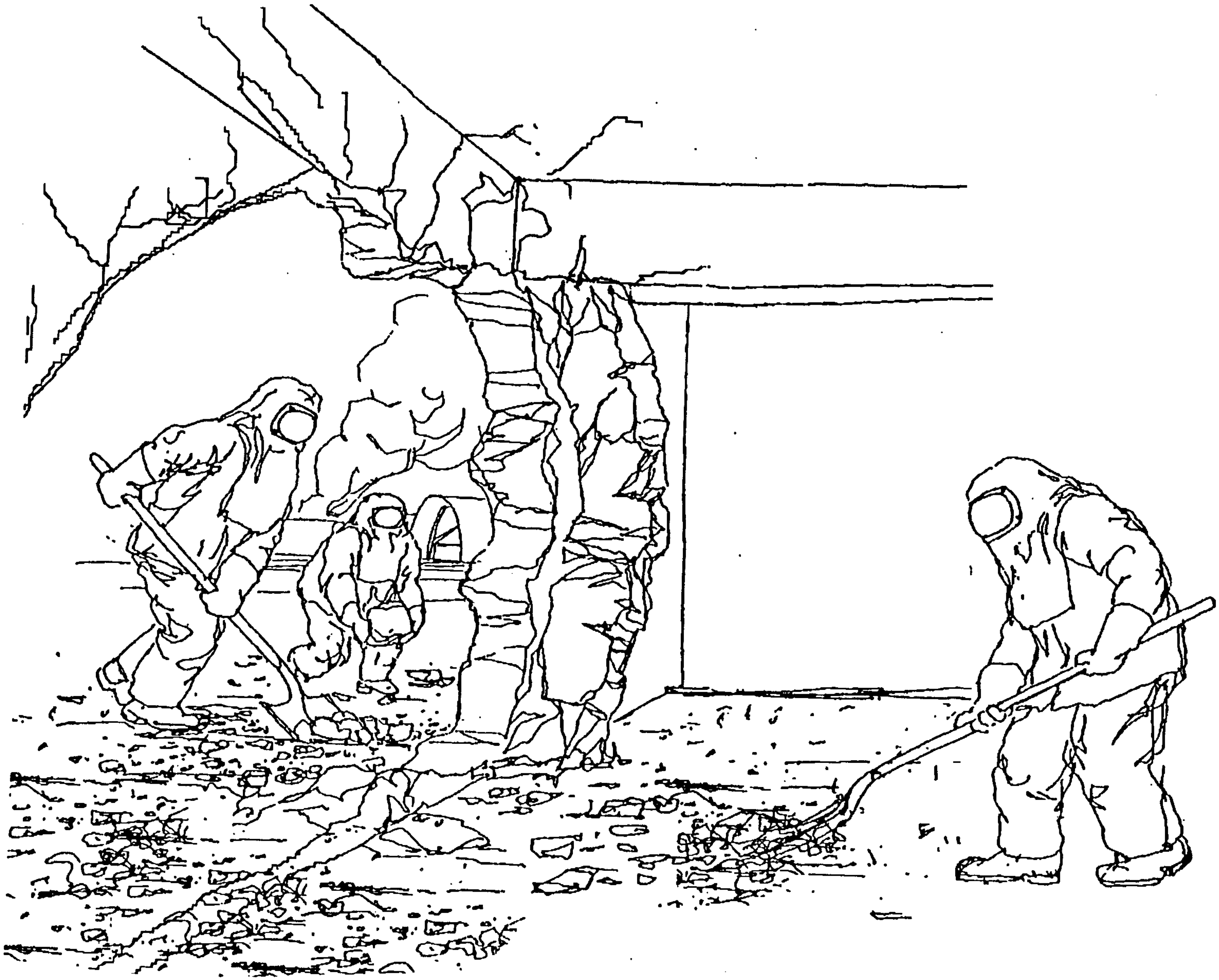


Figure 2. Debris Clearance During Column Replacement.

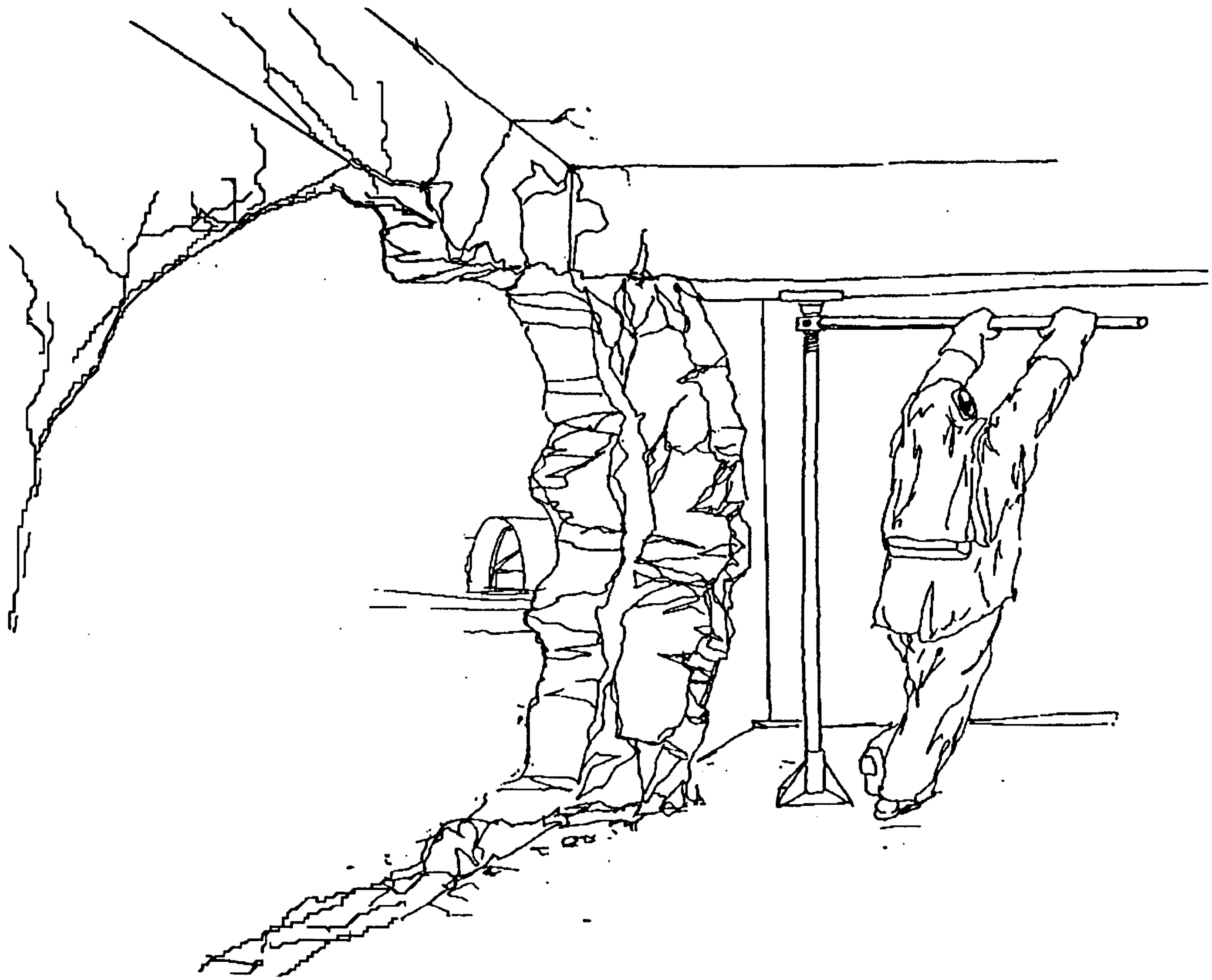


Figure 3. Jacking During Column Replacement.

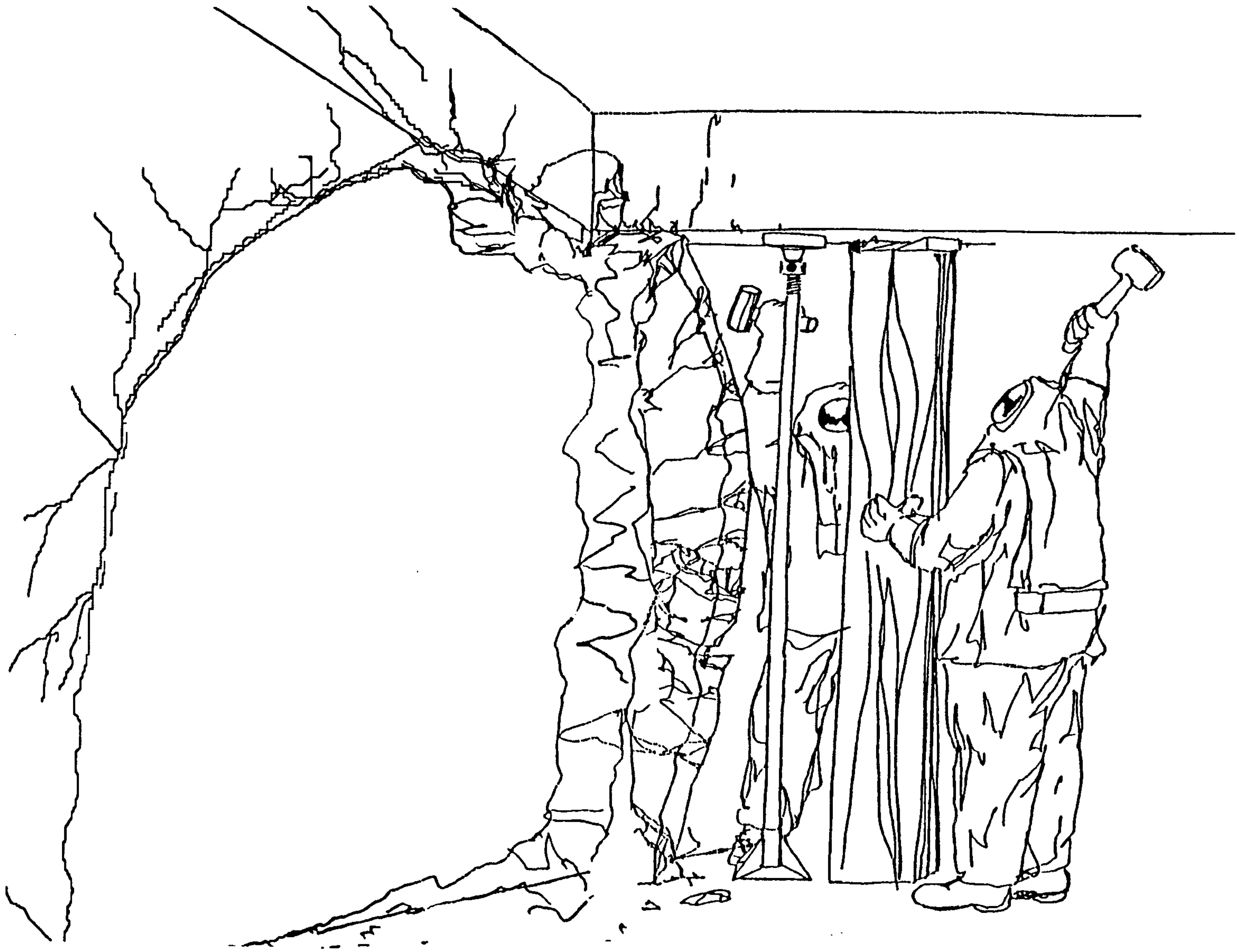


Figure 4. Column Insertion During Column Replacement.

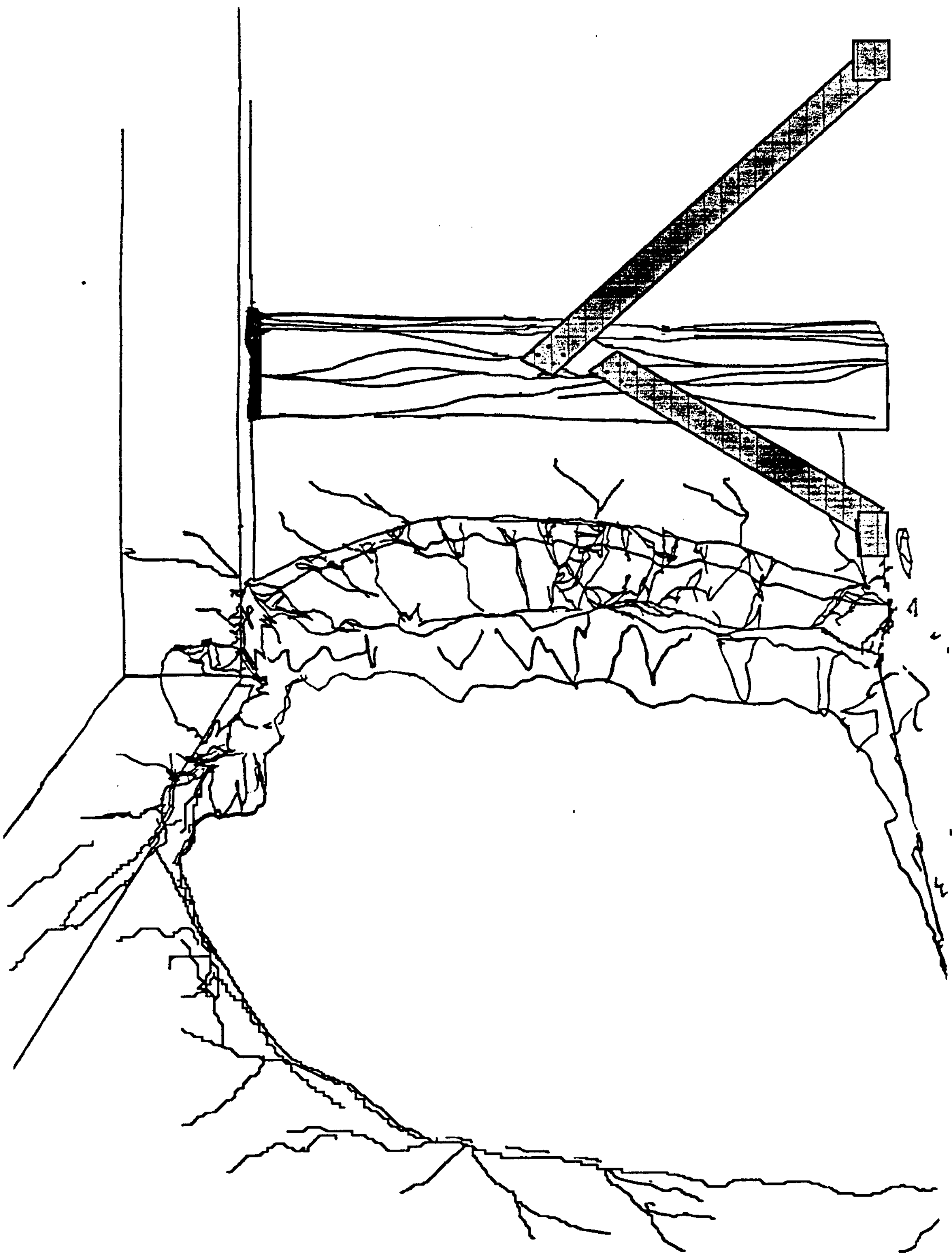


Figure 5. Completed Column Replacement.

GIVEN:

K_s = structural stiffness at the damaged column location, without the damaged column

K_c = axial stiffness of the replacement column

P = load to be supported by the replacement column to prevent progressive collapse, determined by prior structural analysis

REQUIRED:

$\triangle_1$, the structural displacement to be enforced by the shoring jack, so the final load on the replacement column will be P

SOLUTION:

First, the structure is jacked up by an amount $\triangle_1$, resulting in a peak jacking load of

$$F_{MAX} = K_s \triangle_1 \tag{1}$$

Then a replacement column is placed alongside the jack, wedged and braced, and the jack released. Release of the jack causes the structure to settle by an amount $\triangle_2$, decreasing the upward force on the structure and increasing the replacement column force until the two balance. The final force balance equation is:

$$K_s (\triangle_1 - \triangle_2) = K_c \triangle_2 = P \tag{2}$$

The force-displacement diagram shown below illustrates the same balance.

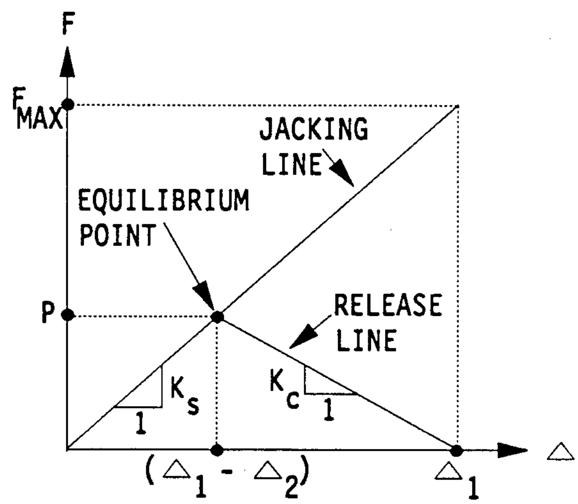


Figure 6. Column Replacement Calculation.

SOLUTION (CONCLUDED):

From the force-displacement diagram or the force balance equation, it is apparent that

$$\triangle_1 = P \left[\frac{1}{K_s} + \frac{1}{K_c} \right] \tag{3}$$

so that Equation (1) yields

$$F_{MAX} = P \left[1 + \frac{K_s}{K_c} \right] \tag{4}$$

The above calculations would be done during preattack expedient repair planning, and the results stored in the POST-DAM expert system database.

Figure 6. Column Replacement Calculation (Concluded).

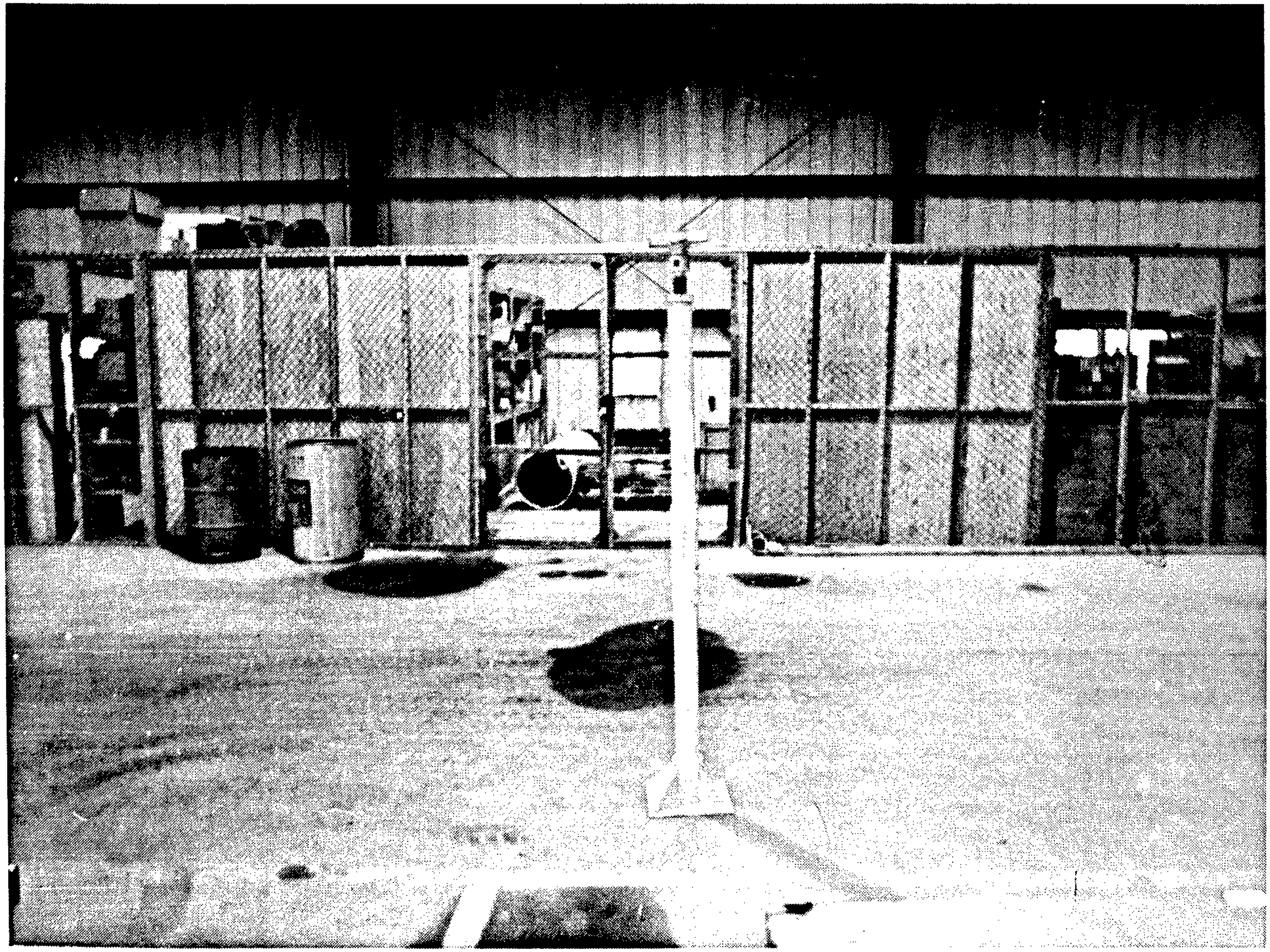


Figure 7. Mechanical (Screw) Shoring Jack.

b. Cracked Reinforced Concrete Column (Column Splint)

In this damage mode, a reinforced concrete column is cracked, but still capable of carrying a load. However, because of the crack it is necessary to laterally constrain the column at the location of the crack(s) to prevent slippage. An example of this damage mode is shown in Figure 8.

Figure 9 shows a method for splinting a fractured reinforced concrete column. First, if required, the surface of the column around the crack(s) is cleaned to proved a smooth working surface. Next, a splint is placed around the column with the middle of the splint flanking the centroid of the crack(s). If required, two-by-fours can be used to prop up the splint while it is being placed around the crack(s). Finally, the nuts of the splint are tightened to clamp the splint against the surface of the column. The splint resists slipping of the two column sections along the crack by its additional stiffness and the strength over and above that used to mobilize the clamping force. The clamping force merely holds the splint in place.

Figure 10 shows how the maximum force in the threaded rods or chains can be quickly determined, when the column load P is known. Such a column splint is simple to use, easy to install, and consists of simple, easily obtained, durable construction materials.

A column splint ERSF system was field demonstrated during this project, and results are presented in Section VI, including a prototype splint design and recommended improvements.

c. Damaged Concrete Girder/Beam (Vertical Shore or King Post)

In this damage mode, a reinforced concrete girder/beam is fractured, but still capable of carrying a reduced load. An example of this damage mode is shown in Figure 11. The beam's load-carrying ability can be increased by using a vertical shore, similar to a column replacement repair, or by the king post device shown in Figure 12. The disadvantages of the king post are the high tensile forces in the rods (essentially the bottom chords of a simple truss), and the difficulty in securely anchoring the rods at both ends of the damaged beam. However, when other structural damage precludes using a vertical shore, a king post may be the only alternative.

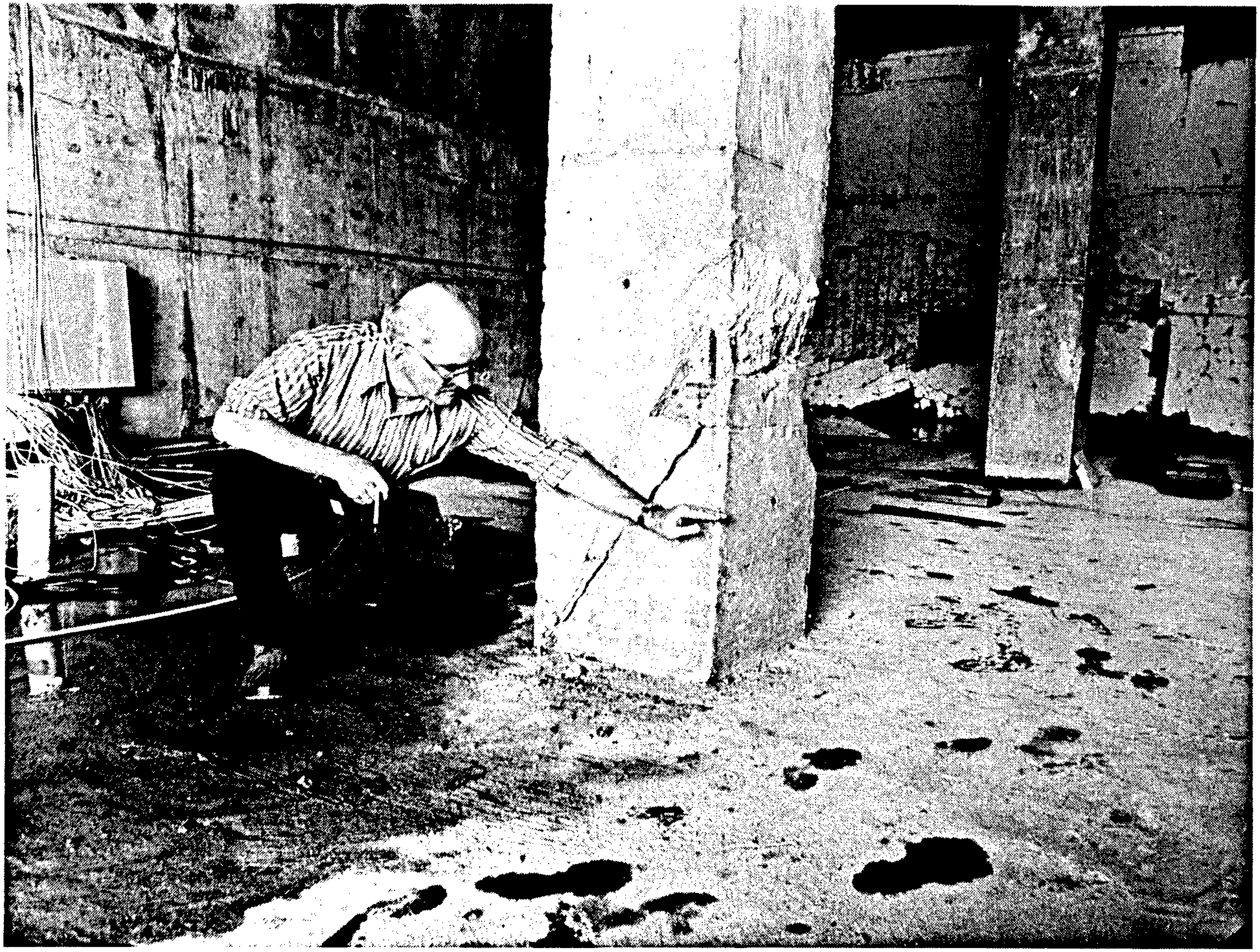


Figure 8. Cracked Concrete Column.

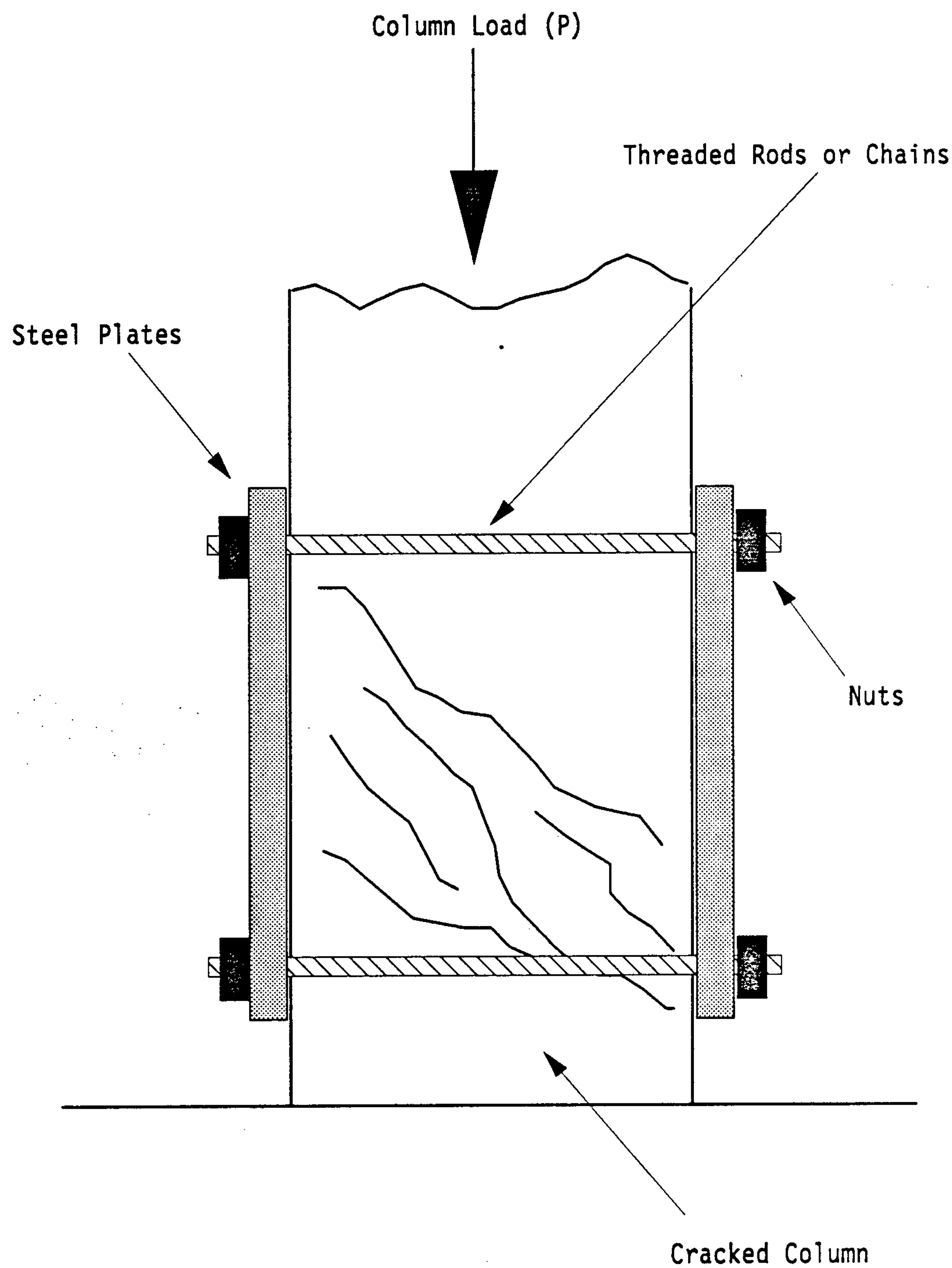


Figure 9. Splinting a Cracked Reinforced Concrete Column.

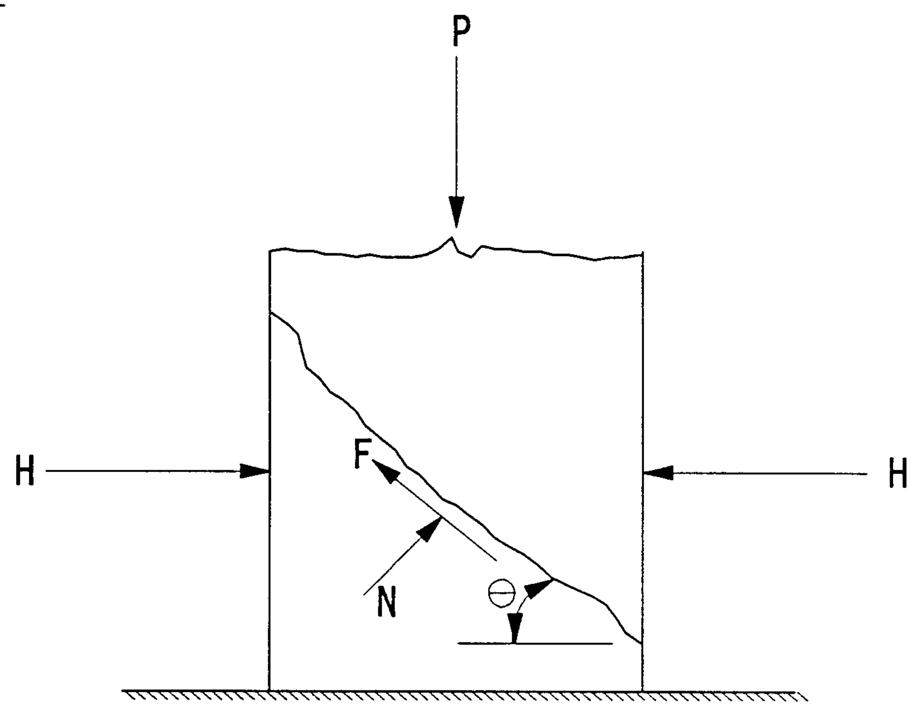
GIVEN:

A fractured reinforced concrete column carries an axial load P. The fracture makes an angle θ with the horizontal, and the angle of friction for the fracture surface is ϕ .

REQUIRED:

Determine the horizontal splinting force, H, required to stabilize the column

SOLUTION:



The quickest solution is graphical. Let:

P = column axial load

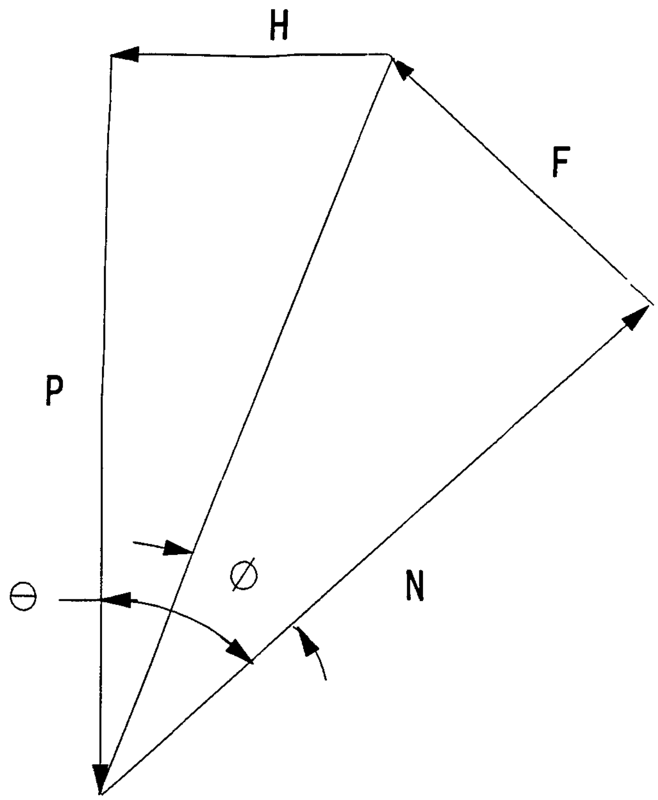
N = normal force acting across fracture surface

F = friction force acting along the fracture surface

H = externally applied horizontal force to stabilize the column

Figure 10. Column Splinting Calculation.

Since the four forces are in equilibrium, they must form a closed vector polygon,



from which the magnitude of the horizontal splinting force, H, can quickly be determined. The equation for the horizontal force is

$$H = P \tan(\ominus - \emptyset) \qquad (5)$$

Figure 10. Column Splinting Calculation (Concluded).

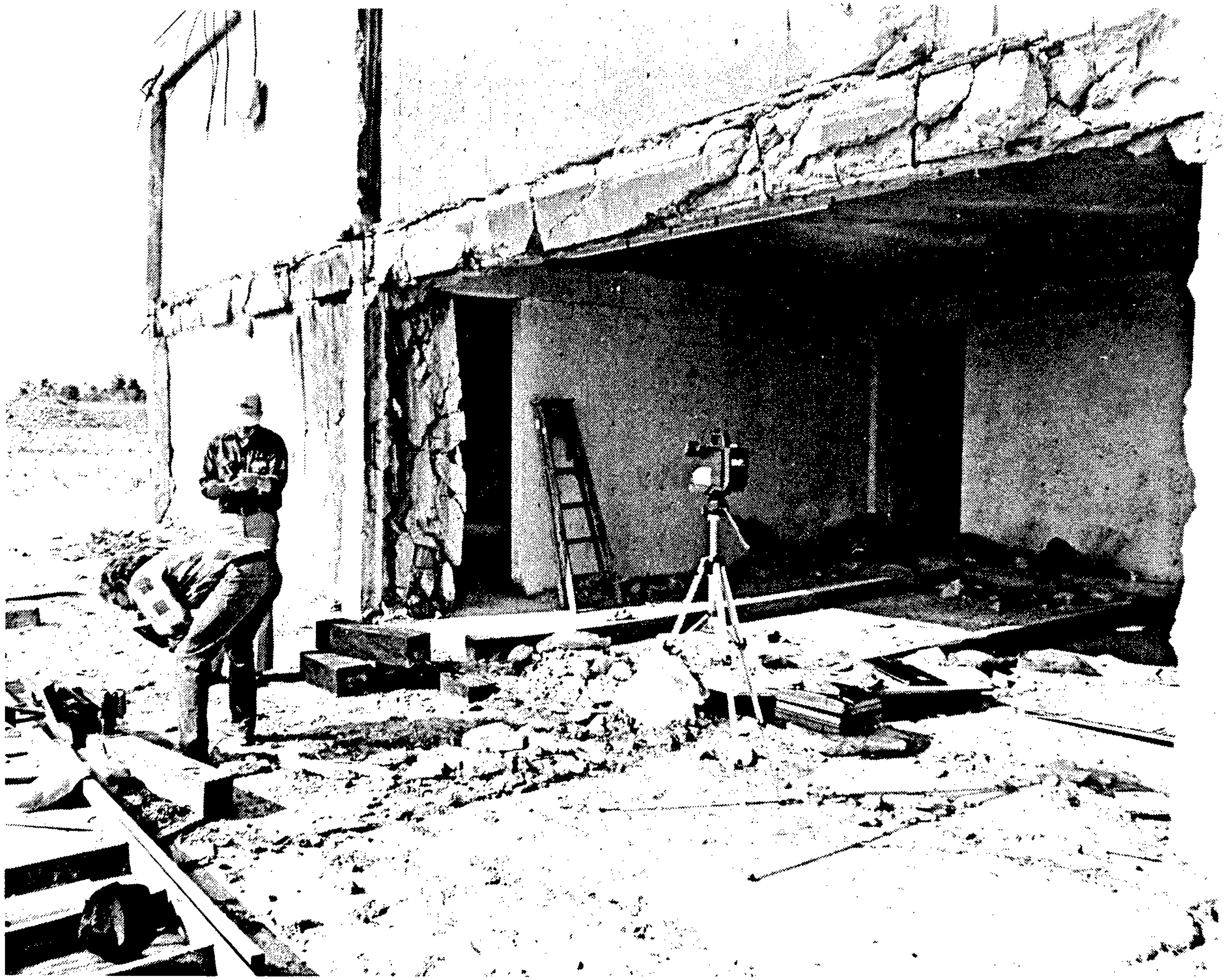


Figure 11. Damaged Reinforced Concrete Beam/Girder.

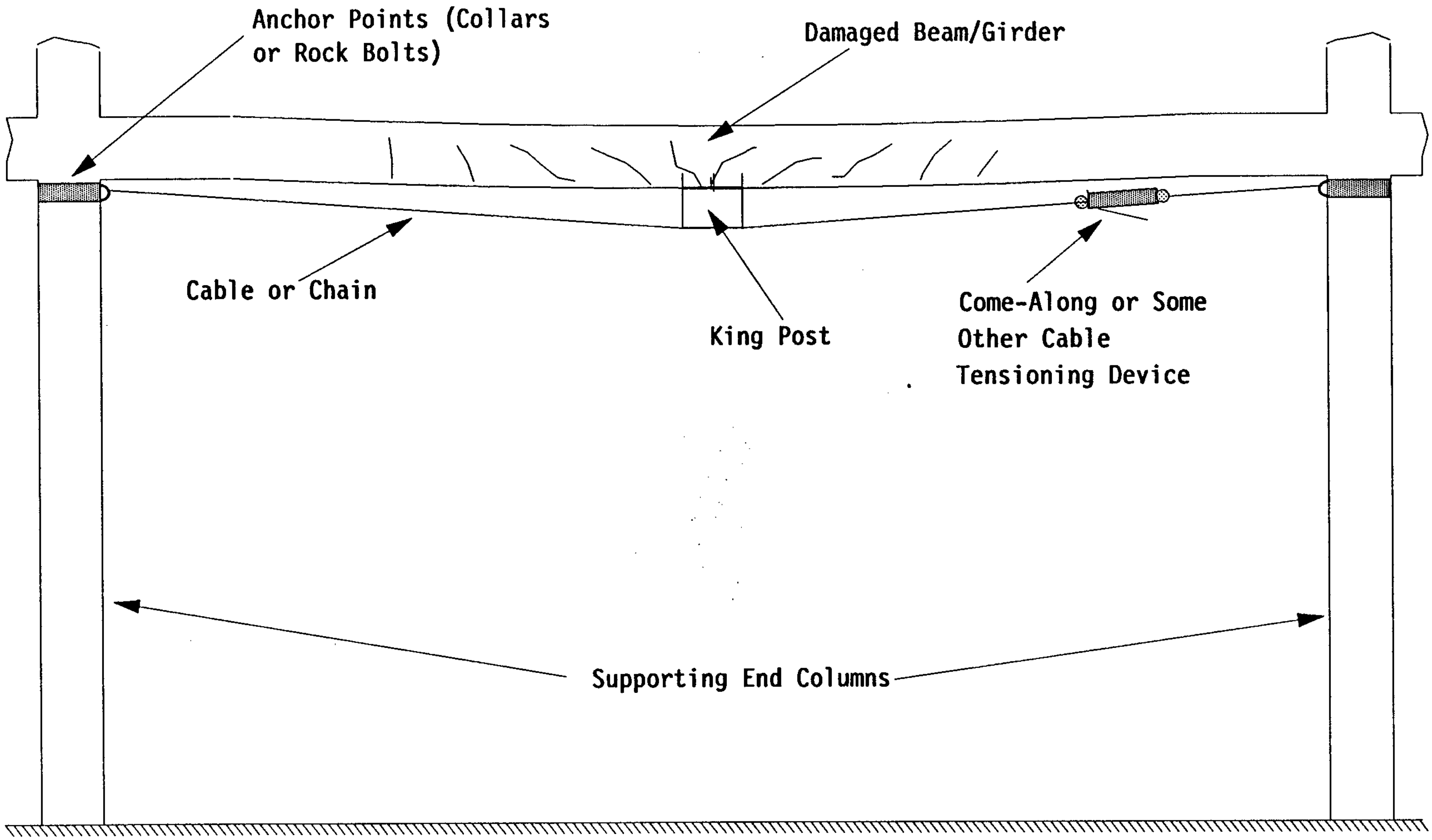


Figure 12. Shoring Badly Damaged Reinforced Concrete Beam with a King Post.

A king post uses steel cables or chains, attached to steel collars around the columns at the ends of the damaged beam, or to anchor bolts embedded in the columns. A come-along, threaded bolts, or cargo snap tie-downs are used to tension the cables/chains, with the vertical component of the cable tension acting through the king post to provide an uplifting force to the damaged beam, thereby forcing the beam back toward its original position. Further, the unused tensile capacity of the king post provides additional structural strength to the beam/girder in case further damage occurs. If collars are used to anchor the cables to the columns, they should be locked into position with bracing timbers or ramset studs, to prevent slippage. If the collars slip, tension in the cables will be reduced. Figure 13 shows how to compute the relation between cable shortening and upward displacement of the damaged beam.

d. Destroyed Reinforced Concrete Wall (Wall Replacement)

In this damage mode, a non-load-bearing, reinforced concrete or masonry block wall has been completely destroyed, with only minimal portions of the wall remaining attached to the surrounding columns and floor or roof beams. An example of such a wall is shown in Figure 14. Candidate expedient repair methods for such a damage mode are described below.

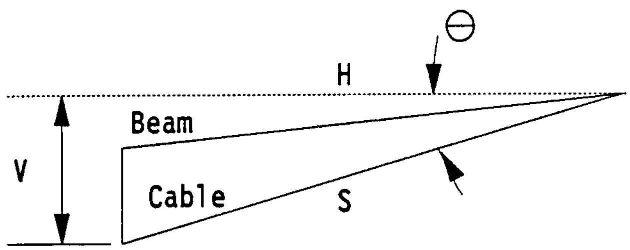
(1) Shotcrete

In this repair, a rapid-setting, high-strength, steel-fiber-reinforced, dry-mixed shotcrete material developed by AFESC/RD's materials branch (AFESC/RDCM) is used to replace the destroyed wall as shown in concept in Figures 15 through 17. Development of this material is described in Reference 18. A general discussion of shotcrete, including expedient repair concepts with the material, are given in Reference 19.

First, loose debris and interfering rebar are removed from the repair area, and backing, such as plywood, is placed behind the repair area. The backing can be secured with bracing or ramset studs. If the shotcrete mix does not contain reinforcing fibers, then conventional steel reinforcing bars will be needed. In this case, the reinforcement should be secured by tying it to existing rebar when possible, or grouting it in holes

GIVEN:

The king post method is to be used to reverse the sag of a badly damaged reinforced concrete column.



REQUIRED:

Calculate the upward beam deflection, ΔV , caused by a shortening of the cable, ΔS . Assume the change in length of the king post to be negligible.

SOLUTION:

The Pythagorean Theorem yields

$$V^2 = S^2 - H^2 \tag{6}$$

so that

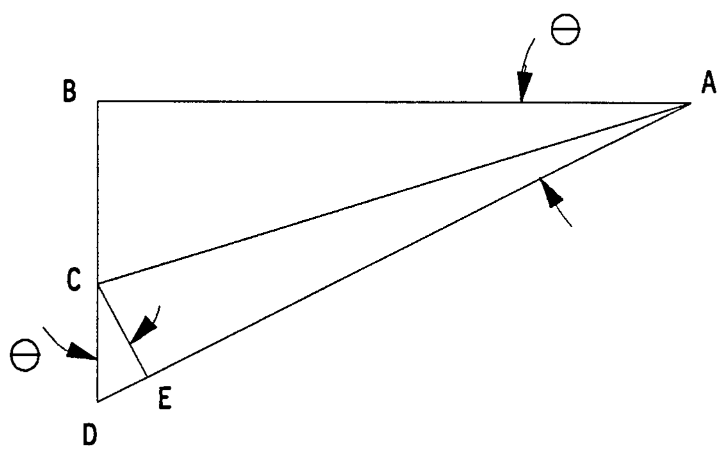
$$2VdV = 2SdS$$

and therefore

$$\frac{dV}{dS} = \frac{S}{V} = \frac{1}{\sin\Theta} \tag{7}$$

Figure 13. Beam Shoring (King Post) Calculation.

The same relationship can be shown graphically.



$$\frac{CD}{DE} = \frac{AD}{BD} = \frac{1}{\sin \Theta} \qquad (8)$$

If

P = compressive force in the king post

T = tension in the cable

then vertical equilibrium of the king post requires that

$$2T \sin \Theta = P \qquad (9)$$

so that

$$T = \frac{P}{2 \sin \Theta} \qquad (10)$$

Therefore, the smaller the angle Θ, the greater the ratio dV/dS. However, the cable tension, T, also increases as the angle Θ decreases.

Figure 13. Beam Shoring (King Post) Calculation (Concluded).

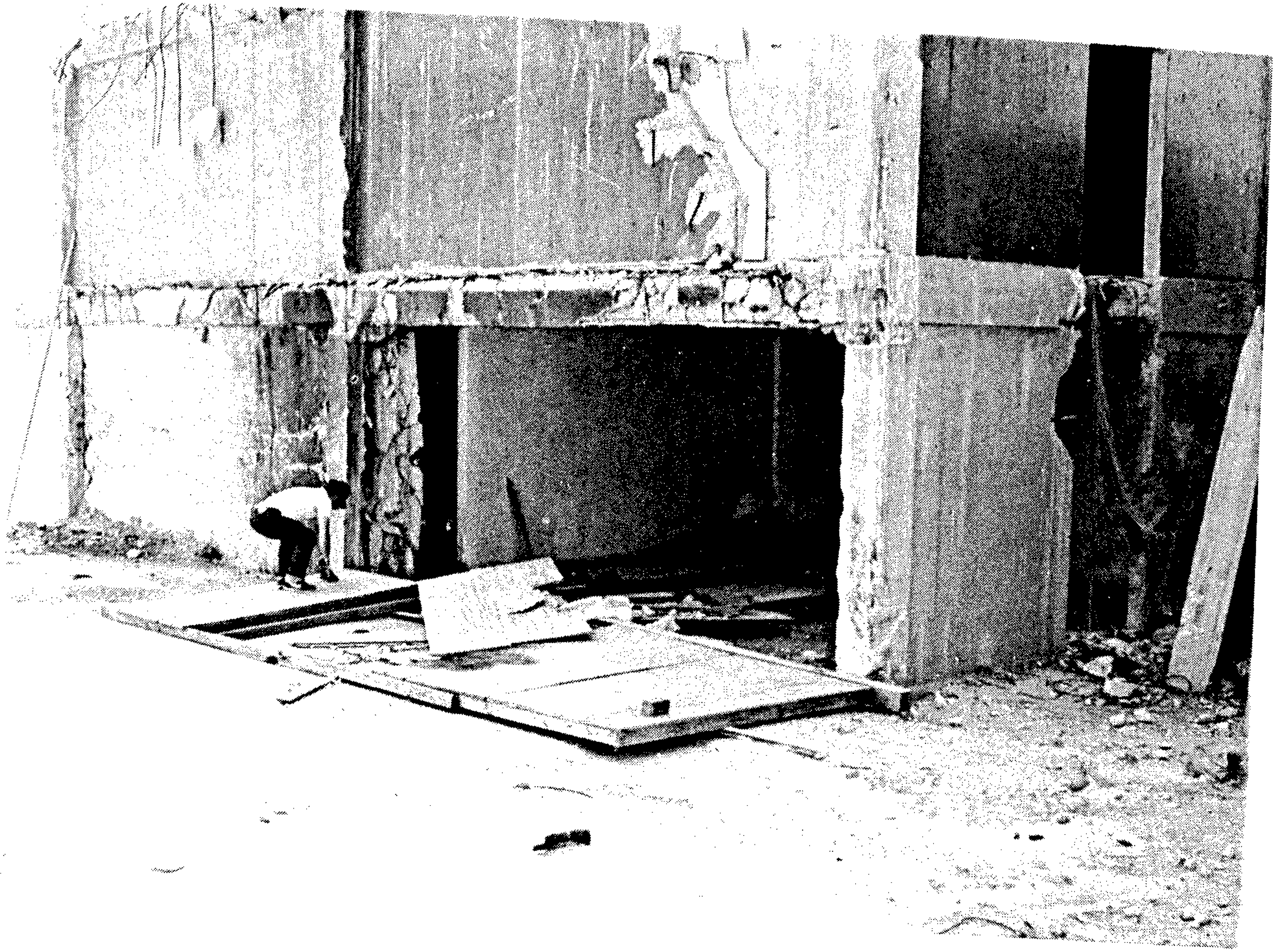


Figure 14. Destroyed Reinforced Concrete Wall.

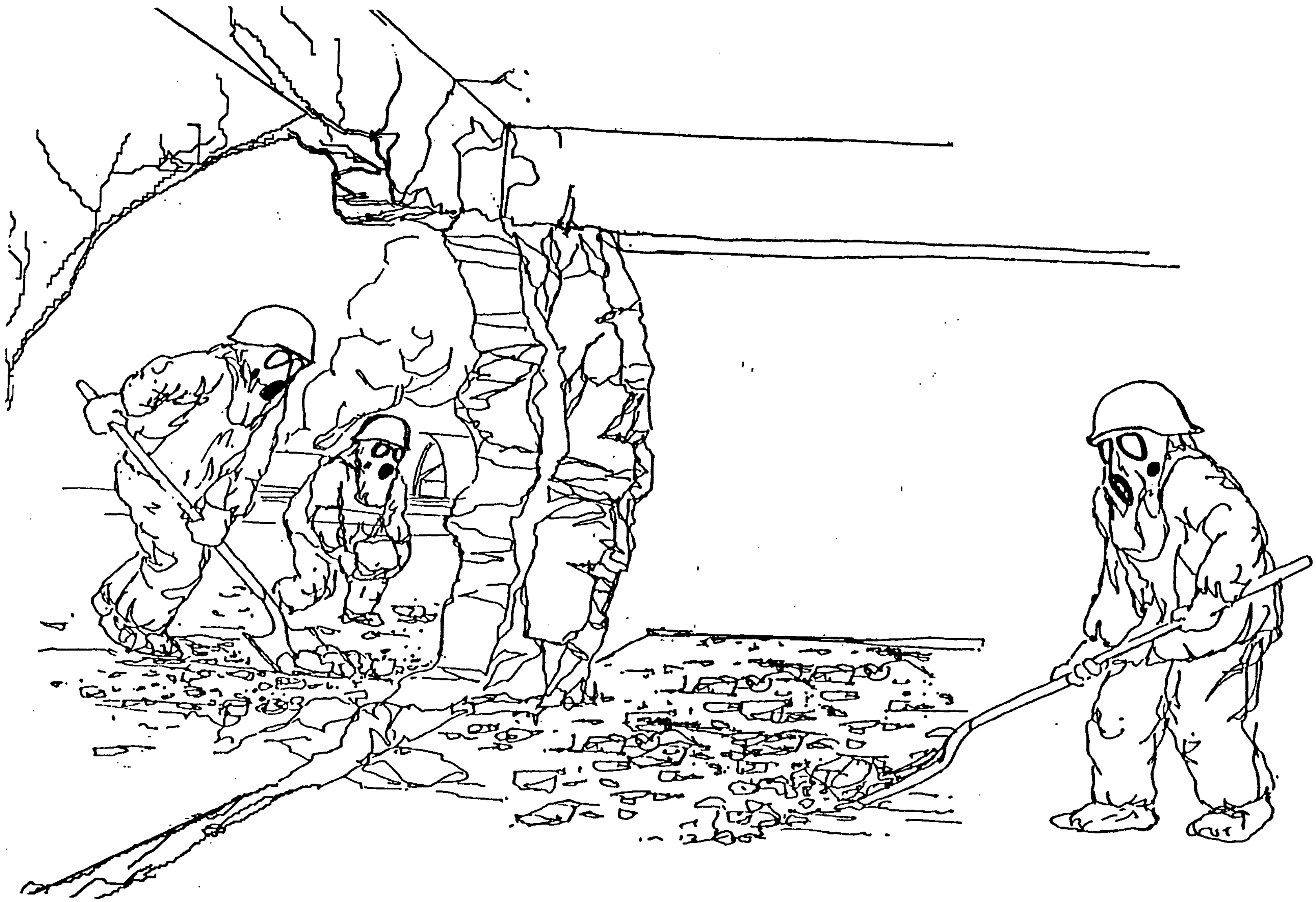


Figure 15. Debris Clearance During Shotcrete Wall Replacement.

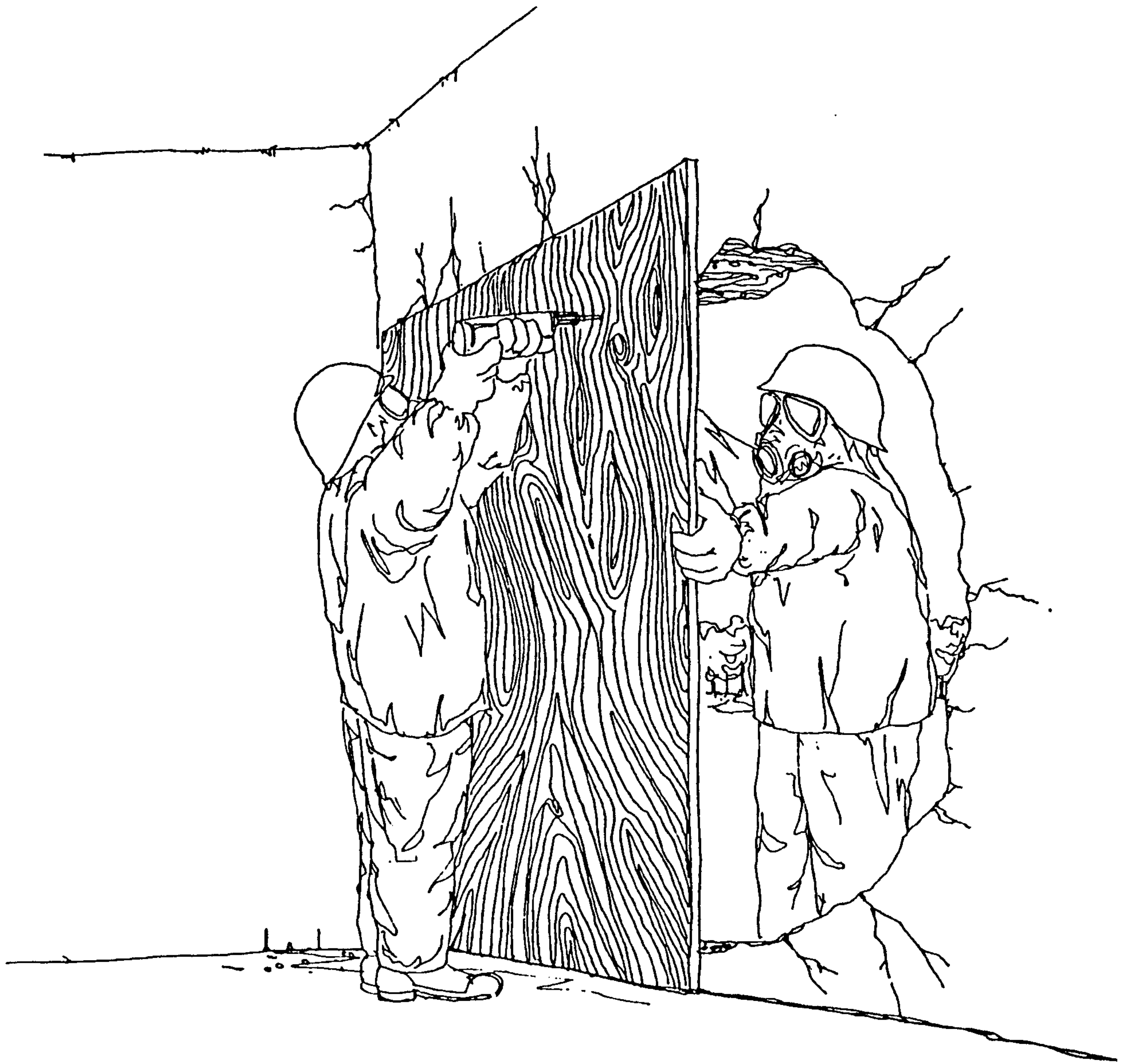


Figure 16. Backing Damaged Area During Shotcrete Wall Replacement.

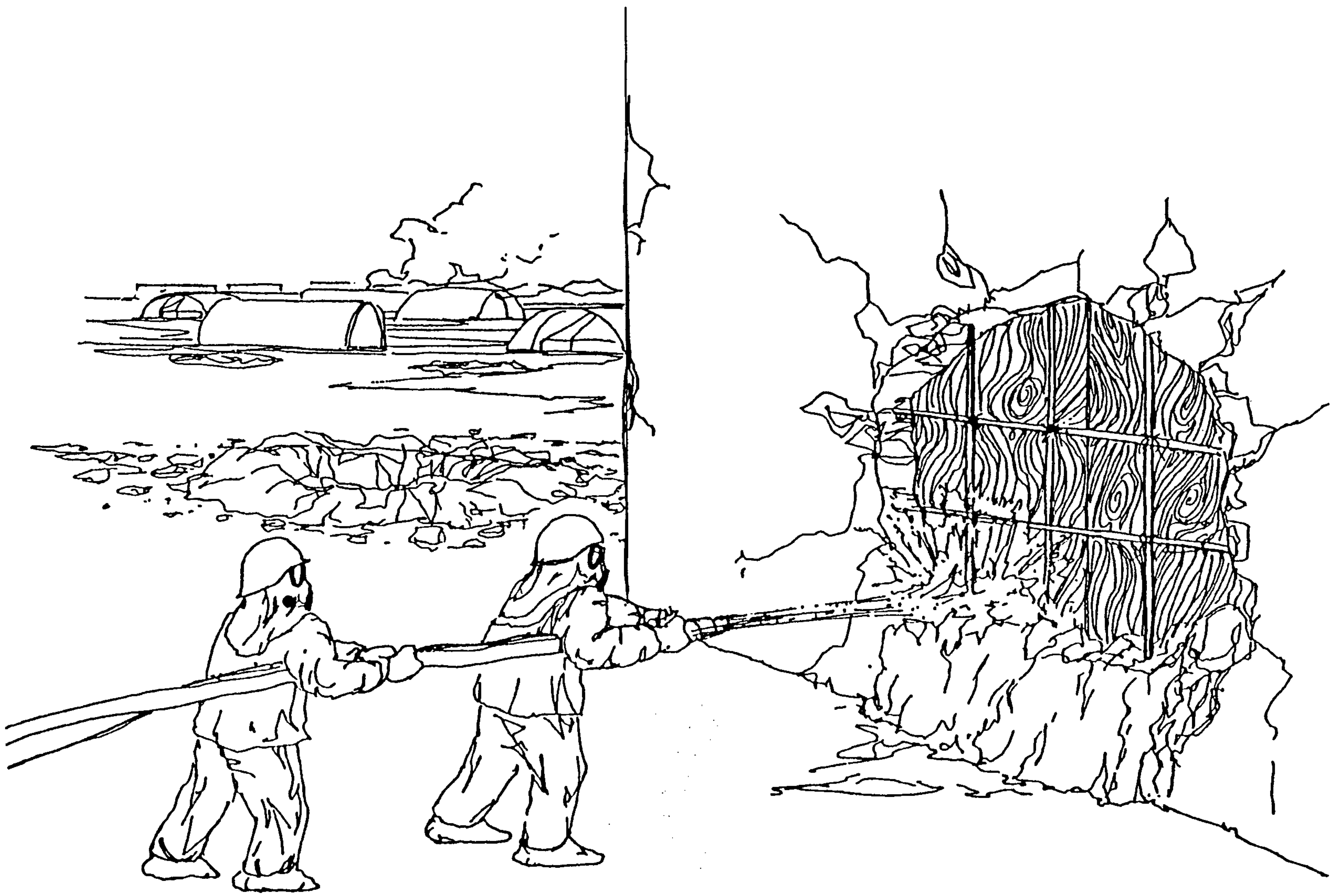


Figure 17. Shotcreting Damaged Area With Rebar In Place (Optional) During Wall Replacement.

drilled into the surrounding concrete. The shotcrete material is sprayed onto the backing, and the spraying continued until the desired thickness is built up. Expect considerable rebound (see Section VI-E.2). Because the material sets up so quickly, the backing can be removed as soon as the spraying is finished. However, to save time, the backing can be left in place if there is no reason to remove it. The material reaches a compressive strength of over 4,000 psi within 1 hour. The design strength of ERSF concretes is 3,000 psi within 1 hour. The resulting repair is airtight, and provides considerable blast and fragment penetration resistance. With the appropriate equipment, as illustrated in Figure 18, the shotcrete repair method can be used on the upper stories of a building and other hard to access locations. The primary disadvantage of this repair method is the specialized equipment it requires, and its complexity.

(2) Earth Berm

In this repair, which is only applicable to ground floor exterior walls, an earth berm is used to protect a wall opening against blast and shrapnel. Prior to forming the berm, a repair material such as plywood, plastic sheeting, or masonry blocks should be used to cover the opening. Plywood can be secured behind the opening with ramset studs or bracing lumber. Precast concrete slabs are then leaned against the outside of the building, to protect the opening and serve as a retaining wall for the berm. Nearby soil, or other appropriate material is then piled up against the tilted-up slabs, using a front-end loader. An earth berm repair is illustrated in Figure 19. The resulting repair should be reasonably airtight and provide blast and fragment penetration resistance.

(3) Masonry Blocks Only

In this repair, only masonry blocks are used to repair a damaged wall, without the earth berm (see Figure 20). Blocks are laid in a lattice pattern and bonded together with a rapid setting cement mortar. While this type of repair method could be used on upper story walls, it is more suitable for ground floor walls, because of the ease of laying the blocks against the outside face of the damaged wall. Upper floor repairs would

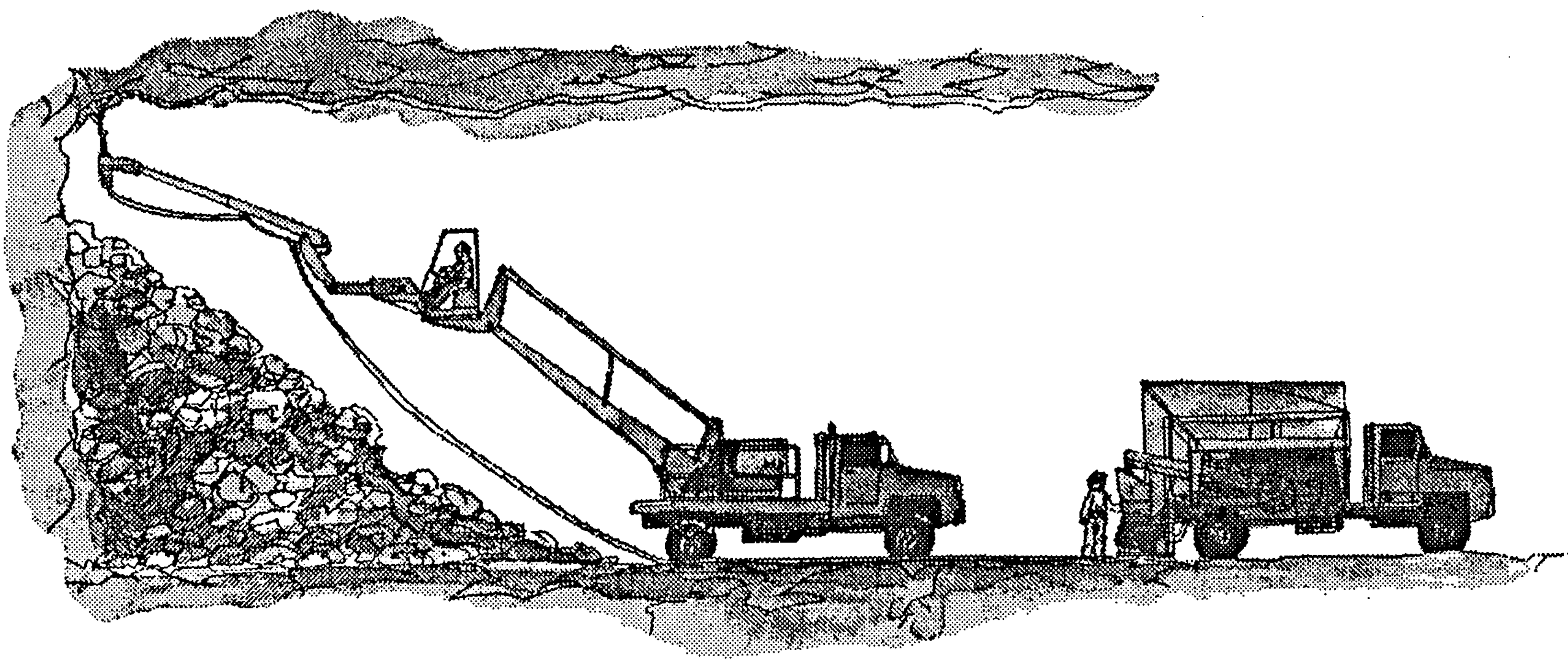


Figure 18. Candidate Shotcrete Equipment for ERSF (Trixer and the Mini-Robot, Manufactured by Stabilator).

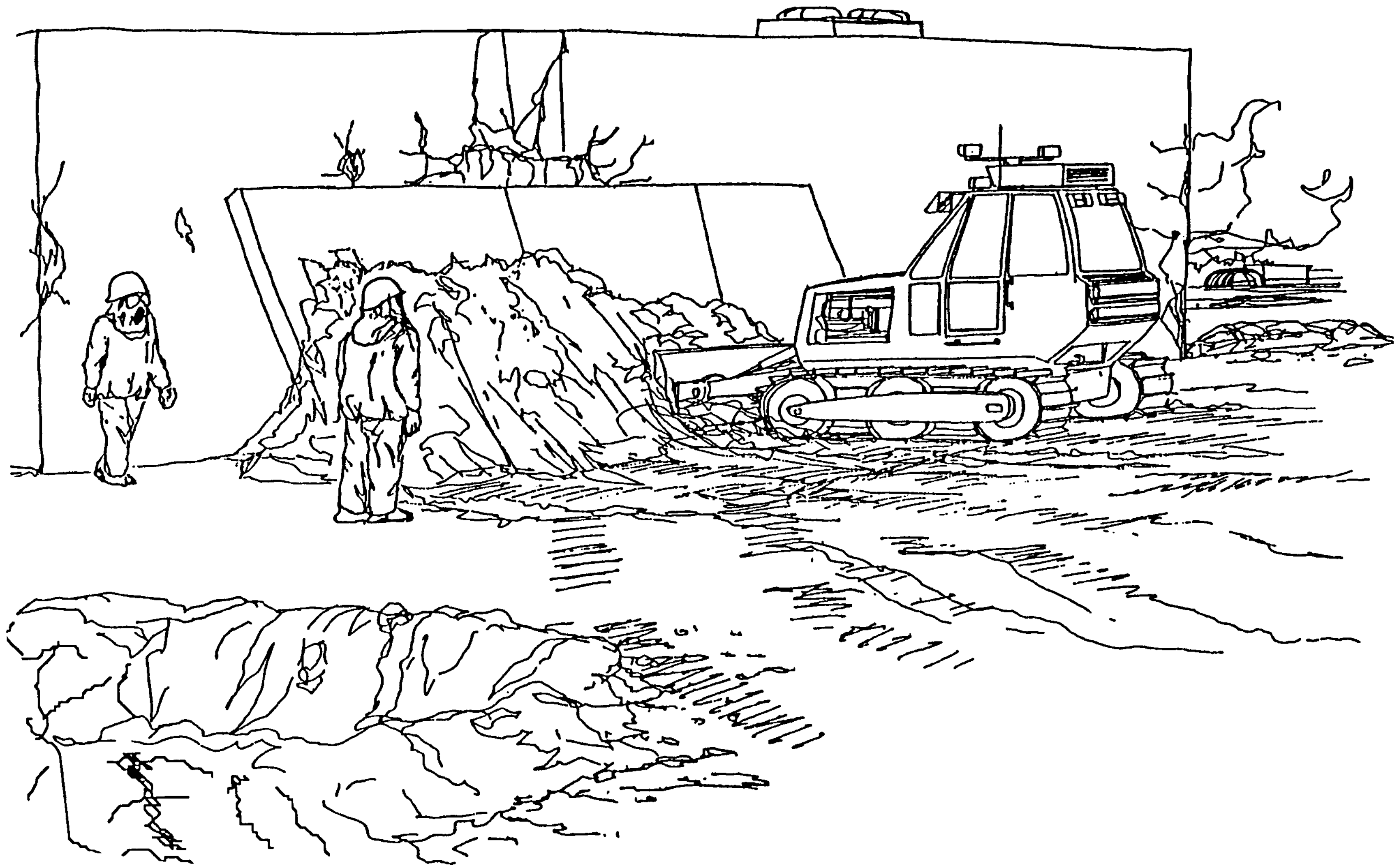


Figure 19. Earth Berm Wall Replacement Repair.

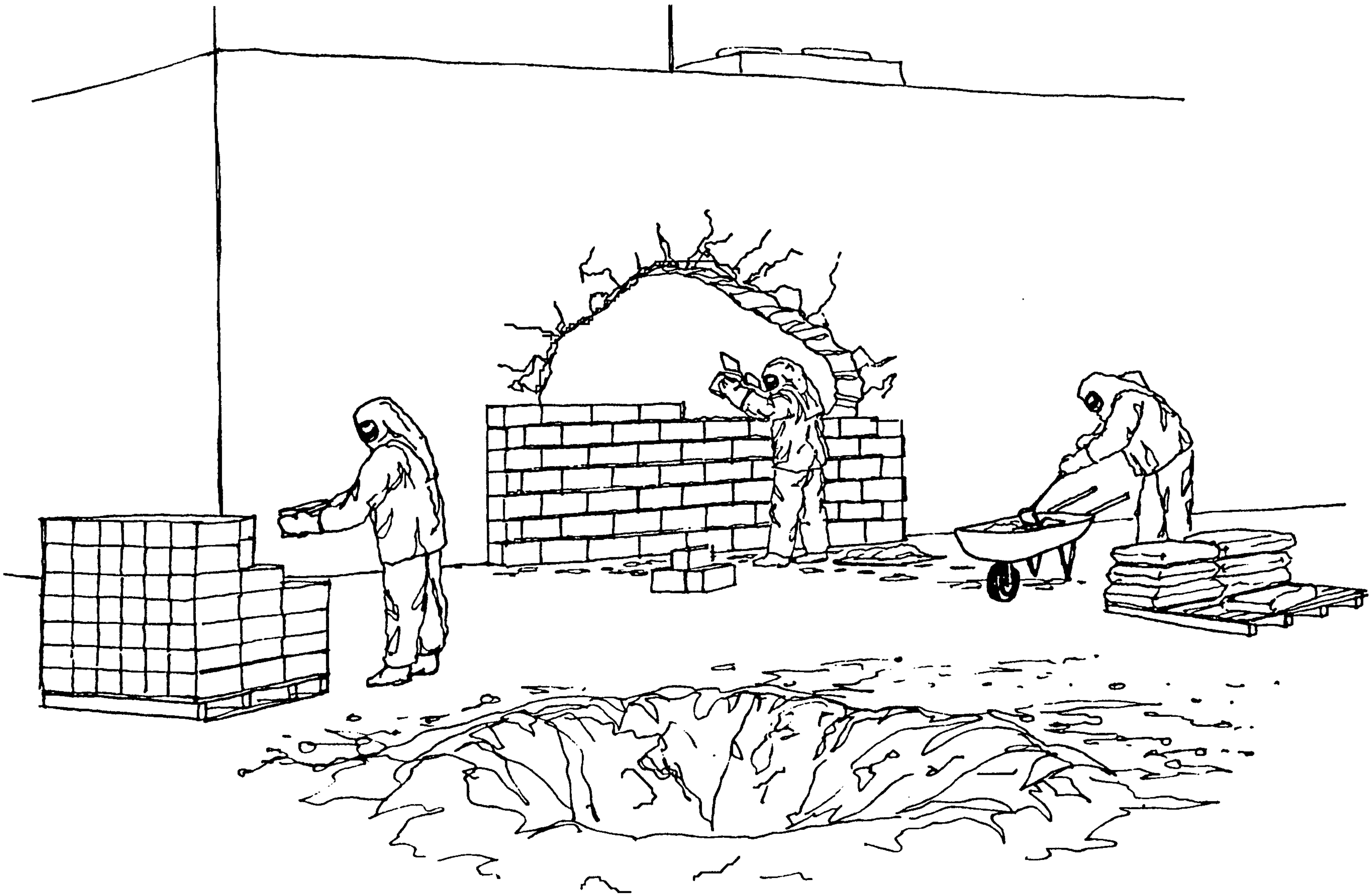


Figure 20. Masonry Block Wall Replacement Repair.

require the blocks to be laid against the inside face of the damaged wall, which would limit the blast resistance of the repair unless the blocks were somehow tied into the existing structure. Tying into the existing structure would complicate the repair procedure and increase repair time. When the blocks are laid against the outside face of the damaged wall, as they can be on the ground floor, they can be extended beyond the boundary of the damaged area to mobilized blast resistance. If done correctly, a masonry block wall repair is airtight and provides moderate blast and fragment penetration resistance.

(4) Concrete Slabs Only

In this repair, precast reinforced concrete slabs, such as used to repair runway craters in USAFE, are used to protect a damaged wall, without the earth berm cover. The slabs are simply leaned against the outside of the building to cover the opening, using a front-end loader with the boom attachment especially designed to lift and move the slabs. This boom attachment is available at FOBs in USAFE. This type of repair is only suitable for ground floor, exterior walls. Tying into the existing structure would be very difficult and time consuming and should not be attempted. This type of repair is not airtight, but provides good fragment penetration resistance and moderate blast resistance.

(5) Plywood Only

In this repair, plywood and two-by-fours are used to cover a hole in an exterior wall. Plywood sections are joined together with two-by-fours, nails, nuts, and bolts until a section large enough to cover the hole is obtained. Plywood is trimmed as needed with a saw. If possible, the plywood section should overlap the hole by 6 inches all around. In the overlap area, ramset studs are used to attach the plywood section to whichever face of the damaged wall is most convenient. A plywood repair is suitable for all building stories and wall materials. This type of repair is not airtight, and provides no fragment protection or blast resistance, but does prevent rain and dust from entering the building.

e. Reinforced Concrete or Masonry Wall Breach (Breach Repair)

In this damage mode, a non-load-bearing reinforced concrete or masonry wall has been breached, but with a significant portion of the wall remaining attached to the surrounding columns, beams, and girders. Candidate expedient repair methods for such a damage mode are basically the same as described for wall replacement. They follow the same procedures, and possess the same advantages and disadvantages.

f. Reinforced Concrete Floor/Roof Breach (Floor/Roof Repair)

In this damage mode, a reinforced concrete floor/roof is breached, but with a significant portion of the floor/roof remaining attached to the surrounding columns, beams, and girders. Since floors and roofs must support service live loads, these must be considered in designing the repair. Descriptions of repair systems given below are grouped by repair type, i.e., floor or roof. Additionally, a method to seal off the upper story of a structure when its roof is severely damaged is presented.

(1) Breached Roof

(a) Shotcrete

The dry-mix, fiber-reinforced shotcrete material developed by AFESC/RDCM is used to repair a roof breach. The repair process is similar to a shotcrete wall replacement repair, but backing the repair area with plywood before placing shotcrete is different. A fabricated plywood section is secured with ramset studs to the underside of the breached roof slab. Once secured, the free span of the plywood must be braced with timber columns, attached to the plywood above and the floor beneath with ramset studs and brackets. After bracing, wire mesh or rebar is placed in the breach to act as additional reinforcement. Then the shotcrete material is sprayed onto the plywood backing. After the material has reached its design strength (within 1 hour), the plywood backing and bracing columns can be removed. The resulting repair is airtight and provides good fragment penetration and blast resistance. An example of this type of repair is shown in Figure 21.

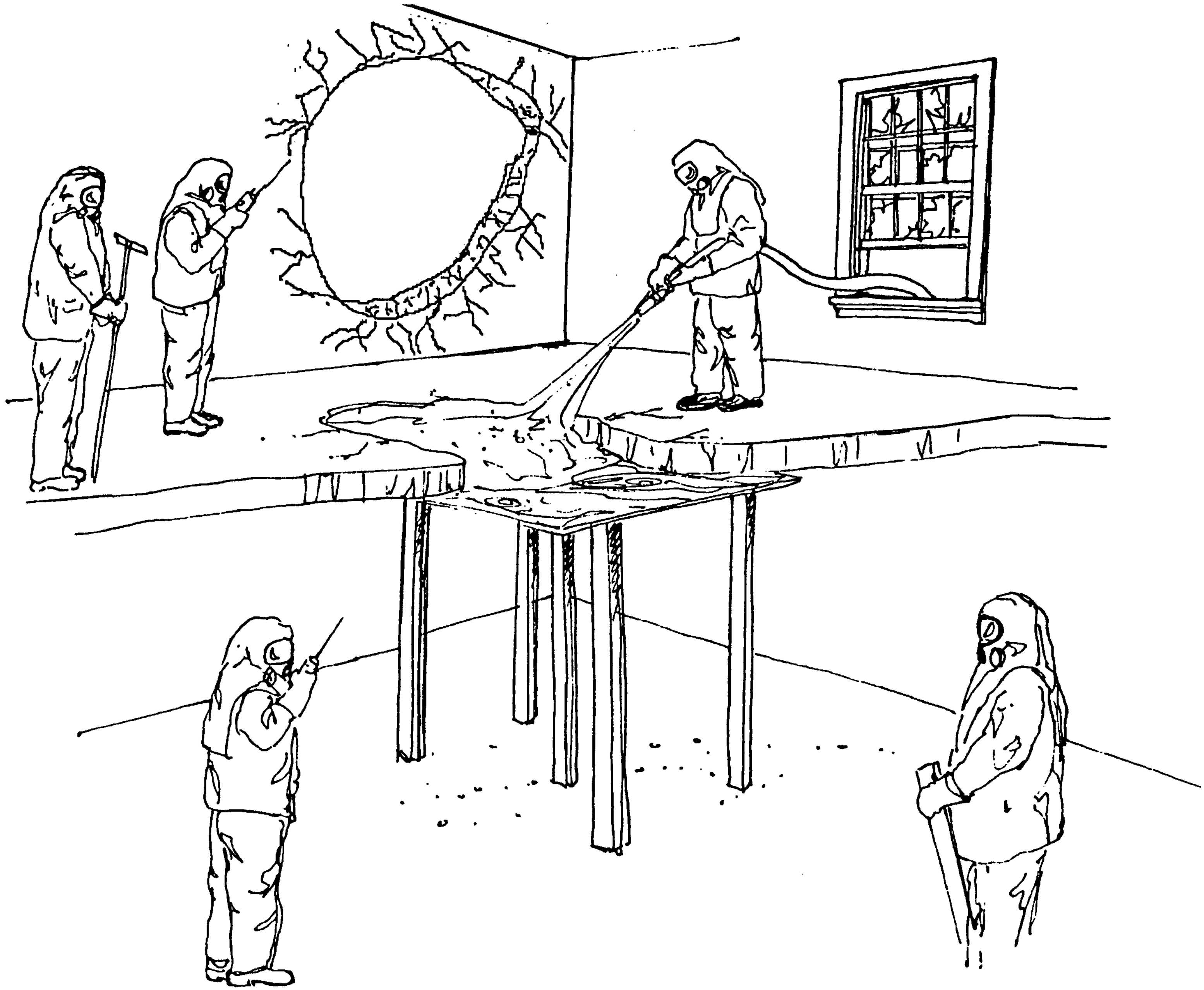


Figure 21. Floor/Roof Breach Shotcrete Repair.

(b) Rapid Setting Concrete

Using the same procedures described for a shotcrete roof repair, a plywood backing is installed beneath the breach. Wire mesh or rebar is placed in the breach to act as reinforcement. Then a fast-setting cement, such as Rapidset™, is mixed with aggregate and water and poured in the breach and spread by hand with shovels, hoes, trowels, and squeegees. The amount of accelerator can be varied to obtain the desired concrete set time. A portable concrete mixer can be used to mix and pour the concrete. After the material has reached it design strength, which depends on the type of cement used, the plywood backing and bracing columns can be removed.

(c) Plywood And Rolled Roofing

Plywood is joined together with two-by-fours, nails, nuts, and bolts until a section large enough to cover the breach has been fabricated. A 6-inch overlap of plywood should exist around the perimeter of the breach. The plywood section is secured with ramset studs through the overlap to the top side of the breached roof. If a service load will be supported by the repair, the free span of the plywood section needs to be braced. This can be done using timber columns between the plywood above and the floor beneath, or by support beams attached to the sides of the breach. Ramset studs and brackets can used to attach the columns or beams. After it is secured and braced, the plywood section is covered with rolled roofing to weatherize it. This repair is not airtight, and provides no blast or fragment penetration protection, but prevents rain and dust from entering the structure.

(d) Seal Stairs

If the roof of a multistory building is severely damaged, it may be necessary to seal the top story off from the remaining stories. By doing this, the remaining stories of the building can be made airtight and more blast resistant. Such a repair can be accomplished by sealing the stairways accessing the top story with shotcrete, or if a more rapid repair is required, with plywood. The repair would follow essentially the same procedures used for a shotcrete or plywood wall replacement repair. This method can also be used to seal off badly damaged portions of a structure so the remaining part of the structure can still be utilized.

(2) Breached Floor

If a floor of a structure is breached, the breach can be encircled with traffic cones to minimize the safety hazard. If a cover is desired, plywood should be used, following the procedures described for a roof repair. However, placement of rolled roofing over the plywood is not necessary.

g. Damaged Chemical/Biological Overpressure Door (Door Repair)

In this damage mode, an overpressure double door used to keep chemical and biological contaminants out of a mission-critical building has been damaged. Candidate expedient repair methods for such a damage mode, based on the extent of damage, are given below.

(1) Shotcrete

When the overpressure double door is completely destroyed, and was not the only door providing access to the facility, a possible expedient repair method is sealing the door opening. The resulting seal must be airtight to prevent entry of chemical and biological agents into the building. The previously described shotcrete technique would allow such an airtight seal to be rapidly installed in the door opening. The sealing process would be very similar to a shotcrete wall replacement repair.

(2) Third Door Insertion

When one of the overpressure doors is damaged to the extent it can no longer function, but the other door is still functional, then inserting of a third door, as shown in Figure 22, is a possible repair method, so long as the structure around the doorway is not to badly damaged. A door

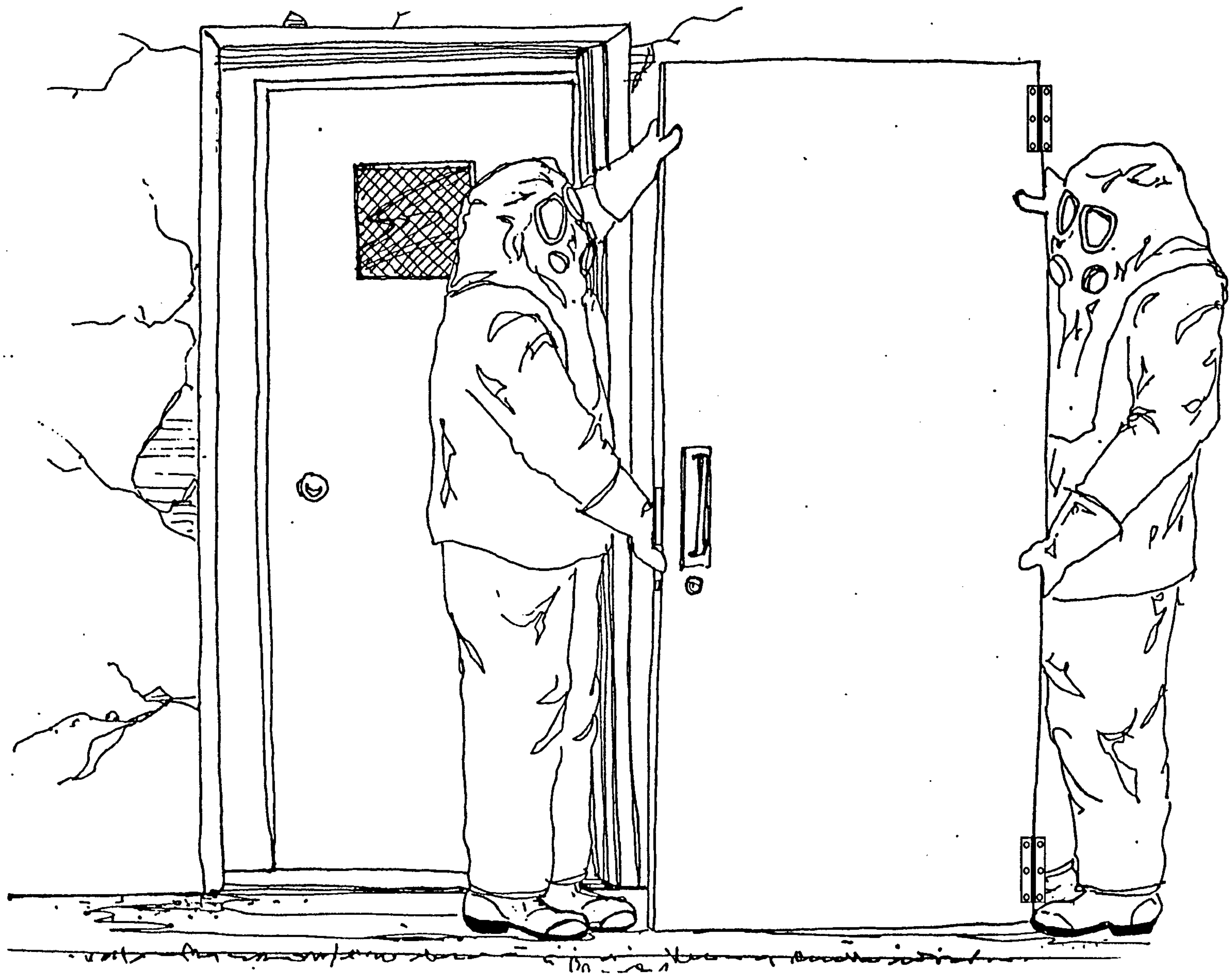


Figure 22. Third Door Insertion Overpressure Door Repair.

frame of the correct dimensions is fabricated from steel angles (see Figure 23) and inserted behind a destroyed exterior door or in front of a destroyed interior door and attached to the surrounding concrete walls, roof, and floor with ramset studs. If steel is the surrounding material, spot welding is used to secure the door frame. The frame is sealed to the walls with caulk or a similar material. A wooden door consisting of two-by-fours and plywood is fabricated to the correct dimensions and attached to the frame with hinges. Seams in the door are sealed with caulk or a similar material. Strips of rubber are nailed along the edges of the door to act as seals.

This type of door will not be completely airtight, but it will minimize overpressure loss inside the building, while still allowing access to the building. Because pressure loss will be small, chemical and biological agents should still be prevented from entering the building.

(3) Door Replacement

When one or both overpressure structure door(s) are damaged, but the door frame is still intact, then replacing the damaged door with a semiairtight door is the repair method of choice. Essentially, the repair process is the same as described for the third door insertion, but does not require installation of a door frame. A two-by-four and plywood door is fabricated to the correct dimensions, and attached to the existing frame's hinges. Seams in the door are sealed with caulk or a similar material. Strips of rubber should be nailed along the edges of the door to act as seals.

As with the third door insertion repair, the new door will not be completely airtight, but will allow adequate overpressure to be maintained in the building to prevent the intrusion of chemical and biological agents.

(4) Canvas Covering

Another possible repair method would use zippered, heavy-weight, waterproof canvas, plastic sheeting, or a similar material. The material is secured to the exterior and/or interior wall of a facility to cover the damaged door opening and act as a door. First, a wood frame is

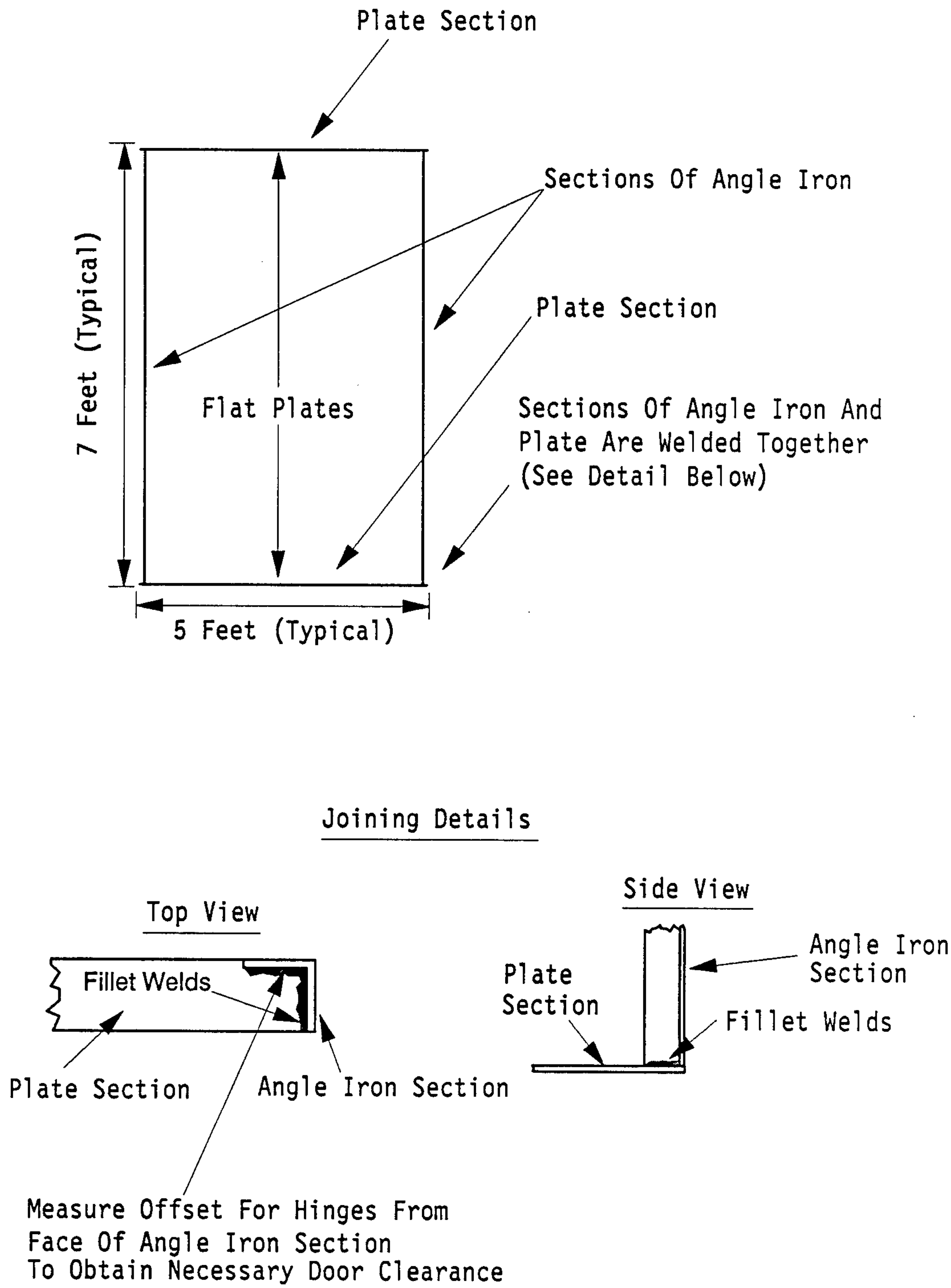


Figure 23. Fabricated Door Frame for Overpressure Door Repair.

fabricated from two-by-fours and attached to the wall around the door opening with ramset studs. The frame is sealed to the wall with caulk. The covering material is secured to the frame with a staple gun. The material's zipper should be oriented vertically to allow access into the facility. Sealing the material to the frame can be done using adhesive weatherizing strips attached around the frame. The covering material is installed on the frame over the strips to form a seal. This repair method is very flexible, and is less sensitive to the extent of door damage than the other methods.

As with the door replacement and door insertion repair methods, this repair will not be completely airtight, but should allow adequate overpressure to be maintained within the facility.

h. Stuck Blast Door (Forcing Open Blast Door)

(1) Aircraft Shelter Blast Door

In this damage mode, a third generation aircraft shelter's blast door (see Figure 24) has been warped by blast effects from a nearby weapon detonation, and will not slide open freely. The goal of expedient repair in this circumstance is to force the door open, so the aircraft inside the shelter can be removed. It is not the intent of the expedient repair to allow the door to be opened and closed again in a normal manner. Consequently, the repair will consist of attaching heavy equipment, such as bulldozers with chains and shackles, to both sections of the door, and prying the door open enough to extract the aircraft. This repair is illustrated in Figure 25.

(2) Other Blast Doors

In this damage mode, a blast door has been stuck closed by fragment damage, which has damaged the door's hinges and/or welded the door to its frame. An example of this damage mode is shown in Figure 26. As with the aircraft shelter blast door, it is not the purpose of expedient repair to make the blast door functional again, but instead to force the door open to gain access to and egress from the building. Consequently, the repair will consist of cutting the door's hinges and/or weld points along the

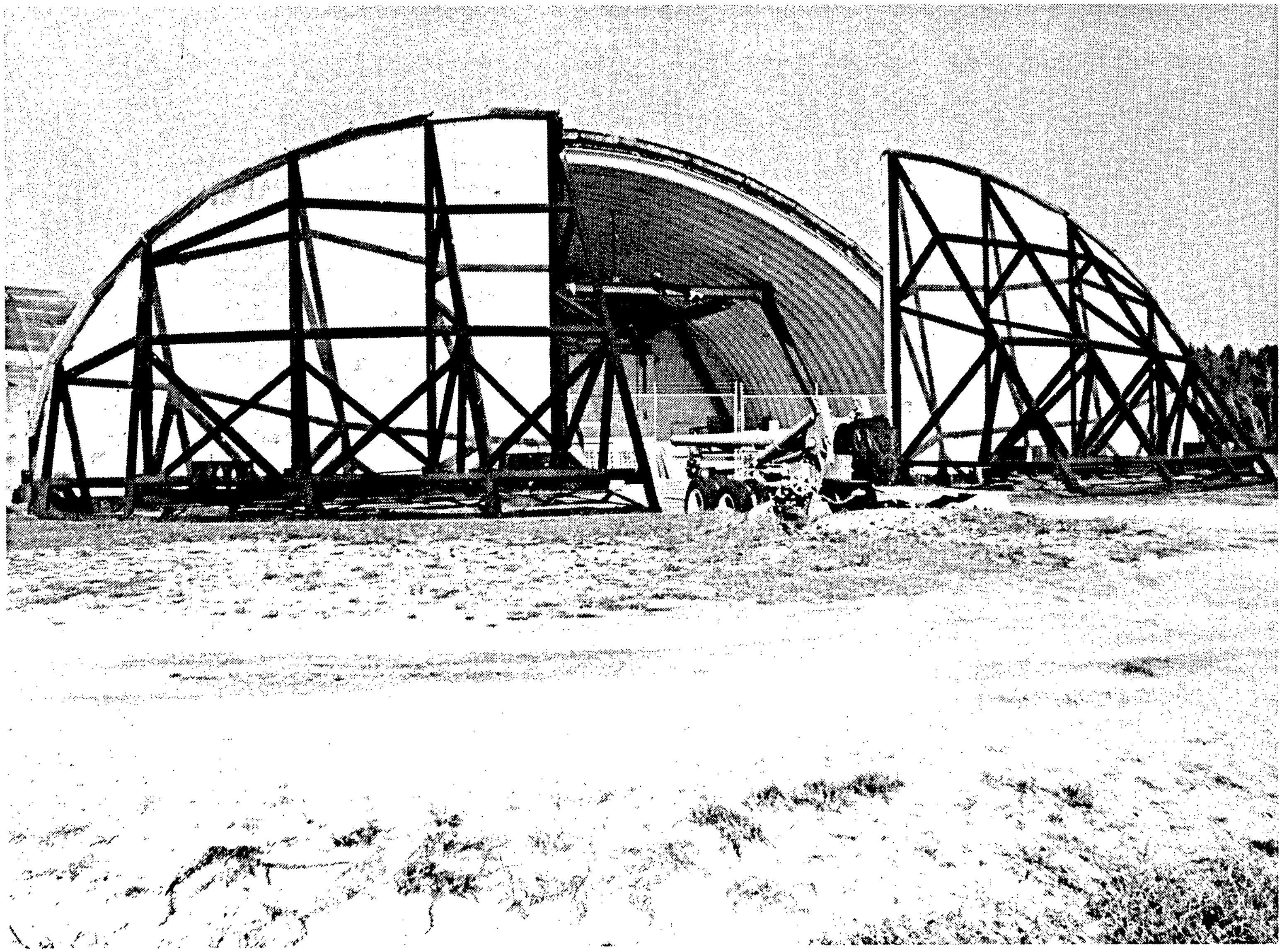


Figure 24. Third Generation Aircraft Shelter's Blast Door.

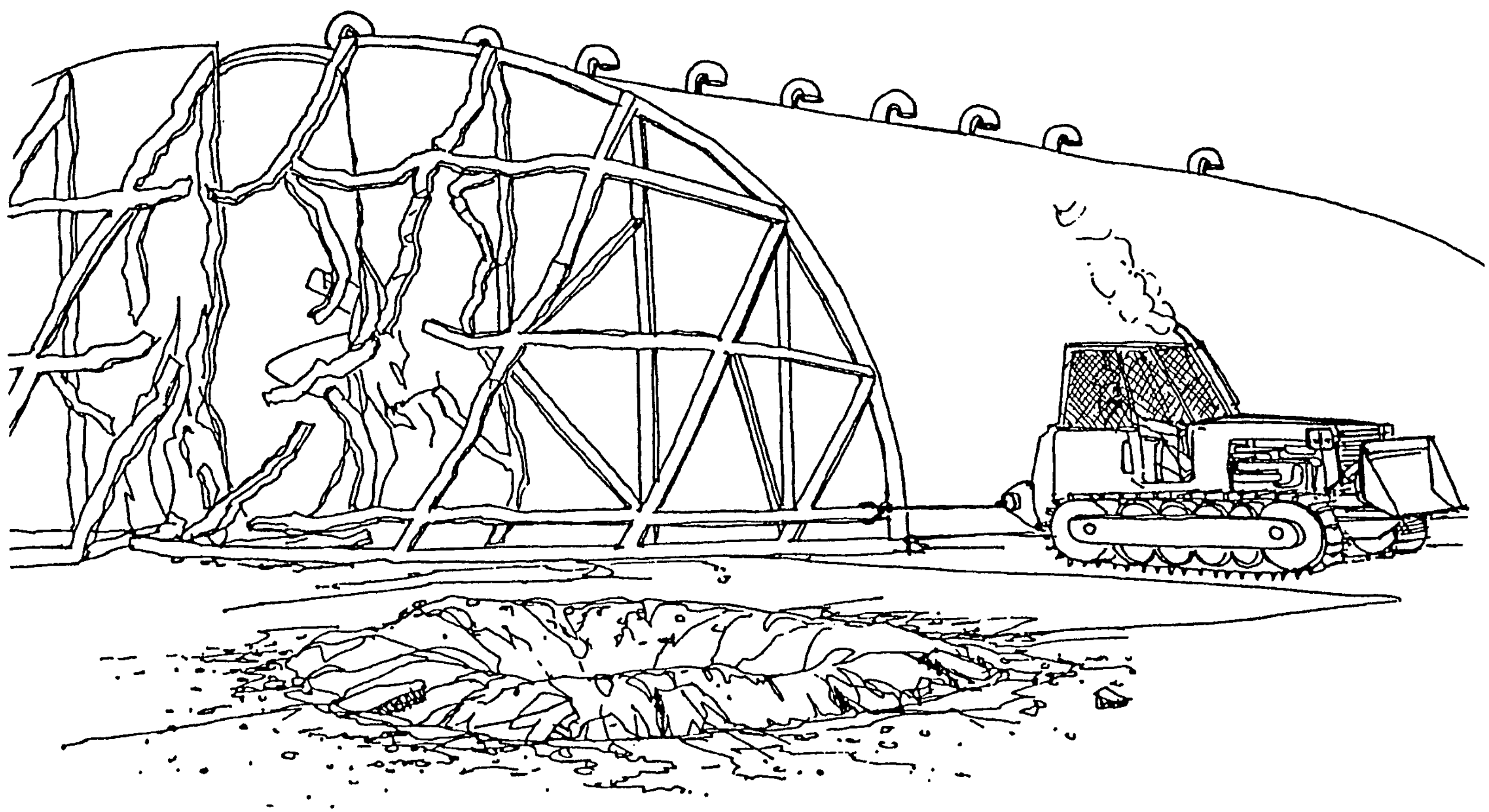


Figure 25. Opening Stuck Aircraft Shelter's Blast Door.

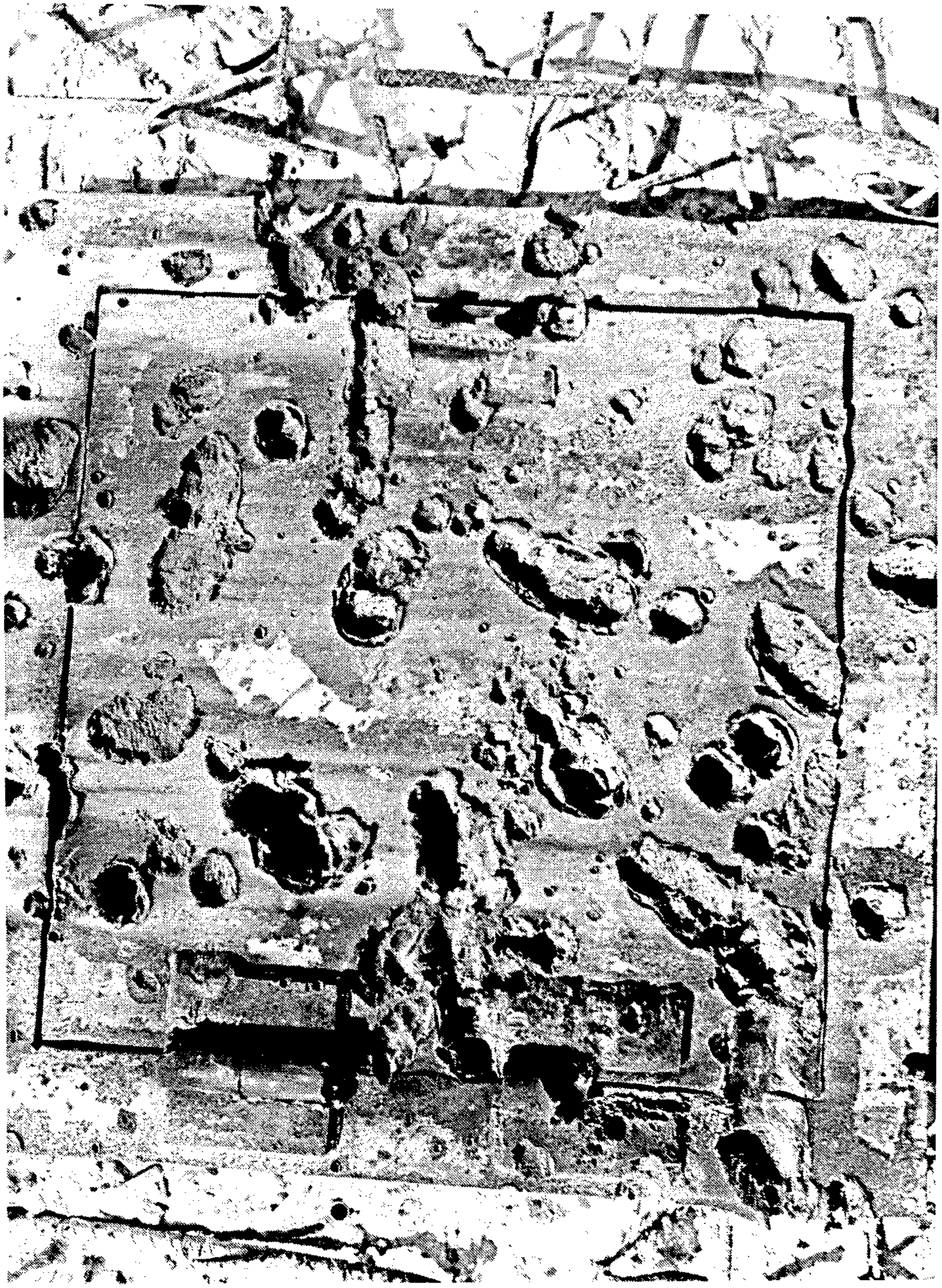


Figure 26. Damaged Blast Door.

door/frame interface with an acetylene torch. Then a front-end-loader or other piece of heavy equipment is attached to the door with chains and shackles, and used to pull the door from its frame.

i. Destroyed Window (Window Replacement)

In this damage mode, a window or windows of a building have been blown out. While the resulting openings in the building could be filled in with shotcrete or other wall breach repair materials previously described, it may be necessary to repair the windows so natural light can still enter the building. This is because, after an attack, electrical power might be off or only available intermittently. Consequently, sunlight may be the only light available within the building. The general concept of a window replacement repair is shown in Figure 27.

Candidate expedient repair methods for window replacement are described below. None of the suggested repairs uses glass, because of its fragility, the difficulty in cutting and drilling it, and the danger glass fragments pose during an air blast. However, glass can be used if a more suitable material is not available.

(1) Acrylic Panels

In this repair, acrylic panels are used to repair the window. There are several advantages to using acrylic. Acrylic is stronger and lighter than glass. Also arcylic can easily be cut and drilled using standard carpentry tools. Panels of arcylic can easily be joined together with simple glue compounds, such as silicone cement. Finally, arcylic is much less prone to break into small sharp fragments during a blast.

To repair a window, the opening is measured. Next, a wood frame of the appropriate dimensions is constructed and attached to the wall around the window opening with ramset studs. A sealent such as caulk is applied around the frame/wall interface. Acrylic panels are trimmed and/or joined to fit the frame. The acrylic section is then placed on the frame and secured to it with screws. A sealant such as caulk is applied to the frame/panel interface. The resulting repair is airtight, will let light into the building, and provides some blast resistance.

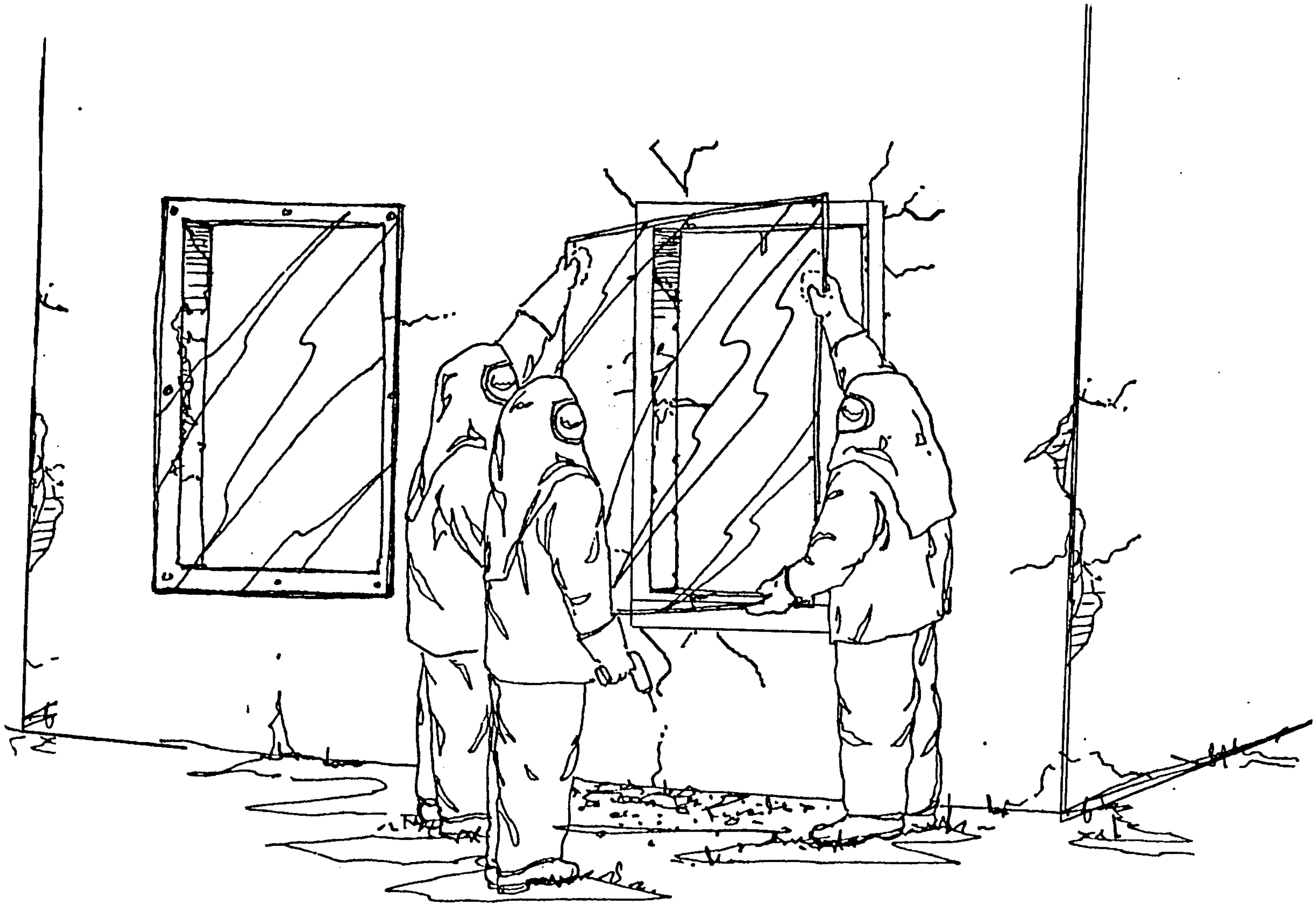


Figure 27. Window Replacement Repair.

(2) Plastic Sheeting

This is a very rapid temporary repair. When time permits, it should be replaced with arcylic panels for a more durable, airtight, and blast resistant cover. The repair process starts by measuring the window opening and constructing a wood frame to fit around the opening. The frame is attached to the wall around the window opening with ramset studs. Next, sheets of 6 mil or thicker, clear polyethylene or similar material are cut and joined with adhesive tape to fit over the frame. The sheeting is then placed on the frame and secured to it with staples. The resulting repair will let light into the building, and prevent rain and dust from entering, but will not be airtight nor provide any blast resistance.

j. Buckled Aircraft Shelter Floor (Slab Repair)

In this damage mode, the floor slab of a third generation aircraft shelter has been fractured, and portions uplifted by a below-ground bomb burst near the structure. The faulted slab prevents the aircraft within the shelter from being removed. Repair of such damage will consist of constructing ramps that allow the aircraft to taxi over the uplifted pavement section. The width of each ramp need only be several feet, so long as their spacing corresponds to the gear-truck spacing of the aircraft within the shelter. A general example of a floor slab repair is shown in Figure 28.

Candidate expedient repair methods for floor slab repair are described below. None of the repair techniques uses epoxy, polyurethane, or similar advanced materials to form the ramp, due to the storage and environmental concerns associated with such materials, already discussed.

(1) Shotcrete

The shotcrete material already described can be used to fabricate ramps to allow aircraft to taxi over the damaged pavement. Because the material does not flow after application, no formwork is required. However, to ease placement and ensure a smooth ramp grade, simple formwork should be used. Formwork for the ramps can be fabricated from a frame of two-by-fours with plywood nailed to its sides, as shown in Figure 29. This

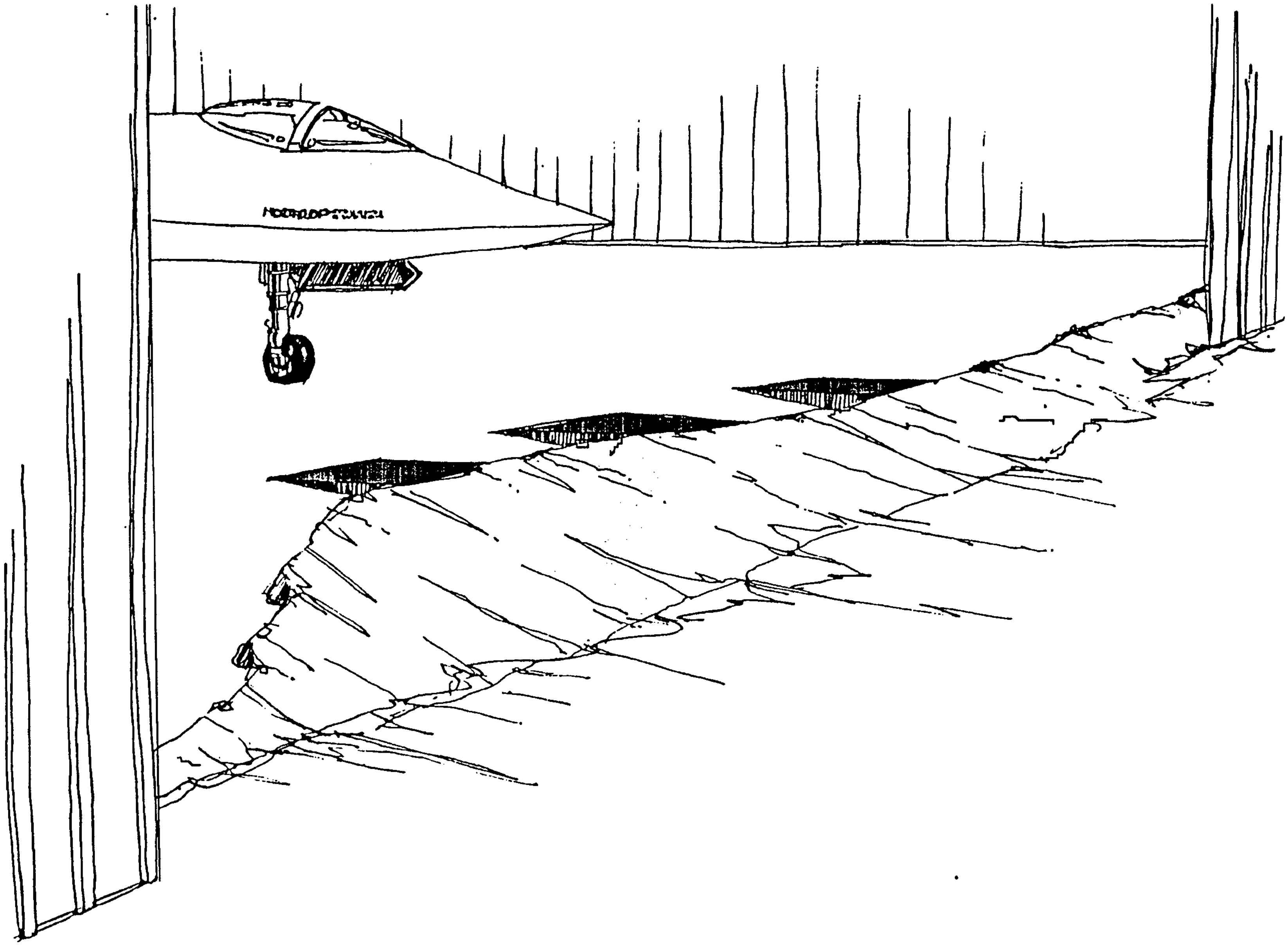


Figure 28. Aircraft Shelter Floor Slab Ramp Repair.

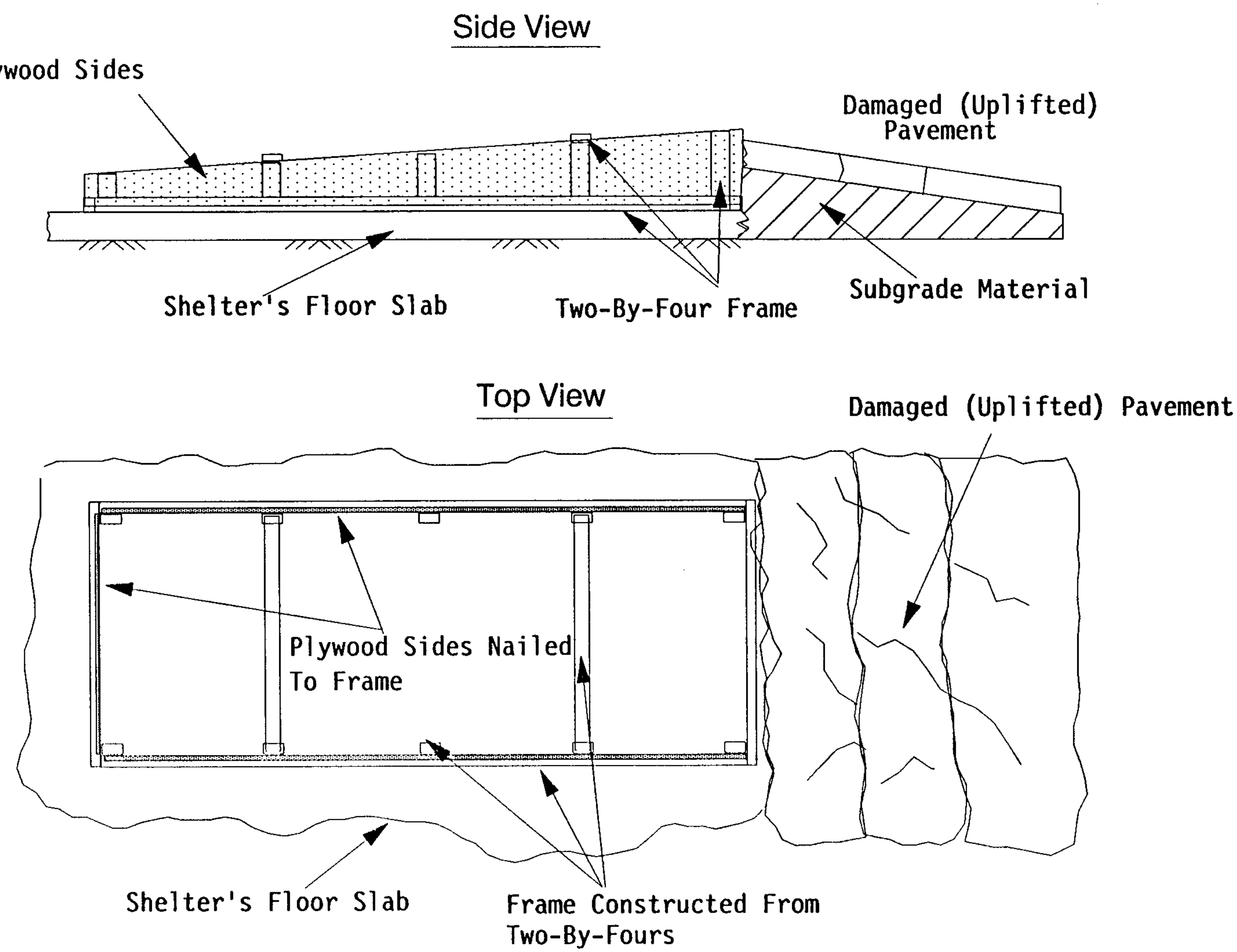


Figure 29. Ramp Formwork.

formwork should be placed against the uplifted pavement before placing the shotcrete material. The length of the formwork should be set to keep the grade of the ramp within reasonable limits, say a 30 percent grade or less. The height of the formwork is the height of the uplifted pavement.

Once the required number of formwork assemblies, having the correct height and length, have been fabricated and placed against the uplifted pavement, shotcrete material is applied. Application of shotcrete within the formwork should start at the location of the uplifted pavement and slowly move backwards, until the ramp is completed.

(2) Rapid-Set Concrete

In this repair, a fast-setting cement, such as Rapidset™, is mixed with aggregate and water, and placed into formwork to create a ramp. Prior to concrete placement, wire mesh can be placed in the bottom of the formwork to act as reinforcement. The formwork is the same as shown in Figure 29, but a partial cover is needed to prevent material overflow. A small concrete mixer can be used to mix the cement, aggregate, and water. The amount of accelerator can be varied to obtain the desired set time. The concrete is poured from the mixer into the formwork, and spread by hand with shovels, hoes, trowels, and squeegees. Sizing of the ramp with respect to length and height follows the same process used for the shotcrete ramp.

(3) AM2 Mat

AM2 panels placed lengthwise to bridge the buckled pavement can be used to fabricate a ramp, as shown in Figure 30. Bracing, such as sand bags, concrete blocks, or wooden blocks, should be placed under the AM2 to prevent excessive deformation under load. The ramp height of this repair system is limited, because the maximum length of the AM2 panels is 6 feet. The ramp grade will exceed the previously stated 30 percent maximum grade criteria when pavement uplift is greater than 1.8 feet.

This repair method should be viewed as a rapid, temporary repair. When time permits, it should be replaced with a shotcrete or rapid-setting concrete ramp repair.

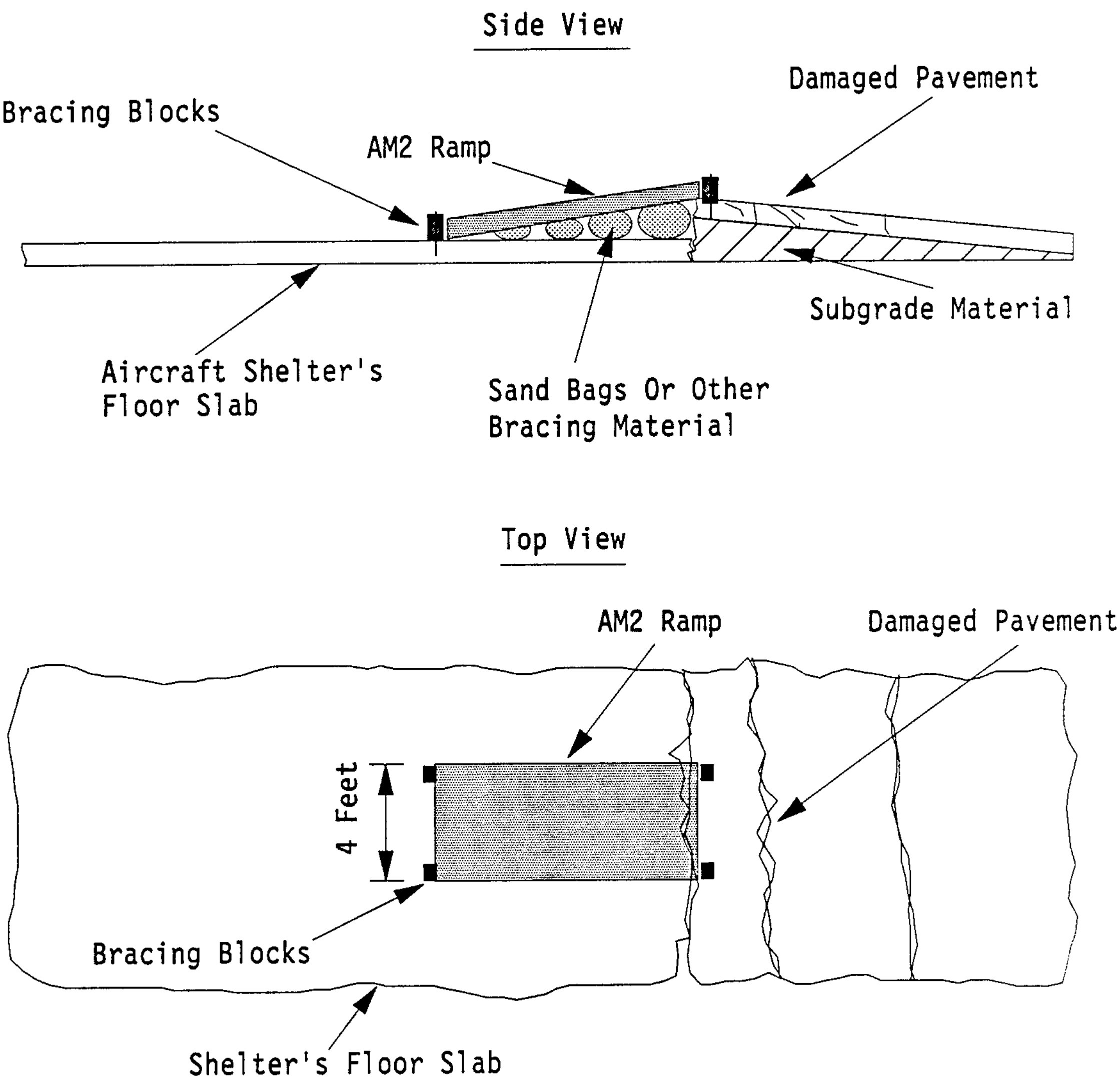


Figure 30. AM2 Aircraft Shelter Floor Slab Ramp Repair.

SECTION V

EVALUATION OF CANDIDATE ERSF SYSTEMS

A. EVALUATION PROCESS AND CRITERIA

In Section IV, expediently repairable damage modes for typical airbase mission-critical structural facilities were identified, and at least one candidate ERSF system was described for repairing each damage mode. In this section, ERSF systems for a particular damage mode are evaluated side-by-side, using evaluation matrices. The evaluation criteria used fall in three categories; (1) operational, (2) structural, and (3) logistic. An example of an evaluation matrix is given in Figure 31. Each of the evaluation categories is given a different weight factor, as shown below, with the sum of the factors equaling 1.00. The overall usability of a system was considered the most important concern, and the operational category was given the most weight. However, because systems should, if possible, produce structurally sound repairs, and must be logistically supportable at FOBs, structural and logistic categories are given only slightly less weight than the operational category.

- Operational Weight Factor = 0.40
- Structural Weight Factor = 0.30
- Logistic Weight Factor = 0.30

Each ERSF system has been scored for each criterion within each category. Score values range from 1 to 5, according to the scale given below.

- 1 is poor
- 2 is marginal
- 3 is average
- 4 is good
- 5 is excellent

For each candidate ERSF system, all scores within a category are summed, and the sum multiplied by the category weight factor to obtain the category score. The three category scores for a particular ERSF system are them summed to obtain a total score, allowing the expedient repair system to be ranked against other systems for the same damage mode.

		Scores For Candidate ERSF Systems
Category	Criterion	
Operational	Manpower	
	Safety	
	Simplicity	
	Versatility	
Weight Factor 0.40	Skill Requirements	
	Heavy Equipment	
	Environmental Range	
	# Of Components	
	Special Equipment	
	Redundancy	
	Transportability	
	Category Score	
	Weighted Score	
Structural	Strength	
Weight Factor 0.30	Durability	
	Blast Resistance	
	Fragment Resistance	
	Airtightness	
	Category Score	
	Weighted Score	
Logistic	Storage Life	
	Cost	
Weight Factor 0.30	Reliability	
	Maintainability	
	Peacetime Use	
	Availability	
	Category Score	
	Weighted Score	
	Total Score	

Figure 31. Example of an ERSF Evaluation Matrix.

Following, grouped by category, are descriptions of each evaluation criterion.

1. Operational Criteria

a. Manpower

Indicates how many personnel are required to operate the system. The fewer the number of personnel required, the higher a system's score.

b. Safety

Indicates how safe a system is, or conversely, how many safety hazards exist while using the system. The fewer the safety hazards, the higher a system's score.

c. Simplicity

Indicates how simple a system is to use. Like many evaluation criteria, this one is admittedly subjective, but nonetheless very important. The simpler the system the higher its score.

d. Versatility

Indicates whether a system can be used for a variety of repair tasks and/or under a range of repair conditions, or is designed solely to do one job without allowance for variations. The more repair tasks/conditions a system can be used for, the higher its score.

e. Skill Requirements

Indicates the Air Force Specialty Code (AFSC) skill levels personnel using a system should have. The lower the skill levels required, the higher the system's score.

f. Heavy Equipment

Indicates if a system requires heavy equipment, such as front-end loaders or bulldozers. Such pieces of equipment will be in high demand at a FOB in a postattack environment. Consequently, the less heavy equipment required by a system, the higher the system's score.

g. Environmental Range

Indicates the range of environmental parameters, such as rainfall, snow, extreme temperature, and fog, a system can tolerate. The wider the range, the higher a system's score.

h. Number Of System Components

Indicates how many major components, such as material ingredients, tools, and pieces of heavy equipment are required by a system. The more components required, the higher the likelihood the system will not be operable in a postattack environment, due to component failure or scarcity. Consequently, the fewer major components needed by a system, the higher the system's score.

i. Special Equipment

Indicates whether a system requires a specialized, single-use piece of equipment, not normally included in a FOB's equipment inventory, such as a shotcrete gun. The more special equipment required by a system, the lower the system's score.

j. Redundancy

Indicates the degree of redundancy built into a system, i.e., its ability to function even if several of its components fail or are unavailable and/or personnel are missing. The higher a system's redundancy, the higher its score.

k. Transportability

Indicates how easy it is, and how much equipment and personnel are required, to transport a system from one mission-critical facility to another. Damaged structures requiring expedient repair may be widely separated. Consequently, transportability of an expedient repair system from one location to another is critical. The more transportable a system, the higher its score.

2. Structural Criteria

a. Strength/Capacity

Indicates how much strength a repair possesses, and how much additional capacity the repair provides to a structure. The more strength and capacity a repair provides, the higher the system's score.

b. Durability

Indicates how many hours, days, or months a repair will remain functional. The longer a repair will last, the higher the system's score.

c. Blast Resistance

Indicates how much air blast resistance a repair provides. The greater a repair's blast resistance, the higher the system's score. This criterion applies only to exterior repairs.

d. Fragment Penetration Resistance

Indicates how much fragment penetration resistance a repair provides. The more penetration resistance a repair provides, the higher the system's score. This criterion applies only to exterior repairs.

e. Airtightness

Indicates how airtight a repair is, its effect on the overpressure system of a structure, and whether it will prevent environmental and chemical/biological agent intrusion. The more airtight a repair, the higher the system's score. This criterion applies only to exterior repairs.

3. Logistic Criteria

a. Storage Life

Indicates how long the components of a system can be stored, and if inspection is required, the interval and complexity of inspection. Additionally, indicates the total storage life of a system with inspection. The longer the storage life, and the less frequent and complex the inspection, the higher a system's score.

b. Cost

Indicates the life-cycle cost of a system. The lower the cost, the higher a system's score.

c. Reliability

Indicates if a system requires frequent maintenance (preventive or otherwise) during use. The less maintenance required, the higher a system's score.

d. Maintainability

Indicates if system maintenance can be done in the field by ERSF personnel, or if maintenance requires specialized facilities and personnel. The more system maintenance that can be done in the field by ERSF personnel, the higher a system's score.

e. Peacetime Use

Indicates if a system is usable only during wartime in a postattack environment, or if it can be used for routine civil engineering tasks during peacetime. The more peacetime uses a system has, the higher its score.

f. Availability

Indicates whether a system's components are currently available in the Air Force supply system, or whether a special procurement action is required to obtain components. The more components of a system that can be obtained through the Air Force supply system, the higher the system's score.

B. EVALUATION OF CANDIDATE ERSF SYSTEMS

Since each expedient repair system described below has already been screened, as described in Section IV, large differences in evaluation scores between ERSF systems for a specific type of repair are infrequent in this final evaluation. Consequently, a one-point difference between the total weighted scores of two systems is significant, and the systems having the highest scores have been recommended. Differences in scores between one half and one point are marginally significant, and differences of less than one half point are not significant.

Following, grouped by repair type, are evaluations of the ERSF systems described in Section IV of this report.

1. Steel Structures

Evaluation of the expedient repair strategy for steel structures, based on welding steel members to damaged column or beams, are given in Table 2. The overall weighted score of such repairs is 31.5 out of a possible 38.5 (82 percent). Repairing steel framed structures by welding of steel members to damaged areas is suitable for ERSF.

TABLE 2. EVALUATION MATRIX FOR STEEL FRAMED ERSF SYSTEMS.

		Scores For Candidate ERSF Systems
Category	Criterion	Cutting And Welding
Operational	Manpower	4
	Safety	3
	Simplicity	4
	Versatility	3
Weight Factor 0.40	Skill Requirements	4
	Heavy Equipment	4
	Environmental Range	4
	# Of Components	4
	Special Equipment	4
	Redundancy	4
	Transportability	4
	Category Score	42
	Weighted Score	16.8
Structural	Strength	5
Weight Factor 0.30	Durability	5
	Blast Resistance	5
	Fragment Resistance	5
	Airtightness	5
	Category Score	25
	Weighted Score	7.5
Logistic	Storage Life	4
	Cost	4
Weight Factor 0.30	Reliability	4
	Maintainability	5
	Peacetime Use	3
	Availability	4
	Category Score	24
	Weighted Score	7.2
	Total Score	31.5 (82%)

2. Column Replacement

Evaluations of the glulam timber and shoring jack column replacement systems are given in Table 3. As seen, the overall weighted scores of the two systems are 0.9 points apart: 28.6 (74 percent) for the glulam timber, and 29.5 (77 percent) for the shoring jack. The shoring jack comes out ahead in the operational category, while the glulam column rates higher in the structural and logistic categories.

In the operational category, the shoring jack has higher scores for manpower, safety, simplicity, skill requirements, heavy equipment, and number of components. For the remaining operational criteria, the two strategies are even.

In the structural category, the glulam column comes out ahead, because it generally has a higher load capacity and is more rugged and durable.

The glulam column also wins in the logistic category, because it can be stored outdoors, requires very little care during long-term storage, and will probably be cheaper in large quantities. Glulam may need to be covered by a tarpaulin for ultraviolet light protection, but otherwise needs very little attention during long-term, outdoor storage under a wide range of climatic conditions. Shoring jacks need to be stored indoors, and to be protected against and inspected for such things as rust, dried and cracked hydraulic seals, and dirt in valves.

Overall, the shoring jack comes out ahead, because it wins six criteria to glulam's five, all in the most heavily weighted operational category. However, the scores of the two systems are close, and both are suitable for ERSF. The system used at a FOB should be left to the discretion of the BCE

3. Column Splinting

Evaluation of the column splint system is given in Table 4. The overall weighted score of the system is 31.7 (82 percent). The column splint system scored well in every category, due to its simplicity and ease of use. The splint system is highly suitable for ERSF, when a discrete column fracture occurs.

TABLE 3. EVALUATION MATRIX FOR COLUMN REPLACEMENT ERSF SYSTEMS.

		Scores For Candidate ERSF Systems	
Category	Criterion	Glulam Column	Shoring Jack
Operational	Manpower	4	5
	Safety	3	4
	Simplicity	3	4
	Versatility	5	5
Weight Factor 0.40	Skill Requirements	4	5
	Heavy Equipment	4	5
	Environmental Range	5	5
	# Of Components	4	5
	Special Equipment	4	4
	Redundancy	5	5
	Transportability	5	5
	Category Score	46	52
	Weighted Score	18.4	20.8
Structural	Strength	4	3
Weight Factor 0.30	Durability	4	3
	Blast Resistance	---	---
	Fragment Resistance	---	---
	Airtightness	---	---
	Category Score	8	6
	Weighted Score	2.4	1.8
Logistic	Storage Life	5	4
	Cost	5	4
Weight Factor 0.30	Reliability	5	5
	Maintainability	5	4
	Peacetime Use	2	2
	Availability	4	4
	Category Score	26	23
	Weighted Score	7.8	6.9
	Total Score	28.6 (74%)	29.5 (77%)

TABLE 4. EVALUATION MATRIX FOR COLUMN SPLINTING ERSF SYSTEMS.

		Scores For Candidate ERSF Systems
Category	Criterion	Column Splint
Operational	Manpower	5
	Safety	4
	Simplicity	5
	Versatility	4
Weight Factor 0.40	Skill Requirements	5
	Heavy Equipment	5
	Environmental Range	5
	# Of Components	5
	Special Equipment	5
	Redundancy	5
	Transportability	5
	Category Score	53
	Weighted Score	21.2
Structural	Strength	4
Weight Factor 0.30	Durability	5
	Blast Resistance	---
	Fragment Resistance	---
	Airtightness	---
	Category Score	9
	Weighted Score	2.7
Logistic	Storage Life	5
	Cost	5
Weight Factor 0.30	Reliability	5
	Maintainability	5
	Peacetime Use	2
	Availability	4
	Category Score	26
	Weighted Score	7.8
	Total Score	31.7 (82%)

4. Beam/Girder Shoring

Evaluations of the king post and vertical shoring systems are given in Table 5. Unless there is no base for vertical shoring, the king post is too risky to be attractive. The tension force in the tie rods is very high, and the tie rod anchors must be well constructed to avoid slip. Vertical shoring, with either glulam timbers or a shoring jack, is the clear choice, when it is possible.

5. Wall Replacement

Evaluations of ERSF wall replacement systems are given in Table 6. The evaluation of the shotcrete system is preliminary, since the equipment to be used in the system is still under investigation by AFESC/RDCS. Consequently, the ranking of the shotcrete system against the other systems may change depending upon the outcome of the equipment investigation effort.

Another factor that could affect the ranking of the systems is how much emphasis is placed on blast and fragment penetration resistance of the repair. In the current evaluations, blast and fragment penetration resistance are not given special consideration. However, if the Base Commander and BCE at a FOB consider these factors critical, ranking of the systems would change. This holds true especially for the shotcrete system, which not only provides excellent blast and fragment penetration resistance, but is also very versatile with respect to the types of repairs for which it can be used.

Based on the overall weighted scores shown in Table 6, the plywood system is the first choice, followed by the earth berm, concrete slab, masonry block, and shotcrete systems, with scores of 29.2 (76 percent), 28.3 (74 percent), 27.1 (70 percent), 26.1 (68 percent), and 24.7 (64 percent), respectively.

In the operational category, the plywood system, because of its simplicity, ranked highest, scoring consistently well on all criteria. All other systems had several areas, such as specialized pieces of equipment, versatility, or number of components where they did not score well. For example, the shotcrete system scored low on specialized equipment and number of components, while the earth berm, masonry block, and concrete slab systems

TABLE 5. EVALUATION MATRIX FOR BEAM/GIRDER SHORING ERSF SYSTEMS.

		Scores For Candidate ERSF Systems	
Category	Criterion	King Post	Vertical Shoring
Operational	Manpower	3	5
	Safety	2	4
	Simplicity	2	4
	Versatility	3	4
Weight Factor 0.40	Skill Requirements	3	5
	Heavy Equipment	4	5
	Environmental Range	5	5
	# Of Components	4	5
	Special Equipment	3	4
	Redundancy	2	5
	Transportability	5	5
	Category Score	36	51
	Weighted Score	14.4	20.4
Structural	Strength	3	3
Weight Factor 0.30	Durability	4	3
	Blast Resistance	---	---
	Fragment Resistance	---	---
	Airtightness	---	---
	Category Score	7	6
	Weighted Score	2.1	1.8
Logistic	Storage Life	5	4
	Cost	5	4
Weight Factor 0.30	Reliability	3	5
	Maintainability	4	4
	Peacetime Use	2	2
	Availability	4	4
	Category Score	23	23
	Weighted Score	6.9	6.9
	Total Score	23.4 (61%)	29.1 (76%)

TABLE 6. EVALUATION MATRIX FOR WALL REPLACEMENT AND WALL BREACH ERSF SYSTEMS.

		Scores For Candidate ERSF Systems				
Category	Criterion	Shotcrete*	Earth Berm	Masonry Blocks	Precast Slabs	Plywood
Operational	Manpower	3	4	3	4	3
	Safety	3	4	4	4	4
	Simplicity	2	4	2	4	3
	Versatility	4	2	1	2	4
Weight Factor 0.40	Skill Requirements	3	4	4	4	4
	Heavy Equipment	3	3	4	3	5
	Environmental Range	3	4	3	4	5
	# Of Components	2	4	4	4	5
	Special Equipment	2	4	4	4	5
	Redundancy	3	4	4	4	3
	Transportability	3	3	3	3	5
	Category Score	31	40	36	40	46
	Weighted Score	12.4	16.0	14.4	16.0	18.4
Structural	Strength	5	2	2	2	1
Weight Factor 0.30	Durability	5	4	5	4	2
	Blast Resistance	5	4	2	3	1
	Fragment Resistance	5	4	2	3	1
	Airtightness	5	3	4	1	1
	Category Score	25	17	15	13	6
	Weighted Score	7.5	5.1	4.5	3.9	1.8
Logistic	Storage Life	3	5	4	5	5
	Cost	2	4	4	4	5
Weight Factor 0.30	Reliability	3	4	4	4	5
	Maintainability	3	4	4	4	5
	Peacetime Use	2	3	4	3	5
	Availability	3	4	4	4	5
	Category Score	16	24	24	24	30
	Weighted Score	4.8	7.2	7.2	7.2	9.0
	Total Score	24.7 (64%)	28.3 (74%)	26.1 (68%)	27.1 (70%)	29.2 (76%)

* System still under development by AFESC/RDCS

all scored low on versatility. They can be used only on ground floor exterior walls, and require a large working area.

In the structural category, the shotcrete system was ranked highest by a wide margin. The shotcrete system provides excellent strength, durability, blast resistance, fragment penetration resistance, and airtightness. All other systems scored significantly lower in this category, especially the plywood system, which provides no structural enhancement to a damaged facility.

In the logistic category, the plywood system scored highest by a wide margin, because it uses such simple materials and tools. The shotcrete system scored lowest, because it is the most complex and has the most stringent storage and maintenance requirements. Additionally, it is the most costly.

At this time, the plywood system appears to be the clear choice for a wall replacement system. The earth berm and concrete slab systems also scored well, and should be used to supplement the plywood system. Due to its low score, the masonry block system should be dropped from consideration. The shotcrete system, while not scoring well at this time, should not be dropped from consideration. The shotcrete system is very versatile, and scored extremely well in the structural category. At this time, its operational category score is low, but this may change depending on the outcome of the shotcrete equipment identification and evaluation effort currently in progress by AFESC/RDCS.

6. Wall Breach Repair

Since the processes are so similar, evaluations of ERSF wall breach repair systems, and associated conclusions and recommendations, are the same as those presented for wall replacement systems. Results of the evaluations are given in Table 6.

7. Floor/Roof Breach Repair

Evaluations of ERSF floor/roof breach repair systems are given in Table 7. These evaluations must be broken down into two types. The first type applies when the damage to a floor or roof can be repaired. The second

TABLE 7. EVALUATION MATRIX FOR FLOOR/ROOF BREACH ERSF SYSTEMS.

		Scores For Candidate ERSF Systems				
Category	Criterion	Shotcrete*	Plywood	R. S. Concrete	Shotcrete**	Plywood**
Operational	Manpower	3	3	3	3	3
	Safety	3	4	4	3	4
	Simplicity	2	3	3	2	3
	Versatility	4	4	4	1	4
Weight Factor 0.40	Skill Requirements	3	4	4	3	4
	Heavy Equipment	3	5	5	3	5
	Environmental Range	3	5	3	3	5
	# Of Components	2	5	4	2	5
	Special Equipment	2	5	4	2	5
	Redundancy	3	3	3	3	3
	Transportability	3	5	4	3	5
	Category Score	31	46	41	28	46
	Weighted Score	12.4	18.4	16.4	11.2	18.4
Structural	Strength	5	1	4	---	---
	Durability	5	2	5	---	---
Weight Factor 0.30	Blast Resistance	5	1	4	---	---
	Fragment Resistance	5	1	4	---	---
	Airtightness	5	1	5	---	---
	Category Score	25	6	22	---	---
	Weighted Score	7.5	1.8	6.6	---	---
Logistic	Storage Life	3	5	3	3	5
	Cost	2	5	4	2	5
Weight Factor 0.30	Reliability	3	5	4	3	5
	Maintainability	3	5	4	3	5
	Peacetime Use	2	5	3	2	5
	Availability	3	5	4	3	5
	Category Score	16	30	22	16	30
	Weighted Score	4.8	9.0	6.6	4.8	9.0
	Total Score	24.7 (64%)	29.2 (76%)	29.6 (77%)	16.0 (42%)	27.4 (76%)

* System still under development by AFESC/RDCS   ** Systems to seal access stairs

type applies when damage too a roof is to severe to repair, and access stairs to the upper story must be sealed.

a. Repair Breach

As was done in Section IV, repairs are grouped by repair type; roof or floor.

(1) Roof Breach

Based on the overall weighted scores shown in Table 7, the rapid-set concrete system scored highest (29.6, 77 percent), followed closely by the plywood system at 29.2 (76 percent) for roof breach repair. The shotcrete system scored a distant third at 24.7 (64 percent).

In the operational category, the plywood system ranked highest, scoring consistently on all criteria. The rapid-set concrete system ranked next, scoring lower than the plywood system on environmental range, number of components, special equipment, and transportability. The shotcrete system scored much lower than the plywood or rapid-set concrete system on most criteria. However, as previously stated, the shotcrete system is still under development and its ranking may change.

In the structural category, the shotcrete system ranked highest followed closely by the rapid-set concrete system. The shotcrete system scored slightly higher than the rapid-set concrete system on strength, blast resistance, and fragment penetration resistance criteria, because the shotcrete contains steel fibers. The plywood system, due to its inherent structural weakness, scored very low on all criteria.

In the logistic category, the plywood system scored highest, because it uses such simple materials and tools. The rapid-set concrete system scored slightly lower on all criteria, because it is more costly, and uses a specialized type of material that requires controlled storage and monitoring. For the same reasons, and because it requires a complex, specialized piece of equipment, the shotcrete system scored much lower on all criteria.

The rapid-set concrete and plywood systems ranked nearly equally, and appear to be the clear choices for roof breach repair. The shotcrete system scored much lower; but because it is still under development and the importance of its excellent blast and fragmentation resistance may increase, it should not be dropped from consideration.

(2) Floor Breach

The plywood system, without using rolled roofing, is the system recommended in Section IV to repair a floor breach. As seen from the results given in Table 7, the plywood system scored very well, and is a viable floor breach repair ERSF system.

If no repair is attempted, traffic cones or rope can be used to cordon off a floor breach as a safety precaution. This method was not evaluated, and should only be considered as a stopgap measure when there is no time to carry out a repair.

b. Seal Stairs

As seen from Table 7, the plywood system scored highest at 27.4 (71 percent) for sealing stairs. The shotcrete system scored a distant second at 16.0 (42 percent). The plywood system, because of the simple tools, procedures, and materials it requires, scored much higher than the shotcrete system on all operational and logistic criteria. The structural category was not considered applicable to this type of repair, because access stairs requiring sealing will be in the interior of a structure.

The clear choice for sealing stairs is the plywood system.

8. Overpressure Door Repair

Evaluations of ERSF overpressure door repair systems are given in Table 8. Based on the overall weighted scores, the canvas system is the clear first choice with a score of 28.1 (73 percent), followed by the door replacement, third door insertion, and shotcrete systems, with scores of 26.3 (68 percent), 25.1 (65 percent), and 20.2 (52 percent), respectively. Evaluations of these systems must consider the fact that three of the systems (door replacement, third door insertion, and shotcrete) are damage-dependent. If only a door has been damaged, the door replacement system is used. If the

TABLE 8. EVALUATION MATRIX FOR OVERPRESSURE DOOR ERSF SYSTEMS.

		Scores For Candidate ERSF Systems			
Category	Criterion	Shotcrete*	Third Door Insertion	Door Replacement	Canvas Covering
Operational	Manpower	3	4	4	4
	Safety	3	4	4	4
	Simplicity	2	3	4	5
	Versatility	4	4	3	5
Weight Factor 0.40	Skill Requirements	3	3	4	4
	Heavy Equipment	3	4	5	5
	Environmental Range	3	4	4	4
	# Of Components	2	4	4	4
	Special Equipment	2	3	4	4
	Redundancy	3	4	4	4
	Transportability	3	4	4	4
	Category Score	31	41	44	47
	Weighted Score	12.4	16.4	17.6	18.8
Structural	Strength	---	---	---	---
Weight Factor 0.30	Durability	5	4	4	3
	Blast Resistance	---	---	--	--
	Fragment Resistance	---	---	--	---
	Airtightness	5	4	4	4
	Category Score	10	8	8	7
	Weighted Score	3.0	2.4	2.4	2.1
Logistic	Storage Life	3	4	4	4
	Cost	2	4	4	4
Weight Factor 0.30	Reliability	3	4	4	4
	Maintainability	3	4	4	4
	Peacetime Use	2	1	1	4
	Availability	3	4	4	4
	Category Score	16	21	21	24
	Weighted Score	4.8	6.3	6.3	7.2
	Total Score	20.2 (52%)	25.1 (65%)	26.3 (68%)	28.1 (73%)

* System still under development by AFESC/RDCS

door's frame is damaged, the third door insertion system is used. If the entire door system is severely damaged, the shotcrete system is used to seal the doorway. The advantage of the canvas system is it can be used for all the damage modes just described. However, if the entire area around the door has been demolished, a wall breach repair should be accomplished using one of the systems recommended in this report.

Because of its flexibility, the canvas system is the recommended overpressure door repair system. The door replacement and third door insertion systems can be used to supplement the canvas system. Use of the shotcrete system depends on the outcome of the shotcrete equipment identification and evaluation effort currently in progress by AFESC/RDCS.

9. Opening Stuck Blast Door

Evaluations of ERSF systems for opening stuck/jammed blast doors are given in Table 9. Since these two systems are for different situations, i.e., opening an aircraft shelter's blast door, and opening a normal structure's blast door, comparison between the two systems serves no purpose. However, as seen from the table, both systems score well in the operational and logistic categories, and can be considered viable ERSF repair options. The strength category is not applicable to this type of repair.

10. Window Replacement

Evaluations of ERSF window repair systems are given in Table 10. The acrylic panel system's score is 29.7 (77 percent), which is slightly lower than the plastic sheeting system's score of 30.5 (79 percent).

In the operational category, the sheeting system scored highest, because of the simple materials, equipment, and procedures required to accomplish a repair. The sheeting system scored higher than the acrylic panel system on all operational criteria but three; environmental range, redundancy, and transportability.

In the structural category, the acrylic system scored much higher than the sheeting system on all criteria, due to the fragile nature of the sheeting system. Additionally, the sheeting system provides only marginal airtightness, which could be quickly compromised by tears and punctures.

TABLE 9. EVALUATION MATRIX FOR BLAST DOOR OPENING ERSF SYSTEMS.

		Scores For Candidate ERSF Systems	
Category	Criterion	Other Blast Door	Aircraft Shelter Blast Door
Operational	Manpower	4	4
	Safety	4	4
	Simplicity	5	5
	Versatility	3	2
Weight Factor 0.40	Skill Requirements	4	4
	Heavy Equipment	3	2
	Environmental Range	4	4
	# Of Components	4	4
	Special Equipment	4	5
	Redundancy	4	4
	Transportability	3	3
	Category Score	42	41
	Weighted Score	16.8	16.4
Structural	Strength	---	---
Weight Factor 0.30	Durability	---	---
	Blast Resistance	---	---
	Fragment Resistance	---	---
	Airtightness	---	---
	Category Score	---	---
	Weighted Score	---	---
Logistic	Storage Life	4	4
	Cost	5	4
Weight Factor 0.30	Reliability	4	4
	Maintainability	4	4
	Peacetime Use	3	3
	Availability	4	4
	Category Score	24	23
	Weighted Score	7.2	6.9
	Total Score	24.0 (62%)	23.3 (61%)

TABLE 10. EVALUATION MATRIX FOR WINDOW REPLACEMENT ERSF SYSTEMS.

		Scores For Candidate ERSF Systems	
Category	Criterion	Acrylic Panels	Plastic Sheeting
Operational	Manpower	4	5
	Safety	4	5
	Simplicity	4	5
	Versatility	4	5
Weight Factor 0.40	Skill Requirements	4	5
	Heavy Equipment	4	5
	Environmental Range	4	4
	# Of Components	4	5
	Special Equipment	4	5
	Redundancy	4	4
	Transportability	5	5
	Category Score	45	53
	Weighted Score	18.0	21.2
Structural	Strength	4	1
Weight Factor 0.30	Durability	4	1
	Blast Resistance	3	1
	Fragment Resistance	3	1
	Airtightness	3	2
	Category Score	17	6
	Weighted Score	5.1	1.8
Logistic	Storage Life	4	4
	Cost	4	5
Weight Factor 0.30	Reliability	4	4
	Maintainability	4	4
	Peacetime Use	3	4
	Availability	3	4
	Category Score	22	25
	Weighted Score	6.6	7.5
	Total Score	29.7 (77%)	30.5 (79%)

In the logistic category, the sheeting system scored slightly higher than the acrylic system, again because of the simple materials and equipment it requires.

Based on weighted scores, both the acrylic panel and plastic sheeting systems are viable ERSF systems. Each system has its advantages. An acrylic panel repair is structurally stronger, while a plastic sheeting repair is easier and faster to install.

11. Aircraft Shelter Floor Slab Repair

Evaluations of ERSF aircraft shelter floor slab repair systems are given in Table 11. The AM2 system scored highest with 26.8 (70 percent), followed by rapid-set concrete at 25.4 (66 percent) and shotcrete at 20.2 (52 percent).

In the operational category, the AM2 system scored highest, because of the simple materials, equipment, and procedures required to accomplish a repair. However, the system's versatility score was only average, because the height of uplifted pavement it can ramp is limited by the maximum AM2 panel length of 6 feet (See Section IV-d.3.j.(3)). The rapid-set concrete system scored higher than the shotcrete system, because it is less complex and does not require a specialized piece of equipment.

In the structural category, the shotcrete and rapid-set concrete systems scored much higher than the AM2 system on all criteria. Both systems are much stronger and durable than the AM2. However, the shotcrete system scored slightly higher than the rapid-set concrete system on strength and durability, because it contains steel fibers.

In the logistic category, the AM2 system scored higher, due to its simple nature. The AM2 system's equipment and supplies can easily be stored for long periods of time. Conversely, the shotcrete and rapid-set concrete systems require more monitoring during storage to ensure they will operate when needed.

The AM2 system should be used when the required ramp height is not excessive in relation to its 6-foot length. For other cases, the rapid-set concrete system should be used. A recommendation concerning use of the shotcrete system cannot be made until system development is completed.

TABLE 11. EVALUATION MATRIX FOR AIRCRAFT SHELTER FLOOR SLAB ERSF SYSTEMS.

		Scores For Candidate ERSF Systems		
Category	Criterion	Shotcrete* Ramp	R. S. Concrete Ramp	AM2 Ramp
Operational	Manpower	2	3	3
	Safety	3	4	4
	Simplicity	3	3	5
	Versatility	4	4	3
Weight Factor 0.40	Skill Requirements	3	4	5
	Heavy Equipment	3	5	5
	Environmental Range	3	3	5
	# Of Components	2	4	4
	Special Equipment	2	4	4
	Redundancy	3	3	4
	Transportability	3	4	4
	Category Score	31	41	46
	Weighted Score	12.4	16.4	18.4
Structural	Strength	5	4	1
Weight Factor 0.30	Durability	5	4	1
	Blast Resistance	---	---	--
	Fragment Resistance	---	---	--
	Airtightness	---	---	---
	Category Score	10	8	2
	Weighted Score	3.0	2.4	0.6
Logistic	Storage Life	3	3	5
	Cost	2	4	4
Weight Factor 0.30	Reliability	3	4	4
	Maintainability	3	4	5
	Peacetime Use	2	3	4
	Availability	3	4	4
	Category Score	16	22	26
	Weighted Score	4.8	6.6	7.8
	Total Score	20.2 (52%)	25.4 (66%)	26.8 (70%)

* System still under development by AFESC/RDCS

C. SUMMARY

For each damage mode discussed in Section IV, several candidate repair systems were evaluated in-depth in this section. At least one repair system was evaluated as satisfactory for each damage mode. For some damage modes, such as column and wall replacement, several ERSF systems were identified.

At the present time, shotcrete-based ERSF systems do not rank highly, because too many unknowns exist with respect to suitable equipment and material storage requirements. These unknowns are discussed in the following paragraph. They are currently being addressed by AFESC/RDCS, and once addressed, will determine the suitability of a shotcrete system for ERSF.

If the equipment and storage issues can be resolved, the shotcrete system is highly desriable for ERFS because of its versatility. First, shotcrete repairs provide substantial structural benefits in the areas of strength, durability, blast resistance, fragment penetration resistance, and airtightness. Second, if a shotcrete system can be used for ERSF, the number of repair systems a FOB must support can be reduced. Shotcrete can be used for wall replacement, wall breach repair, roof breach repair, ramp construction, and in some cases, shoring of damaged steel framed structures. Third, if the Base Commander or BCE at a FOB puts great emphasis on blast and fragment penetration resistance of expedient repairs, a shotcrete system becomes much more desirable. For these reasons, and if the problems already discussed can be solved, an ERSF shotcrete system would provide significant benefits to a FOB in a postattack environment.

The two serious unknowns with a shotcrete-based ERSF system have already been briefly mentioned. The first unknown involves identifying dry-mix shotcrete equipment suitable for ERSF. Desired features of the equipment include high mobility; large on-board storage of shotcrete material, water, and other additives (if any); a sufficient material application rate to meet required repair times; and, if possible, an semiautomated application process. The second concern is the moisture-sensitive nature of the shotcrete material. If the material is left uncovered in the rain, or in high humidity conditions, it will begin to set up. This problem might be solved by storing the shotcrete material in plastic-lined, puncture-resistant bags under cover to ensure dry conditions.

In the following section, field demonstrations of three ERSF system are described. The demonstrated systems are the glulam column replacement system, the column splint system, and the shotcrete wall replacement and wall breach repair system.

SECTION VI

ERSF SYSTEM FIELD DEMONSTRATIONS

A. BACKGROUND

Three ERSF systems were field-demonstrated during 1990. The demonstrated systems were; 1) the column splint system, 2) the glulam column replacement system, and 3) the shotcrete wall replacement and wall breach repair system. The goal of each demonstration was to validate the concept of the system, with respect to equipment, materials, supplies, procedures, and personnel. When possible, Air Force personnel were used to accomplish the repairs, after receiving the required training. If Air Force personnel were not available, SETA personnel were used. Summaries of each demonstration are given below.

B. DEMONSTRATION PLAN

A field demonstration plan was developed to conduct the field demonstrations indicated above (Reference 20). This plan described the responsibilities, coordination, materials, supplies, equipment, personnel, etc., needed to conduct the demonstrations. The plan also specified data collection requirements. When necessary, applicable portions of the demonstration plan are included in the following descriptions of the demonstration results.

C. COLUMN SPLINT SYSTEM FIELD DEMONSTRATION

1. Prototype Column Splint Design

a. Design Approach

Instead of determining the exact splinting force required to bring a cracked column to its original structural condition, a splint of known capacity, made of steel plates, threaded rods, washers, and nuts, can be used to prevent further movement along the fracture plane. The reason the problem is approached in this way is due to the very complex structural behavior of a cracked reinforced concrete column.

The structural behavior, and hence the remaining structural strength of a cracked column, depends on many factors. First, what is the column load and is there any eccentricity in the loading? Second, is the concrete cracked the entire way through the column? Third, how much horizontal resistance is the rebar within the column providing? Forth, what is the friction coefficient for cracked concrete? All of these factors will vary from column to column, making the analysis well outside the scope of ERSF.

b. Splint Design

The prototype column splint design used during the demonstration is shown in Figures 32 to 34. This design, which utilized materials already on-hand at AFESC/RD's operations branch (AFESC/RDCO), consisted of four turnbuckles, attached to two 1/2-inch thick, 24- by 16-inch rectangular steel plates by chains, having 3/8-inch diameter links. The idea of replacing the chains and turnbuckles by threaded rods evolved from the demonstration. This splint, once placed around a cracked column, will provide lateral restraint to the column, thereby resisting further slippage of the column along the crack face.

A summary of a conservative structural analysis of the prototype column splint capacity is given in Table 12. Based on this analysis, the capacity of the splint used in the demonstration was less than 5,000 pounds. As illustrated in Figure 35, this splint capacity is insufficient for ERSF. Typical column loads will be over 150,000 pounds, and corresponding splinting forces of over 25,000 pounds are required. However, before the splint was redesigned to increase its capacity, it was used in the field demonstration. This was done for two reasons. First, even through the capacity of the splint was known to be insufficient, it would still allow the validity of the column-splinting concept to be evaluated. Second, any operational problems involving the use of the splint would be uncovered during the demonstration. Consequently, ways to solve these problems would be incorporated into the new, higher capacity splint design.

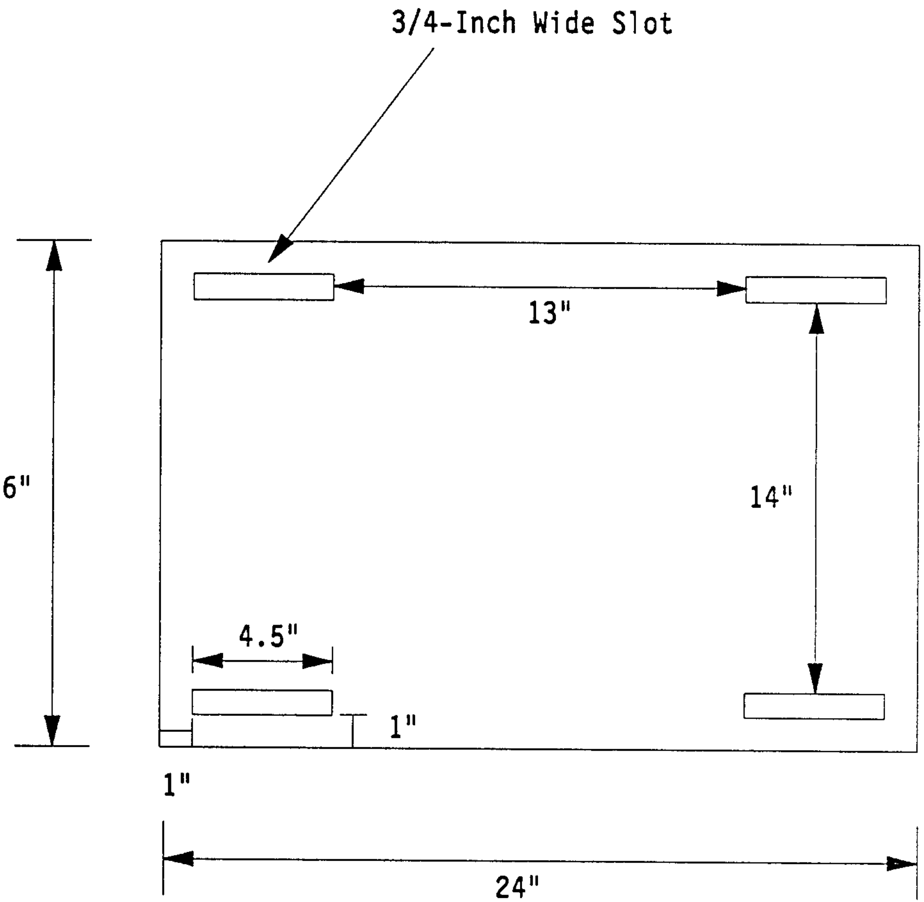


Figure 32. Plate Detail of Prototype Column Splint.

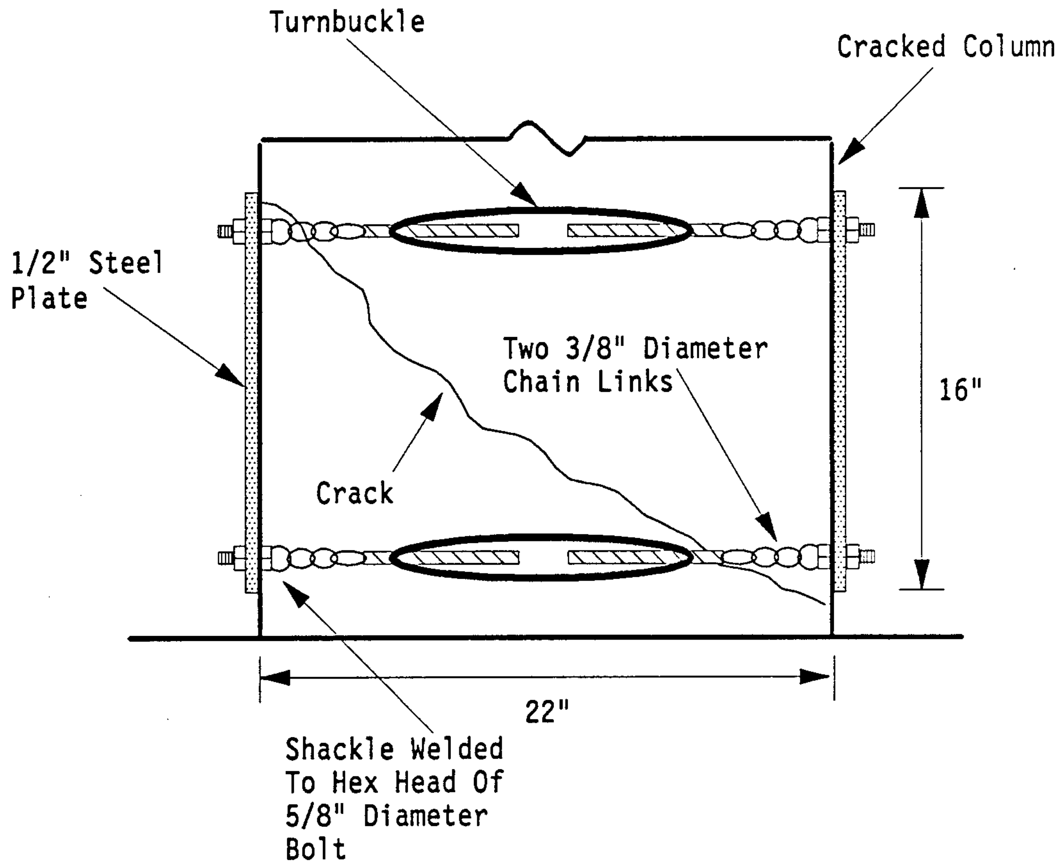


Figure 33. Side View of Prototype Column Splint.

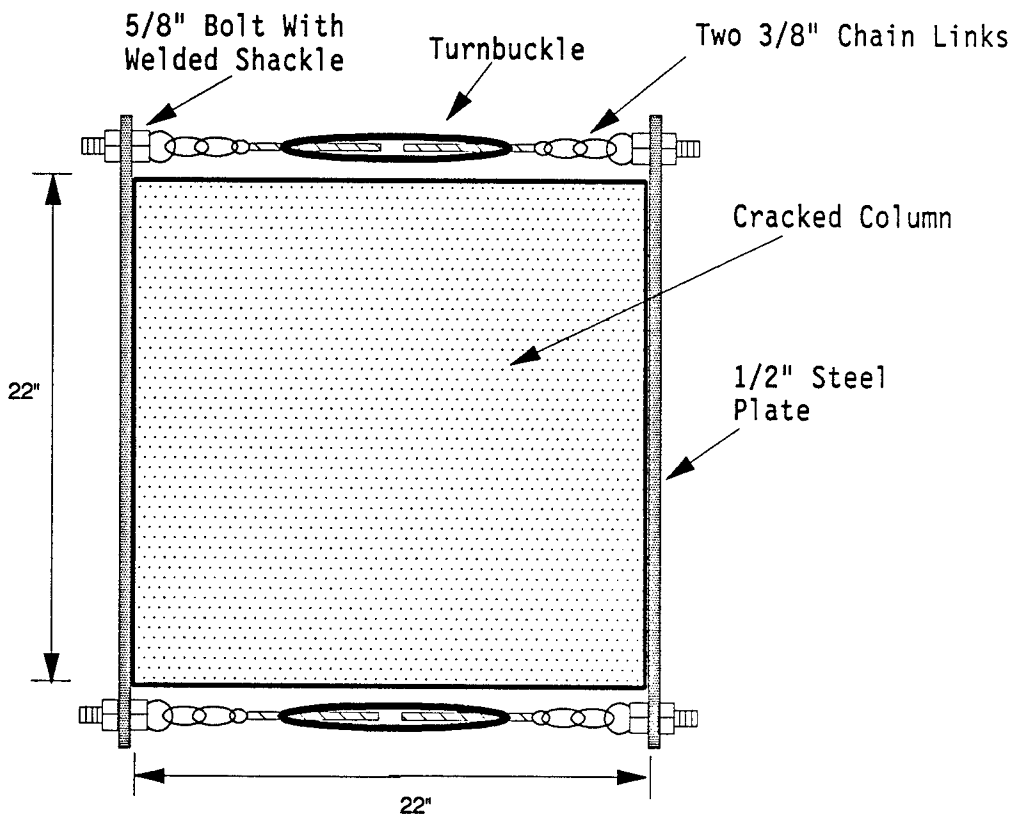


Figure 34. Top View of Prototype Column Splint.

TABLE 12. SUMMARY OF THE STRUCTURAL ANALYSIS OF PROTOTYPE SPLINT.

STRUCTURAL COMPONENT	CAPACITY (POUNDS)	STRESS (PSI)	SOURCE
1/2 INCH THICK STEEL PLATE (Fu=58ksi)	28,000 (7,000 PER ATTACHMENT POINT, 4 POINTS PER PLATE)	0.9Fu	SAP90*
5/8 INCH HEX HEAD BOLTS, ASTM GRADE 449 (Fu=120ksi)	97,600 (24,400 PER BOLT, 4 BOLTS PER PER PLATE)	0.9Fu	AISC
3/8 INCH CHAINS, HIGH STRENGTH (GRADE 80)	28,400 (7,100 PER CHAIN, 4 CHAINS PER SPLINT)	N/A	MCMASTER-CARRIER CATALOG
1/2 INCH TURNBUCKLE	8,800 (2,220 PER TURNBUCKLE, 4 TURNBUCKLES PER SPLINT)	N/A	MCMASTER-CARRIER CATALOG
CHAIN TO BOLT WELDS, E70 ELECTRODE	38,000 (9,500 PER WELD, 4 WELDS PER PLATE)	0.9Fu	AISC

SPLINT CAPACITY: 8,800 POUNDS (TURNBUCKLE GOVERNS)

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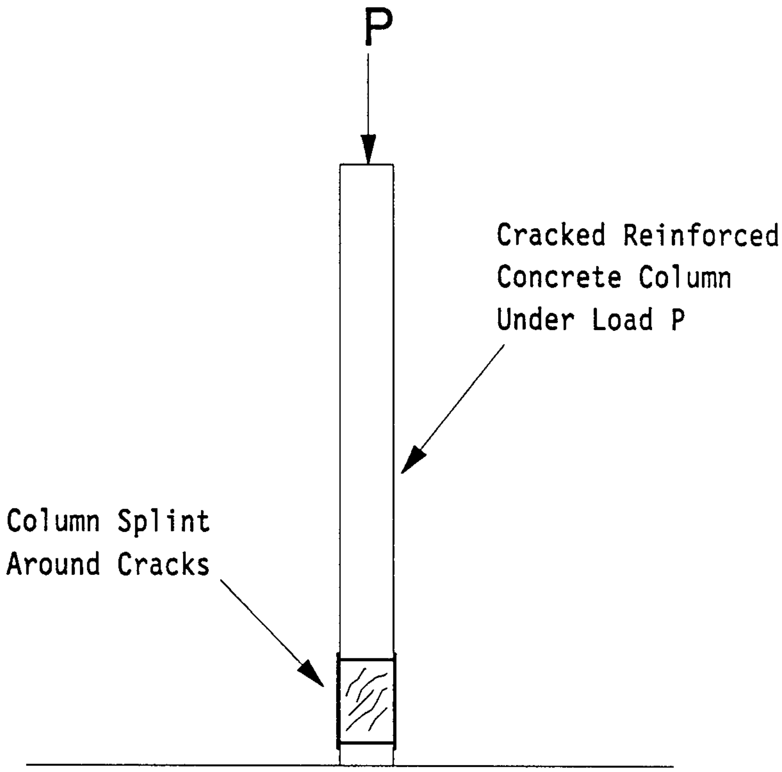
* BASED ON STRUCTURAL ANALYSIS OF 1/2 INCH, THICK SLOTTED STEEL PLATE USING THE FINITE ELEMENT STRUCTURAL ANALYSIS PROGRAM SAP90.



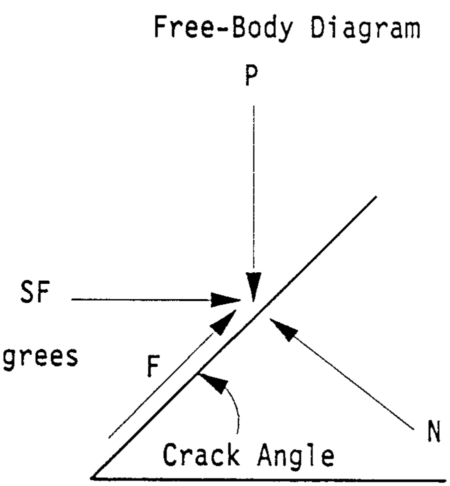
Splinting Force Calculations

Where:

SF = Splinting Force
F = Friction Force
N = Normal Force
P = Column Load

Given:

Crack Angle = 45 Degrees (Demo)
Concrete Friction
Coefficient (u) = 0.7, ∅ = 35 Degrees
Column Load = 150K



Required:

Splinting Force (SF) = P(Tan(B))

Where

B = Crack Angle - ∅ = 10 Degrees

Thus

SF = 150K(Tan(10)) = $\boxed{26.4K}$

Figure 35. Typical Required Column Splint Capacity.

2. Demonstration Description

On 23 February 1990 at the NATO structure, located at the SKY TEN explosive test area, Tyndall AFB, Florida, AFESC/RDCS conducted a field evaluation/demonstration of the ERSF column splint system. The demonstration was done using the cracked, 22-inch square reinforced concrete column of the NATO structure, shown in Figure 36.

The splinting process was accomplished three times, using two SETA personnel. Because SETA personnel were familiar with the splinting process and hardware, no formal training was needed before testing began. Splinting was done twice at the bottom of the column, at the location of the crack, and once at a location approximately 4 feet high on the column. Splinting 4 feet high on the column was done using sections of two-by-four lumber to prop the plates up against the sides of the column while the turnbuckles, nuts, and bolts were tightened. There were no major difficulties encountered during the splinting process 4 feet high on the column, nor when splinting was done at the bottom of the column. Views of the column splinting process are shown in Figures 37 through 40.

In general, the splinting process was accomplished as follows. The splint plates, with chains preattached to one plate with nuts and bolts, were positioned at the correct height on the column, as shown in Figure 37 (bottom of column) and Figure 38 (4 feet high on column). At the 4-foot height, rope was used to bind the two-by-fours to two sides of the column. The chains were then connected to the other plate with nuts and bolts, as shown in Figure 39, then tightened to clamp both plates to the column. The chain tightening process is shown in Figure 40.

3. Demonstration Results And Conclusions

Test results are summarized in Table 13. The splinting process took from 4 minutes and 27 seconds to 7 minutes and 38 seconds to complete. Even through the splinting process was very rapid, it was determined during the demonstration that using chains, turnbuckles, and nuts and bolts to clamp the plates against the column made the process more cumbersome and time-consuming than necessary. This problem can be solved by using threaded rods that pass through the slots in the plates, which also solves the load

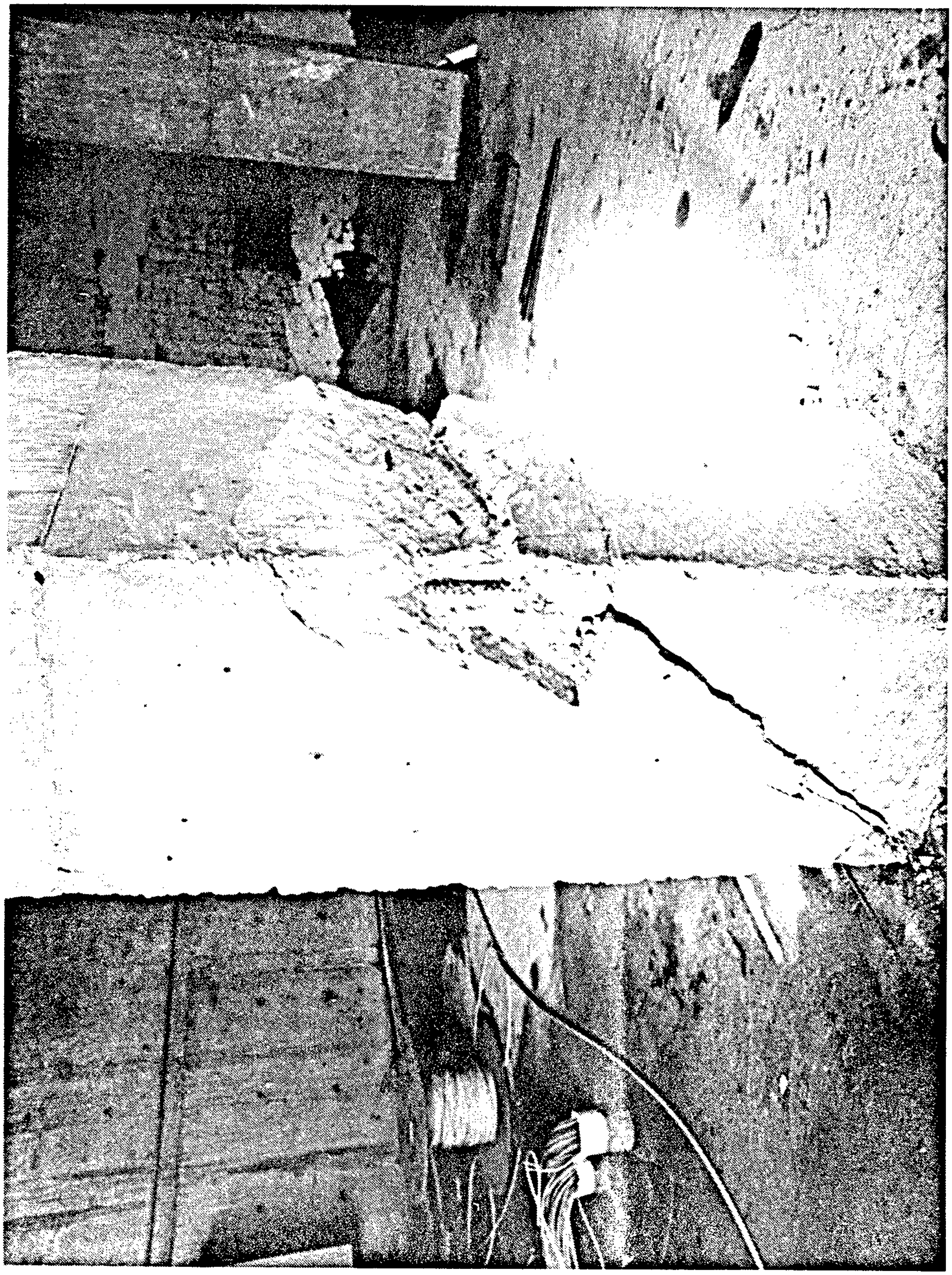


Figure 36. Cracked Concrete Column Used for the Column Splint Field Demonstration.

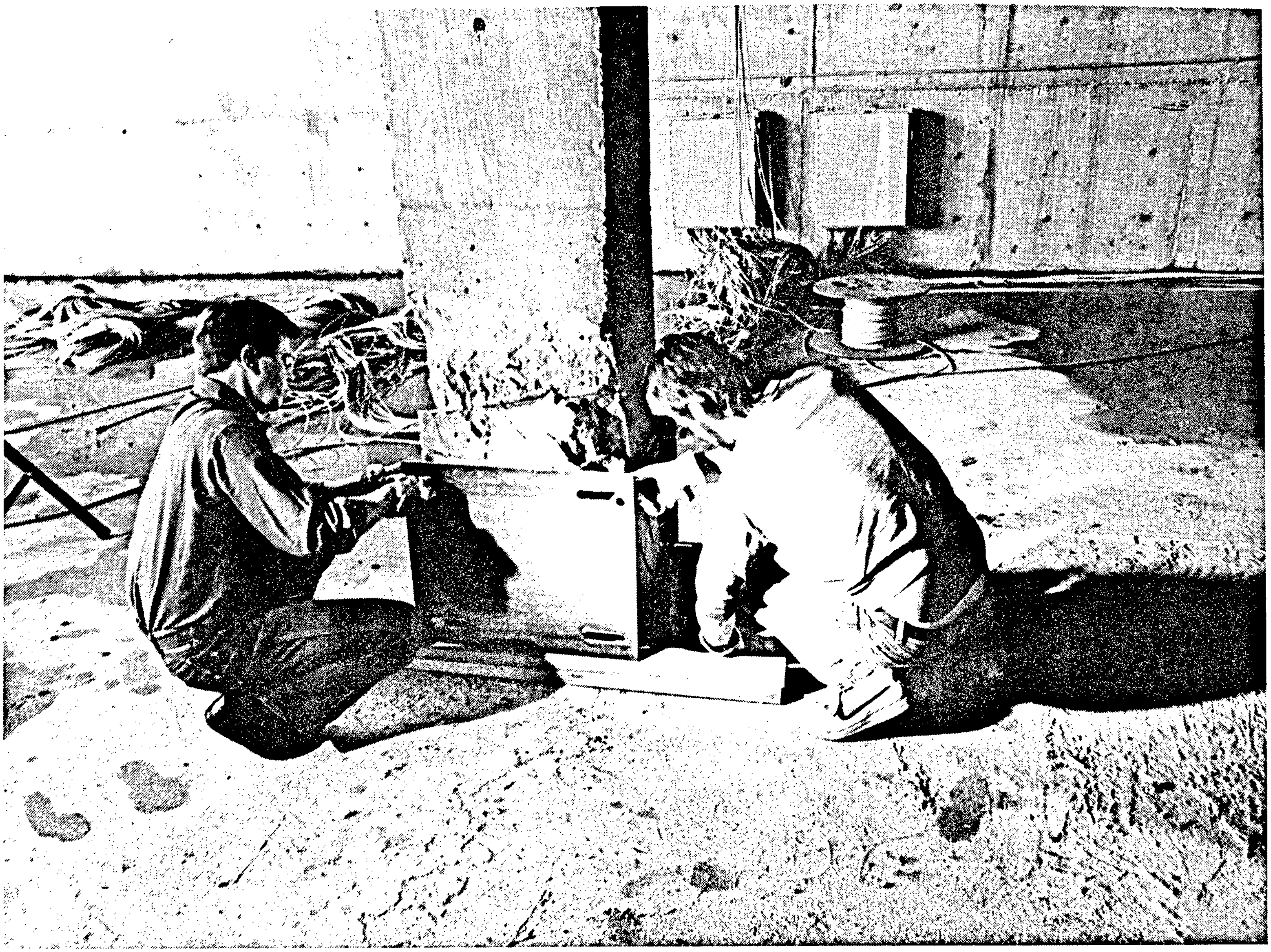


Figure 37. Positioning Splint Plates at the Bottom of the Column.

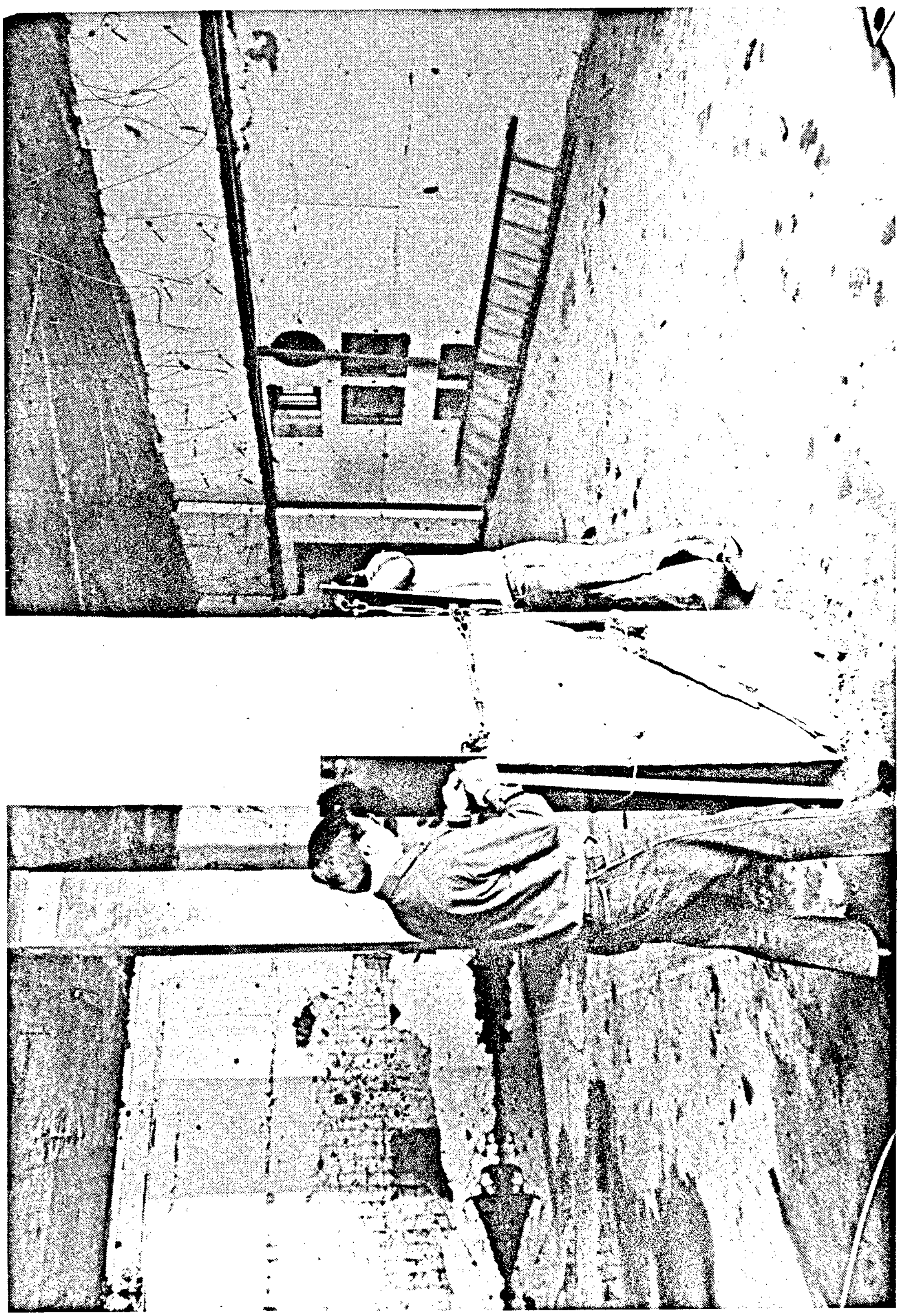


Figure 38. Positioning Splint Plates 4 Feet High On the Column.

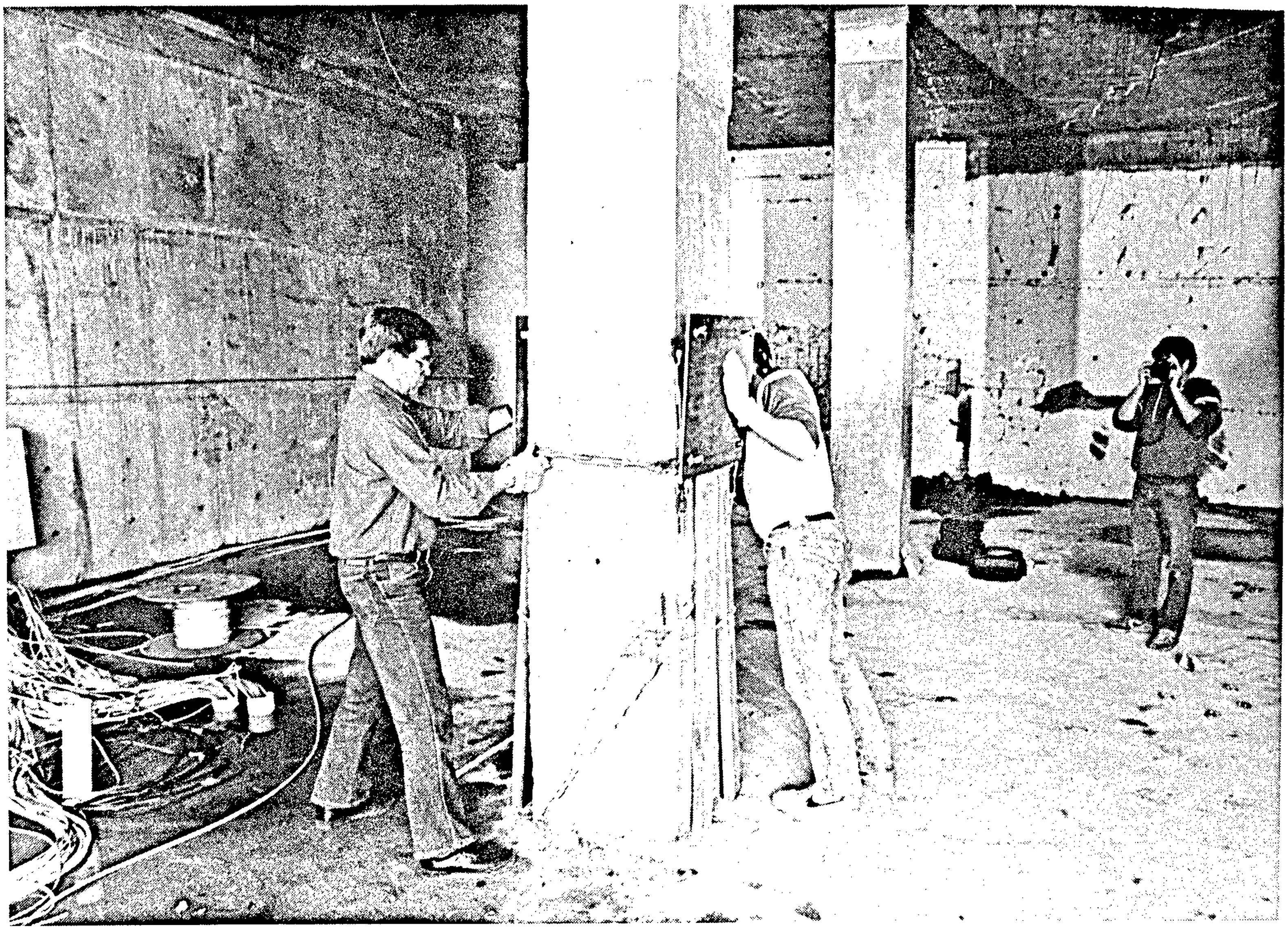


Figure 39. Placing Splint Chains Around the Column.

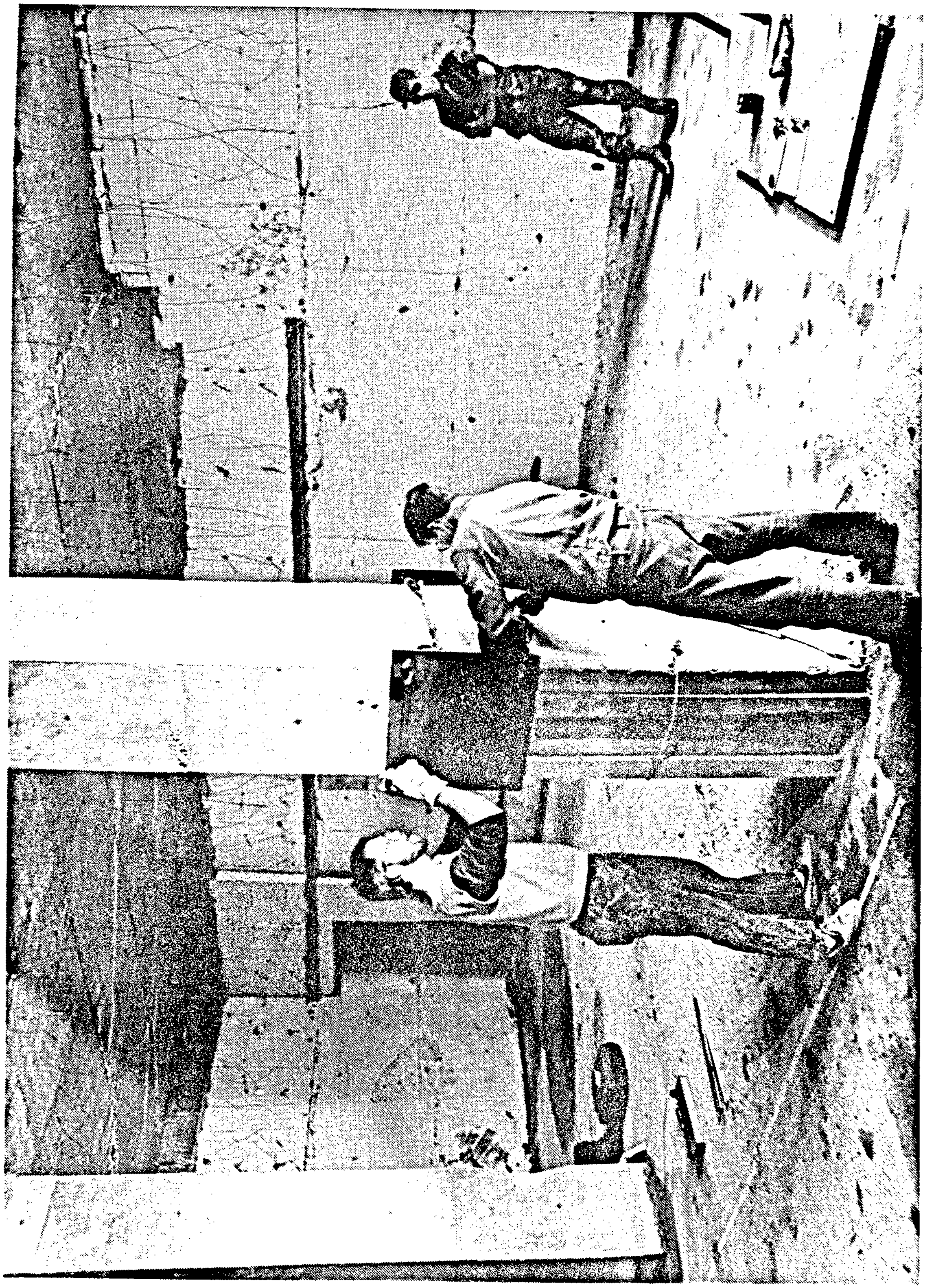


Figure 40. Tightening Splint Chains Around the Column.

TABLE 13. SUMMARY OF COLUMN SPLINTING FIELD DEMONSTRATION RESULTS.

TEST ITERATION	ACTIVITY TIME (MINUTES:SECONDS)				
	POSITION TWO-BY-FOURS	POSITION PLATES	ATTACH CHAINS	TIGHTEN SPLINT	TOTAL TIME
1*	0:12	0:18	1:50	4:17	6:37
2*	0:08	0:16	1:04	2:59	4:27
3**	0:27	0:38	0:57	5:36	7:38

* Splint placed at the bottom of the column.
** Splint placed 4 feet high on the column.

capacity problem noted above. Nuts on the outside face of the plates can quickly be tightened with ratcheted, socket wrenches to clamp the plates against the column.

Based on test results, the column splinting process is very fast and the concept is viable for ERSF. Some modifications to the splint are required to increase its capacity and make it easier to use. Once the modifications are completed, the splint will be easy to use and install, mechanically simple, and easy to store and maintain. All of the attributes just cited are highly desirable in an ERSF system. The successful demonstration of this system indicates the development, screening, and in-depth evaluation process described in Sections IV and V produces viable ERSF systems.

4. New Splint Design

The new splint design is shown in Figures 41 to 43. As indicated above, instead of using turnbuckles and chains, the new splint uses threaded rods that pass through slots in the steel plates, and nuts on the rods to clamp the plates against the side of a column. The slots in the plates, in conjunction with the threaded rods, allow the width and length of the splint to be adjusted to accommodate different column dimensions. The capacity of this splint, which is summarized in Table 14, is 28,000 pounds. Any future testing with the column splint will use this new design.

D. GLULAM COLUMN REPLACEMENT SYSTEM FIELD DEMONSTRATION

1. Column Design

a. Column Dimensions

Following the National Design Specification For Wood Construction (NDS) (Reference 21), the effective column length, l_e, of a compression member can be calculated from:

$$l_e = k_e l \tag{11}$$

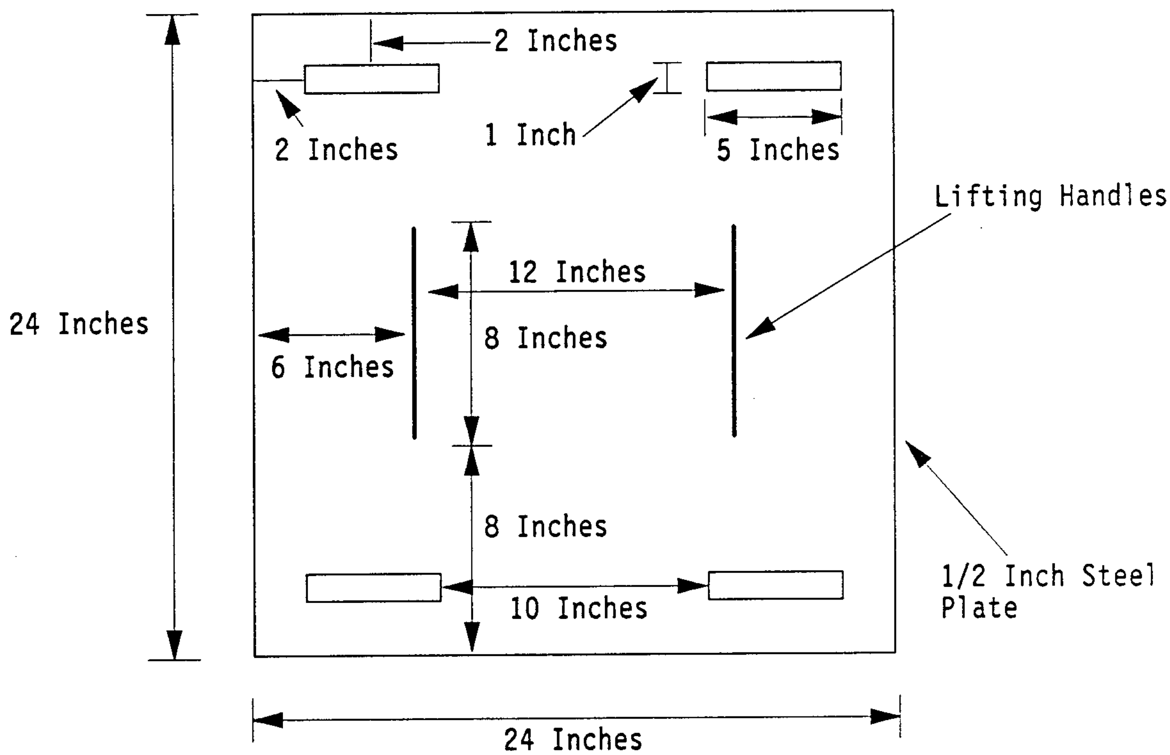


Figure 41. Plate Detail of New Column Splint Design.

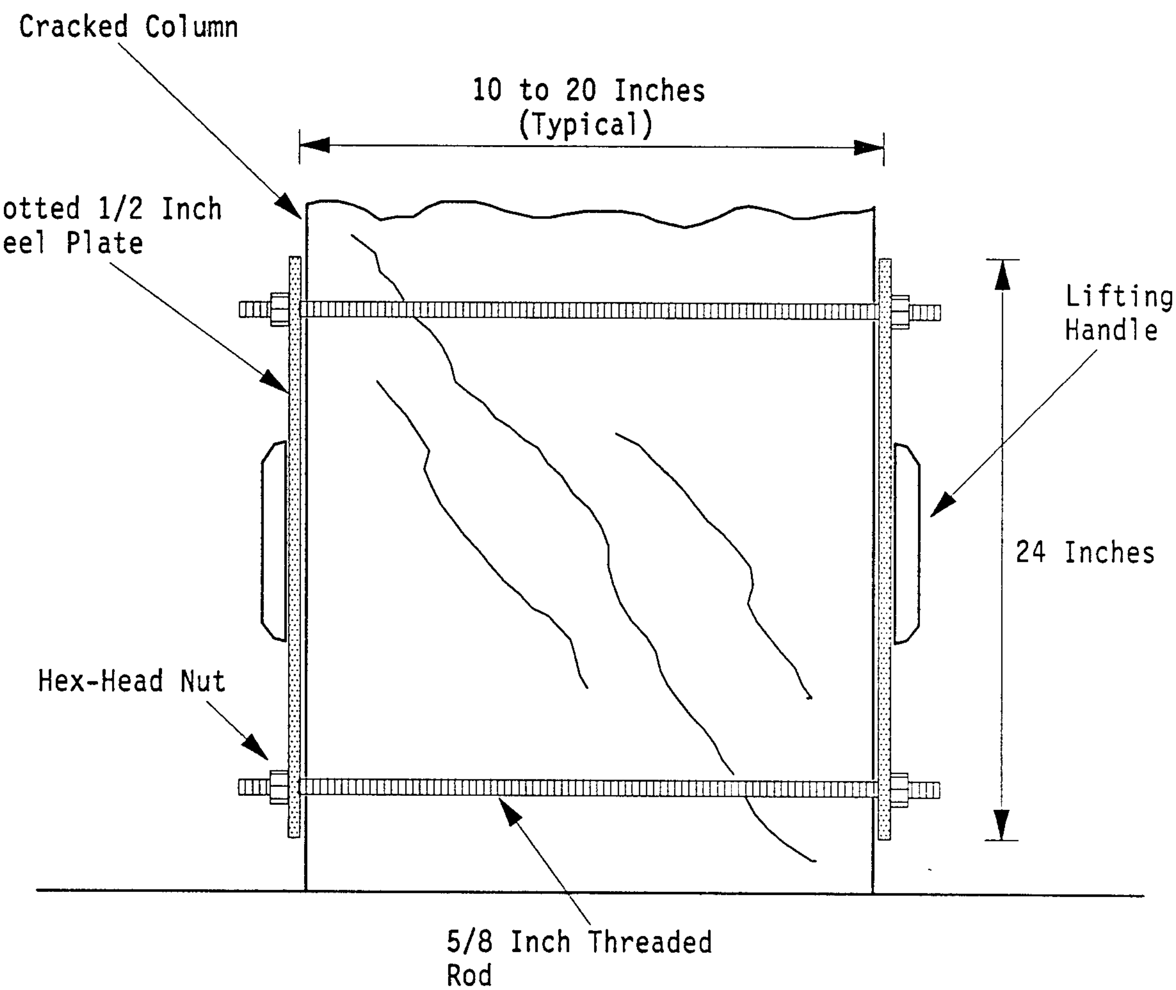


Figure 42. Side View of New Column Splint Design.

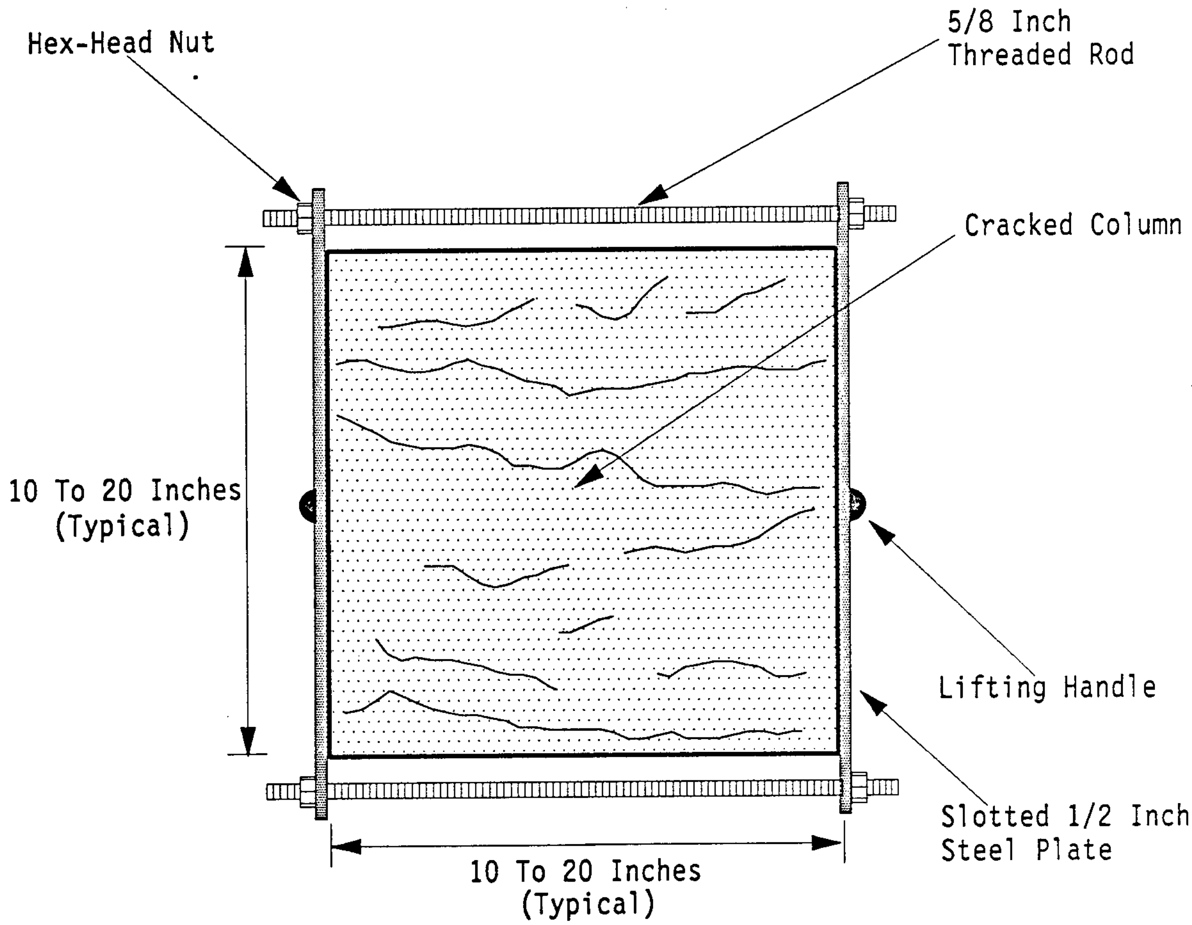


Figure 43. Top View of New Column Splint Design.

TABLE 14. SUMMARY OF STRUCTURAL ANALYSIS OF NEW SPLINT DESIGN.

STRUCTURAL COMPONENT	CAPACITY (POUNDS)	STRESS (PSI)	SOURCE
1/2 INCH THICK STEEL PLATE (Fu=58ksi)	28,000 (7,000 PER ATTACHMENT POINT, 4 POINTS PER PLATE)	0.9Fu	SAP90*
5/8 INCH THREADED RODS, ATSM GRADE 449 (Fu=120ksi)	97,600 (24,400 PER ROD, 4 RODS PER PER PLATE)	0.9Fu	AISC

SPLINT CAPACITY: 28,000 POUNDS (STEEL PLATE GOVERNS)

* BASED ON STRUCTURAL ANALYSIS OF 1/2 INCH THICK, SLOTTED STEEL PLATE USING THE FINITE ELEMENT STRUCTURAL ANALYSIS PROGRAM SAP90.

where k_e is the effective buckling length factor, and l is the actual column length.

For a column with two pinned ends ($k_e = 1.0$), which are the the end conditions assumed for ERSF column replacement, and an actual length of 8.5 feet (story height of the Eglin AFB C 74 Test Range structure), and using Equation (11), l_e is:

$$l_e = (1.0)(8.5) = 8.5 \text{ feet}$$

From Section 3.7.3.1 of the NDS, assuming:

$$l_e/d < 11 \tag{12}$$

where d is the least cross-section dimension of the column, then

$$F'_c = F_c \tag{13}$$

where, F'_c is the allowable design compressive stress, and F_c is the tabulated compressive stress limit for a particular type of wood.

From Table 5B, on page 39 of the June 1988 NDS Supplement, Design Values For Wood Construction (Reference 22), F_c for Visually Graded Southern Pine glulam with 2 or 3 laminations varies from 550 to 1,850 psi. Assuming combination 47 gives an F'_c of 1,150 psi (assuming $F'_c = F_c$ as stated above).

The required cross-sectional area, A, of a timber column for a given load, P, can be calculated from:

$$A = d^2 = P/F'_c \tag{14}$$

where, d is the column width and length, assuming a square column.

From a structural analysis of the damaged C 74 structure, using the STructural Analysis And Design (STAAD-III) computer program on a personnel computer, the design column load was determined to be 130 kips (see Reference 20). Using Equation (14), the square timber column must have dimensions of:

$$d = (130{,}000/1{,}150)^{1/2} = 10.6 \text{ inches}$$

or greater. If 10.75 inches is used then:

$$l_e/d = (8.5)(12)/10.75 = 9.49$$

which is less than 11, and meets the design assumption.

b. Column Connections

The column used in the demonstration was designed as a pinned-pinned column. This assumes no bending moment can be transferred to the column at either end. Thus, the column is assumed to carry only a pure axial load. All lateral loads applied to the structure must be resisted by the remaining, undamaged columns and shear walls.

Since the replacement column is not designed to carry a bending moment, it's end connections do not need to be designed for moment transfer. Securely wedging the column in place is sufficient for axial load transfer. Wedging can be accomplished by leaving a small gap between the top of the column and the roof beam. Then wooden wedges are pounded into the gap using mallets. The column should then be braced laterally to ensure stability.

2. Demonstration Description

On 26 March 1990 at the Eglin AFB, AFESC/RDCS conducted a field evaluation/demonstration of the ERSF glulam column replacement system. The demonstration was done at the Eglin C-74 test range, using the reinforced concrete frame structure shown in Figure 44. This structure, including a 14-inch square reinforced concrete column, was severely damaged when used as a target for testing explosive munitions. The damaged column was replaced by a 10.75-inch square glulam column. The damaged column is shown in Figure 45. Engineering drawings of the column replacement process are shown in Figures 46 and 47. The column replacement process was accomplished twice, by a team of five Air Force Reserve personnel brought in for the demonstration by Mr. Bob McMahon of AFESC/DEO. The team was from the Indiana Air National Guard's

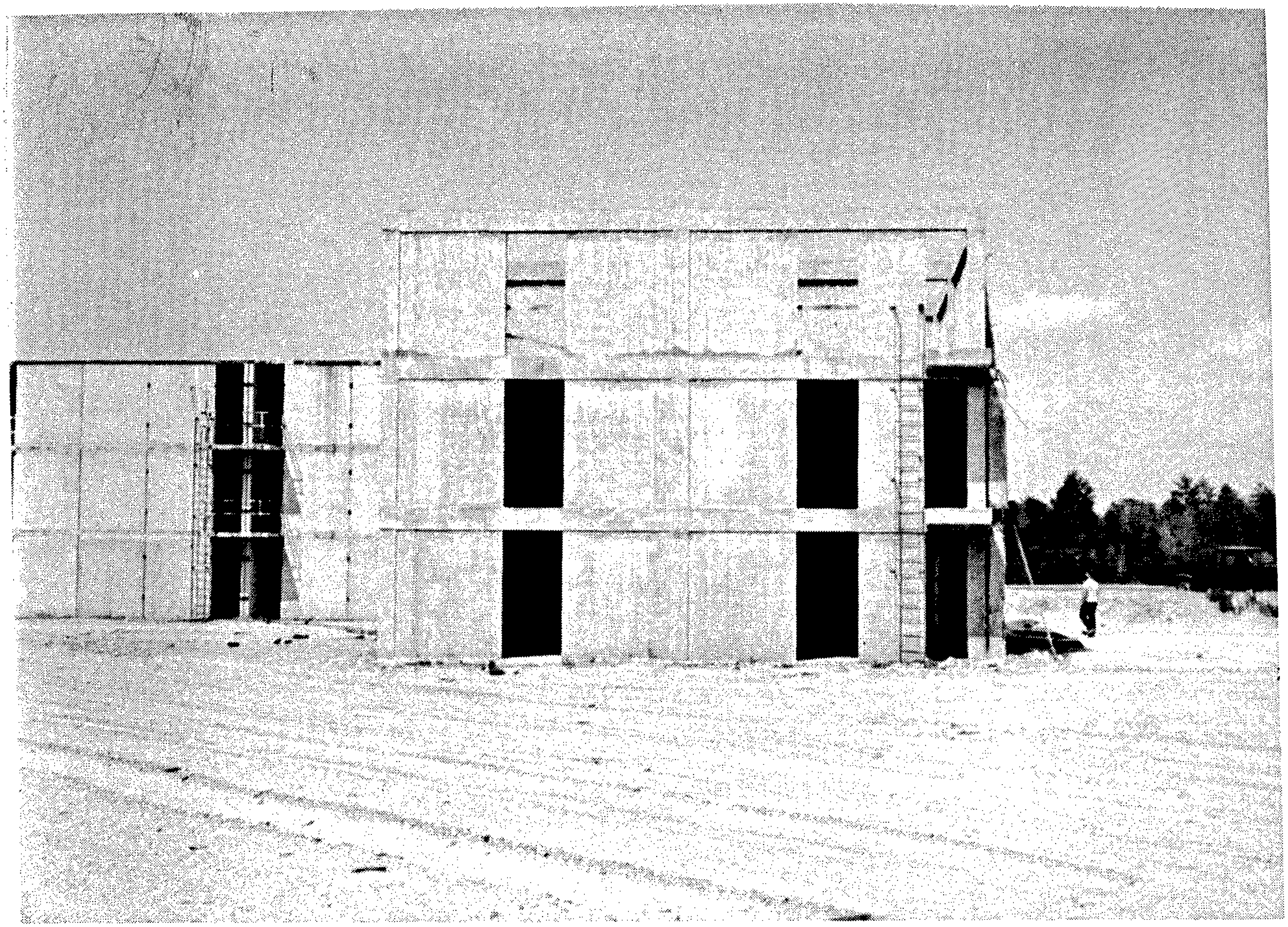


Figure 44. C 74 Structure Used for the Column Replacement Field Demonstration.

Figure 45. C 74 Structure's Destroyed Column Used for the Column Replacement Field Demonstration.

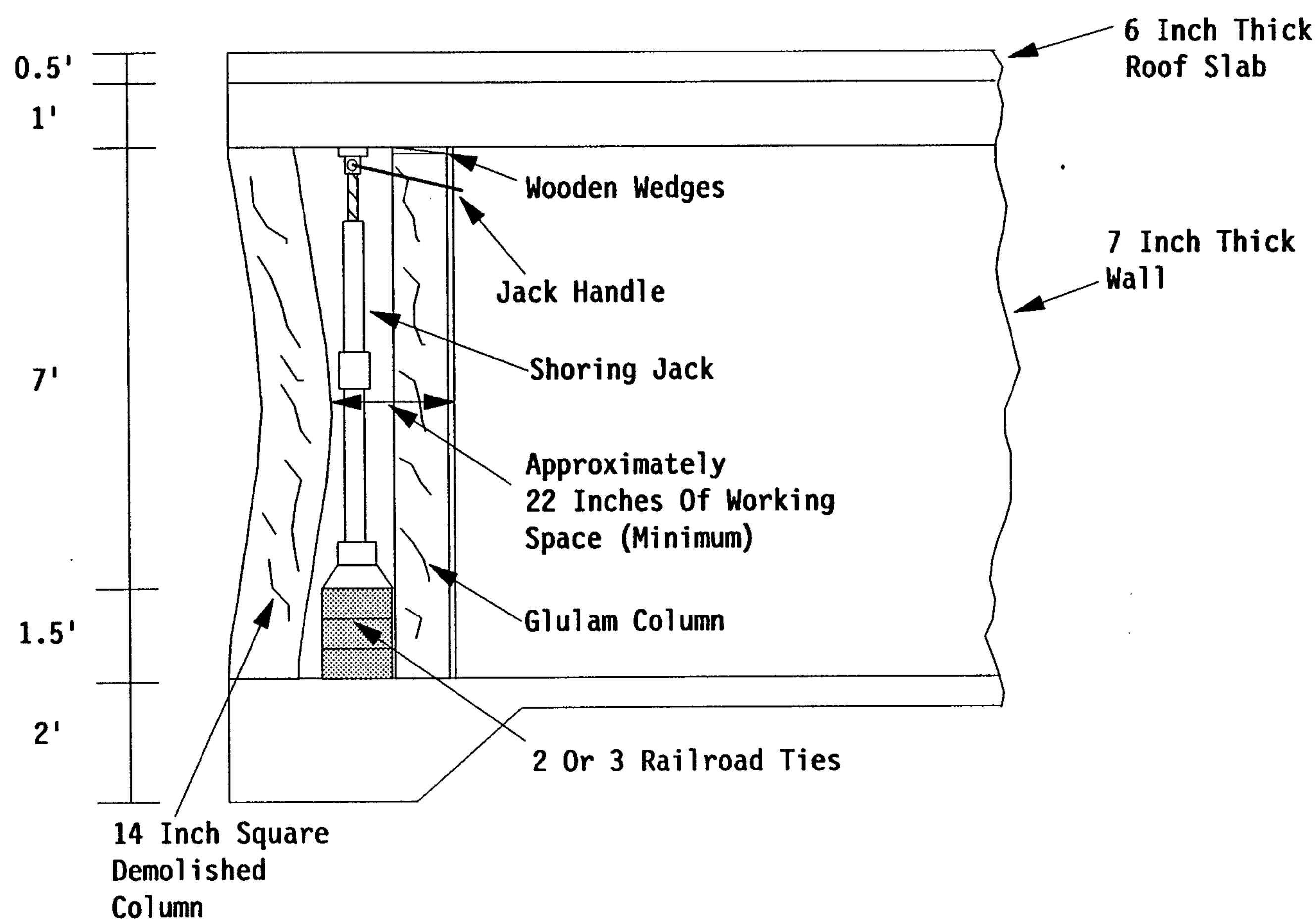


Figure 46. Detail of Column Replacement with Shoring Jack in Place.

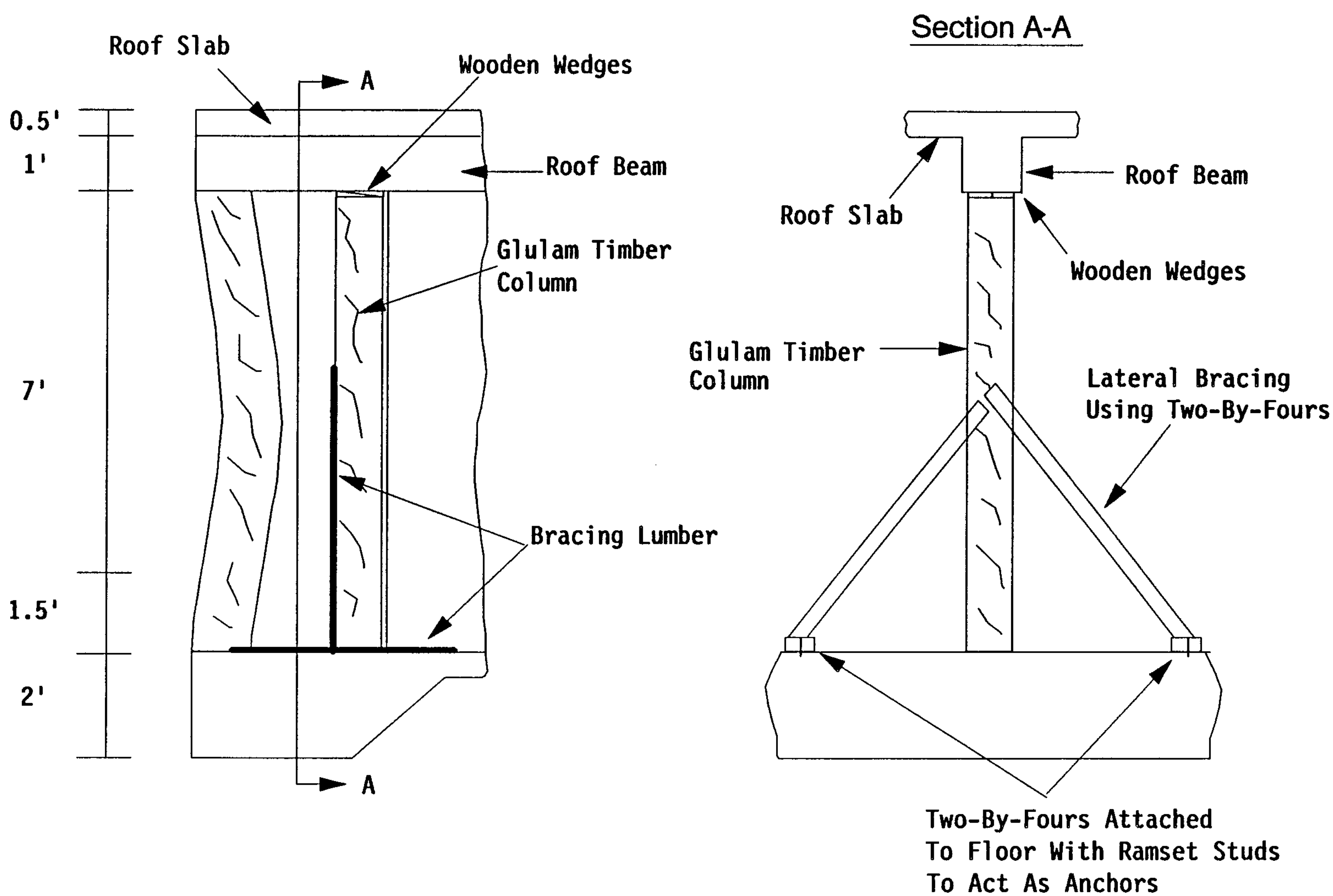


Figure 47. Detail of Column Replacement with Bracing Lumber in Place.

181st Civil Engineering Squadron, Terre Haute, IN. A list of the personnel by rank and AFSC is given below.

Position	Number	AFSC	Rank	Name
Structural Superintendent	1	55299	MSGT	Ernest A. Freeze
Structural Technician	1	55270	TSGT	Charles N. Gilbert
Structural Specialist	2	55250	SRA	James J. Matherly
			AMN	Roger L. Wright
Equipment Operator	1	55151	SGT	Alan D. Alstott

Training of the Air Force personnel was done immediately before the start of testing, by simply explaining the repair process in detail. Training took approximately 30 minutes.

Views of the column replacement process are shown in Figures 48 through 55. Debris was cleared from around the column (Figure 48). A height measurement was taken next to the damaged column, to find the required replacement column length (Figure 49). The glulam column was then trimmed to the correct length using a chainsaw (Figure 50), while a shoring jack was placed next to the damaged column and extended by hand to refusal (Figure 51). The length of the glulam column was trimmed to leave a 1/2-inch gap between the top of the column and the bottom of the roof beam. This allowed wooden wedges to be inserted between the column and the roof beam to firmly secure the column in place. The glulam column was then positioned next to the shoring jack (Figure 52), and the wedges inserted (Figure 53). Lateral bracing consisting of two-by-fours was attached to the glulam column with nails, and anchored to two-by-fours secured to the concrete floor of the structure with ramset studs (Figure 54). Finally, the shoring jack was removed (Figure 55) completing the column replacement process.

3. Demonstration Results And Conclusions

a. Test Sequence One

In this test sequence, the column replacement process took 23 minutes and 52 seconds to complete. Clock times required to accomplish

Figure 48. Debris Clearance Around Destroyed Column.

Figure 49. Height Measurement Next to Destroyed Column.

Figure 50. Trimming Glulam Timber Column to Correct Height.

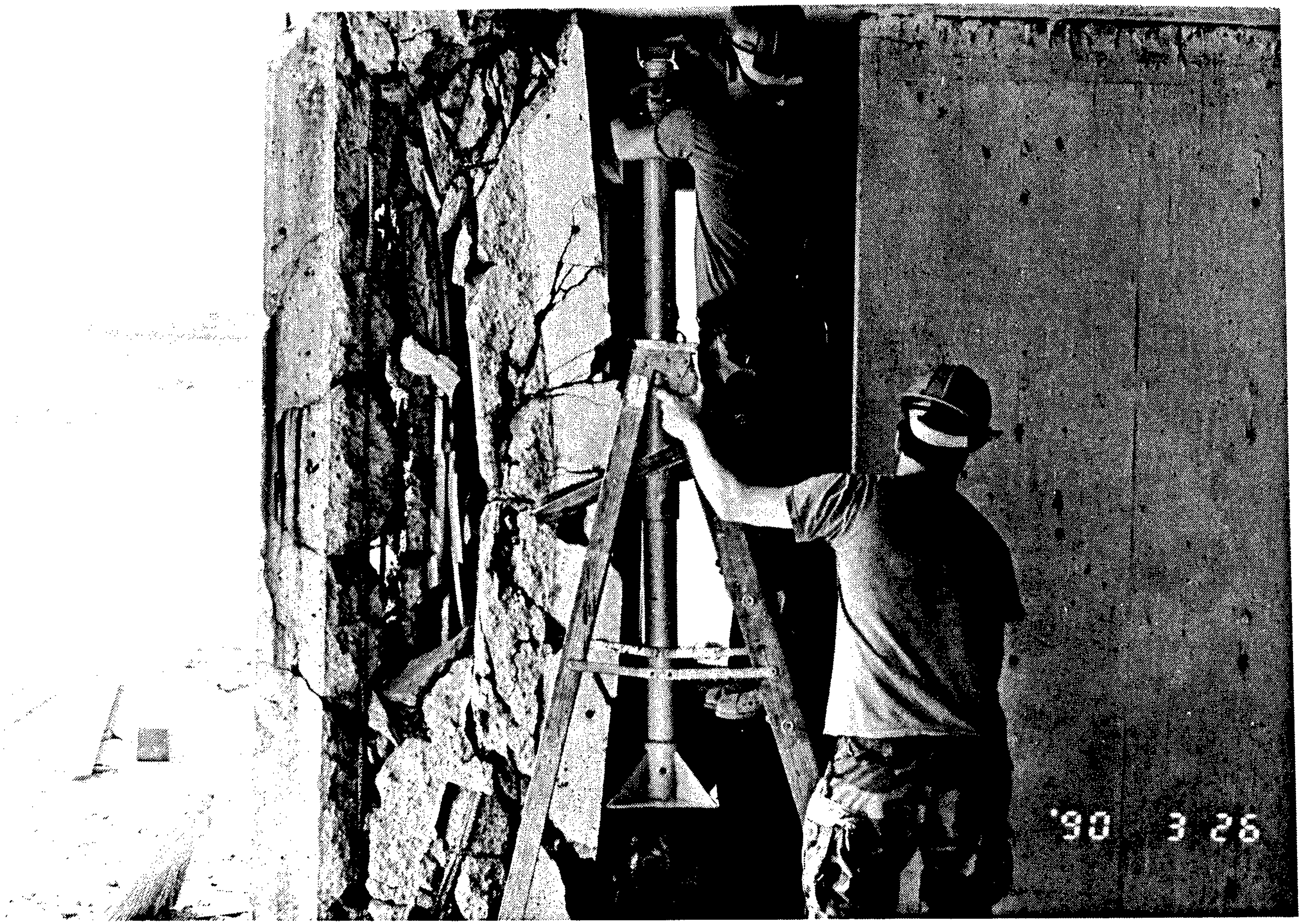


Figure 51. Placing Shoring Jack Next to Destroyed Column.

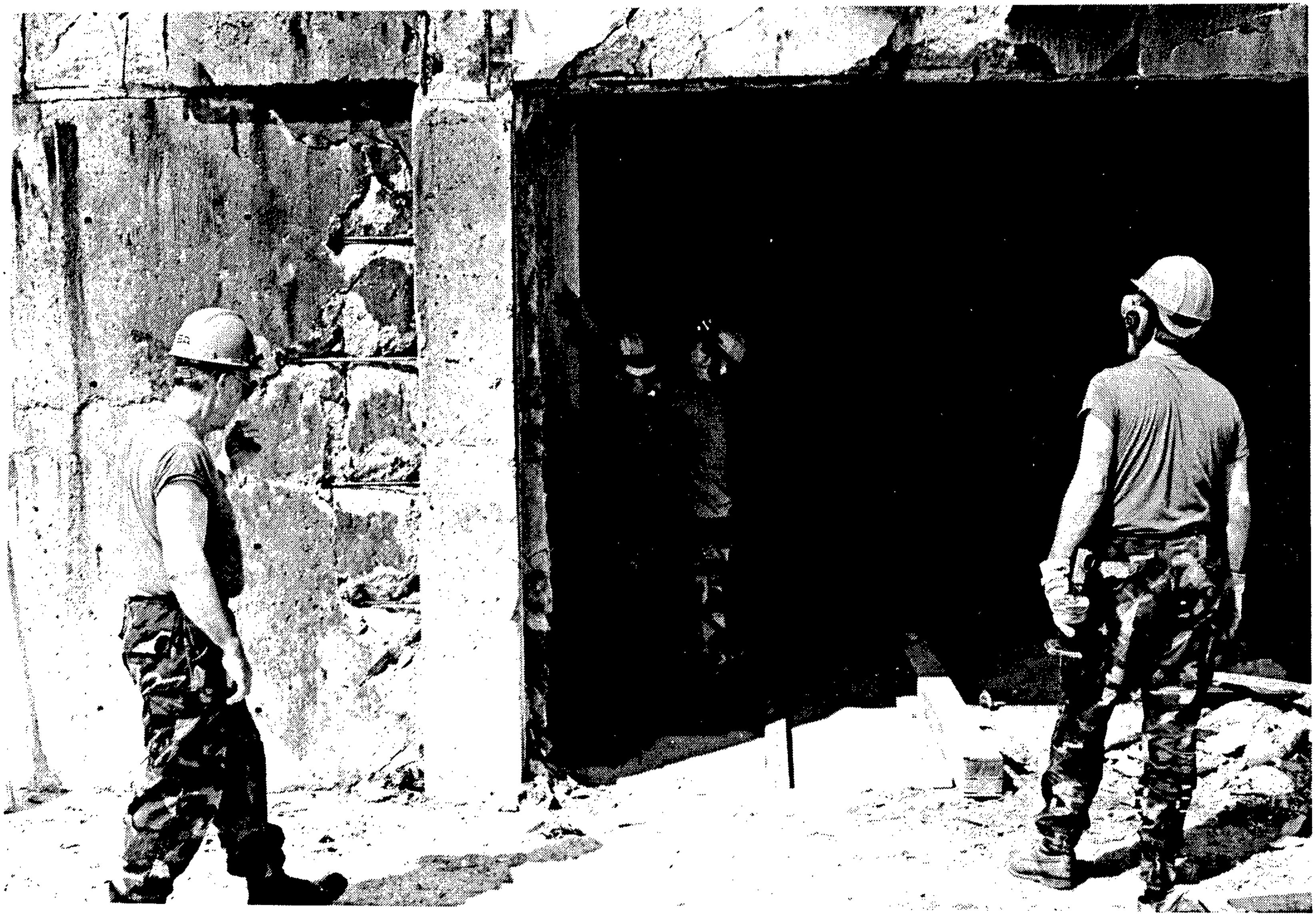


Figure 52. Placing Trimmed Glulam Timber Column Next to Shoring Jack.

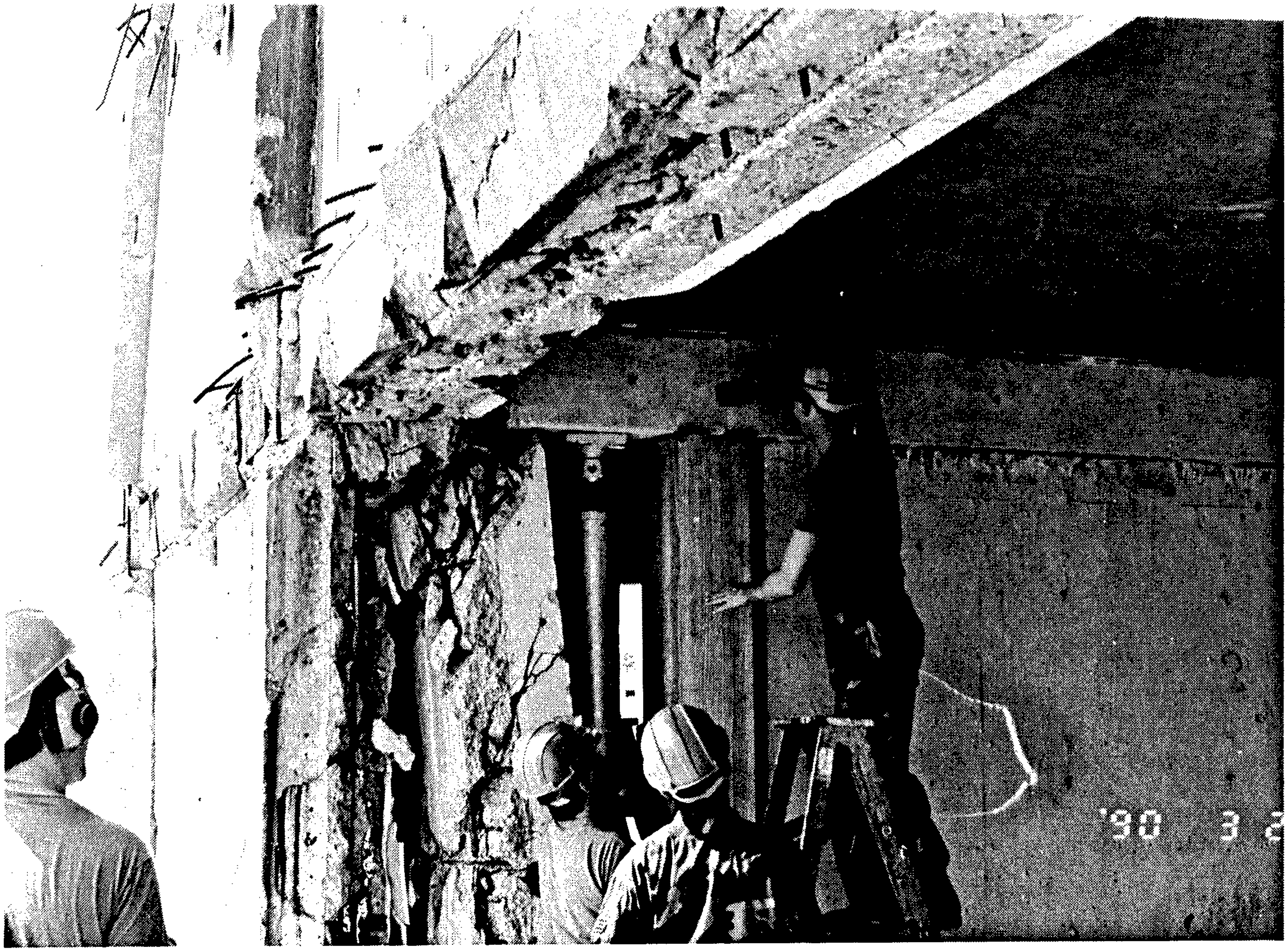


Figure 53. Inserting Wooden Wedges Between Replacement Column and Roof Beam.

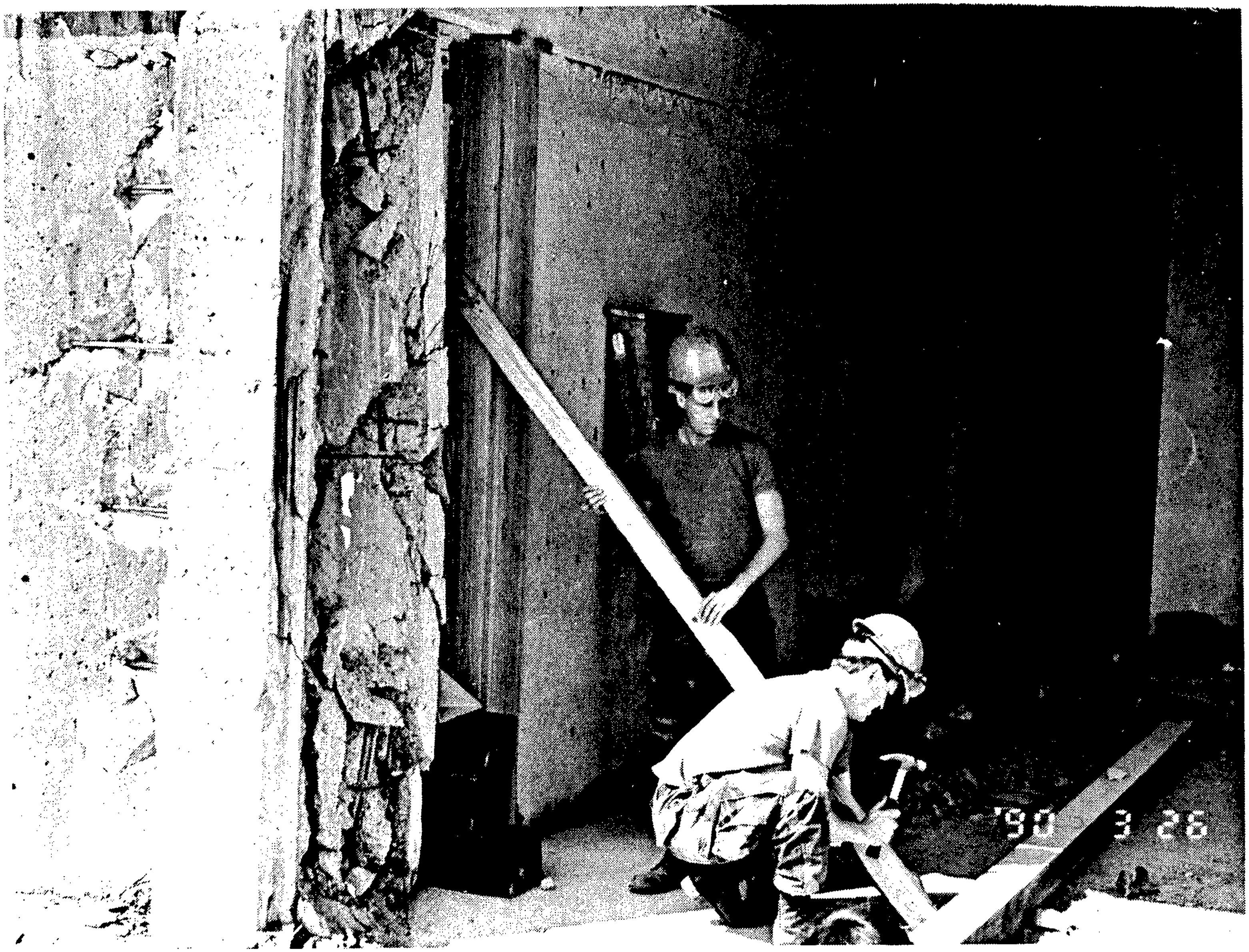


Figure 54. Attaching Lateral Bracing to Replacement Column.

Figure 55. Removing Shoring Jack to Complete the Repair Process.

individual tasks are given in Table 15. Four major problems were encountered during testing. Each problem is described below.

(1) First, the glulam column was not trimmed enough to leave the required 1/2-inch gap between the column and roof beam. The gap was only a tenth of an inch. This made placing the glulam column next to the shoring jack difficult and time-consuming. During placement, the column came in contact with the roof beam before the column was completely vertical, due to the Pythagorean effect.

(2) Second, the angle of the wooden wedges placed in the gap between the glulam column and beam was too steep. This made it difficult to pound the wedges into position with mallets. Additionally, the wedges were too short, which again made placing the wedges difficult.

(3) Third, the height of the shoring jack when fully extended was not long enough for the top of the jack to come in contact with the bottom of the roof beam when the base of the jack was placed on the floor. Consequently, the base of the jack had to be placed on wood blocks (cut up railroad ties) to obtain the required height. Using the blocks increased repair time and reduced the stability of the jack. Additionally, during this test sequence, only two wood blocks were used under the jack, and as a result, the jack had to be fully extended to come in contact with the roof beam, which increased repair time and reduced jack stability.

(4) Finally, the charge size and stud length used with the ramset stud gun had to be corrected during testing. Initially, the charge was too weak and the stud length too short. The stud gun was used to attach two-by-fours to the concrete floor of the C-74 structure to act as anchors for the lateral bracing members of the glulam column. Adjusting charge size and stud length increased repair time.

b. Test Sequence Two

In this test sequence, the column replacement process took 12 minutes and 52 seconds to complete. Clock times required to accomplish

TABLE 15. SUMMARY OF COLUMN REPLACEMENT FIELD DEMONSTRATION RESULTS, TEST SEQUENCE 1.

TEST ACTIVITY	CLOCK TIME (MIN:SEC) START	CLOCK TIME (MIN:SEC) STOP	ELAPSED TIME (MIN:SEC)
POSITION JACK	0:00	4:00	4:00
RAISE JACK	4:00	4:30	0:30
TRIM GLULAM COLUMN	4:30	5:00	0:30
POSITION GLULAM COLUMN	5:00	7:45	2:45
WEDGE GLULAM COLUMN	7:45	11:10	3:25
BRACE GLULAM COLUMN	11:10	22:30	11:20
REMOVE JACK	22:30	23:52	1:22

individual tasks are given in Table 16. Except for the shoring jack being too short and the angle and length of the wooden wedges being incorrect, the column replacement process went very smoothly. The shoring jack length problem was lessened by using three wood blocks, instead of the previously used two, so the jack did not have to be fully extended. However, this solution further decreased the stability of the jack.

It was apparent during the second test that the repair team had become comfortable with the column replacement process, which led to a corresponding reduction in repair time. This shows that a learning curve existed during the first test sequence.

Overall, the column replacement process is very simple, and personnel can be easily trained to carry out the repair. However, fine tuning of equipment and procedures to overcome the problems encountered during testing needs to be done, which in turn should lead to even greater time savings and possibly reduce manpower requirements.

Glulam timber-based column replacement is a viable ERSF system. Additionally, demonstration results showed that if an appropriately sized shoring jack is used, a jack alone can be used for column replacement. Based on field demonstration results, both column replacement systems are suitable for ERSF. As with the column splint demonstration, results from the column replacement demonstration indicate the process used to develop candidate ERSF systems is effective.

E. SHOTCRETE WALL BREACH REPAIR AND WALL REPLACEMENT FIELD DEMONSTRATION

1. Demonstration Description

On 19 and 22 October 1990 at the Tyndall AFB, SKY TEN explosive test range, AFESC/RDCS conducted a field evaluation/demonstration of the shotcrete-based ERSF system for non-load-bearing wall replacement and wall breach repair. Because of Desert Shield, the Air Force Reserve personnel used in the column replacement demonstration were unavailable. For the same reason, active duty Air Force civil engineering personnel were unavailable. Consequently, to avoid delaying testing until Air Force personnel became available, four SETA personnel comprised the test team, with test support

TABLE 16. SUMMARY OF COLUMN REPLACEMENT FIELD DEMONSTRATION RESULTS, TEST SEQUENCE 2.

TEST ACTIVITY	CLOCK TIME (MIN:SEC) START	CLOCK TIME (MIN:SEC) STOP	ELAPSED TIME (MIN:SEC)
POSITION JACK	0:00	2:00	2:00
RAISE JACK	2:00	3:07	[1:07]
TRIM GLULAM COLUMN	2:00	4:20	2:20
POSITION GLULAM COLUMN	4:20	6:00	1:40
WEDGE GLULAM COLUMN	6:00	7:30	1:30
BRACE GLULAM COLUMN	7:30	11:00	3:30
REMOVE JACK	11:00	11:45	0:45

personnel coming from AFESC/RDCM and AFESC/RDCO. The demonstration was done using the NATO structure located at the Tyndall AFB SKY TEN test range.

a. Test Locations

(1) Wall Breach Repair

To simulate a wall breach repair, a spalled area of the NATO structure, shown in Figure 56, was used. This area is located on the northern wall of the structure. A portion of this spalled area approximately 3 feet wide and 4 feet high, was filled in with shotcrete.

(2) Non-Load-Bearing Wall Replacement

To simulate a non-load-bearing wall replacement, a door opening in the NATO structure was used. This door opening, which is shown in Figure 57, is located in the eastern wall of the structure. Prior to the repair, Number 4 rebar stubs were welded along the top, bottom, and sides of the door frame at 1-foot intervals, as shown in Figure 58. The rebar was butt-welded and fillet-welded on both sides for 4 inches. The rebar stubs protruded 6 inches beyond the edge of the door frame. After placing the rebar, a plywood backing was installed in the door opening, as shown in Figures 59 and 60.

Instrumentation conduits were placed in the plywood backing, and secured with sections of rebar as shown in Figure 61. The instrumentation conduits were used to place pressure gages in the completed shotcrete repair. The pressure gages were used to measure blast pressure during explosive testing conducted afterward by AFESC/RDCM.

Engineering drawings of the prepared door opening, without hardware for instrumentation, are given in Figures 62 to 65.

b. Shotcrete Material

The shotcrete material used for these demonstrations was developed by AFESC/RDCM during the spring and summer of 1990. This material consists of 3/8-inch diameter or less pea gravel (45.6 percent by weight),

Figure 56. Spall Area of NATO Structure Used for the Wall Breach Repair Field Demonstration.

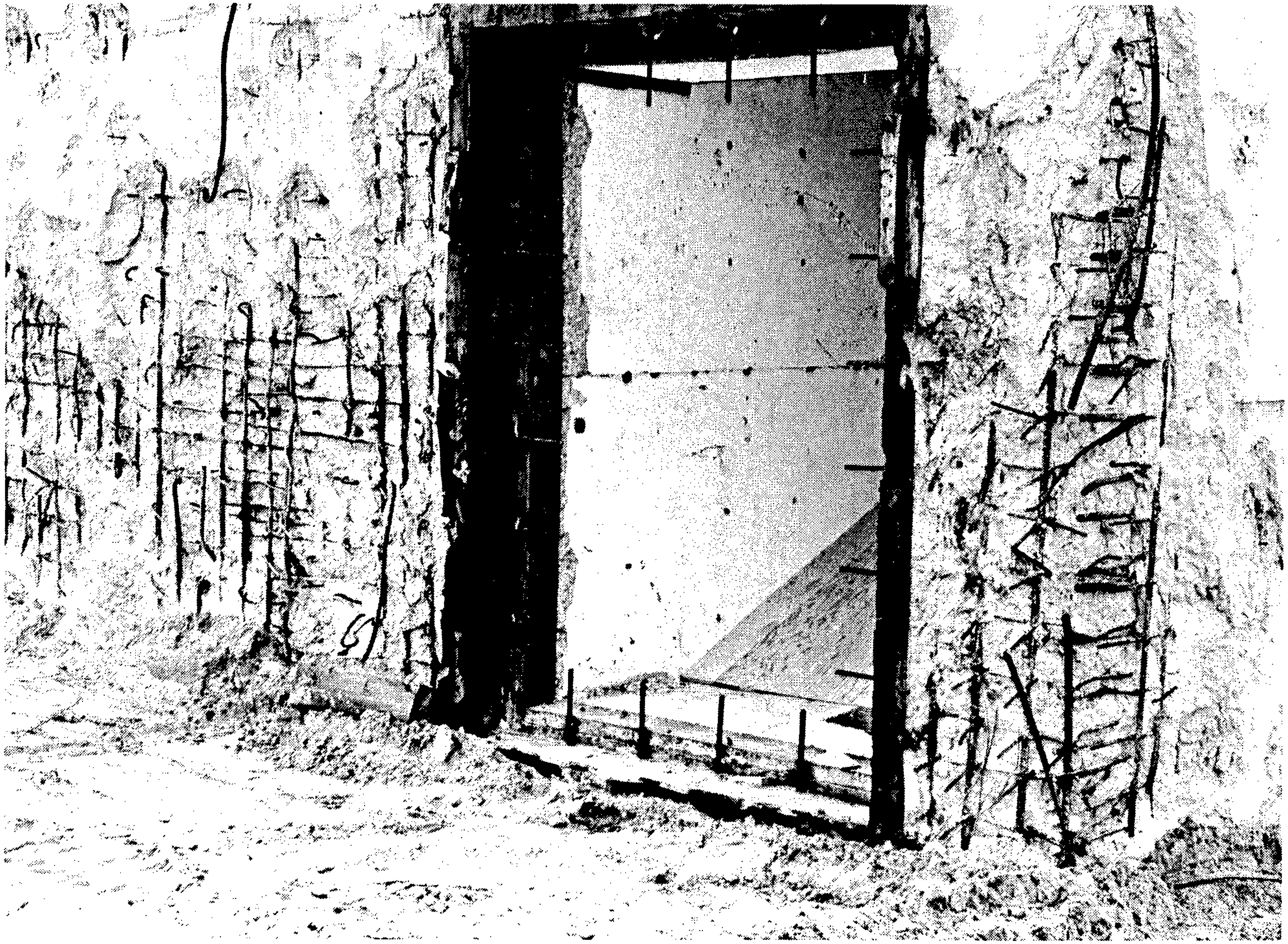


Figure 57. Door Opening in NATO Structure Used for the Wall Replacement Field Demonstration.

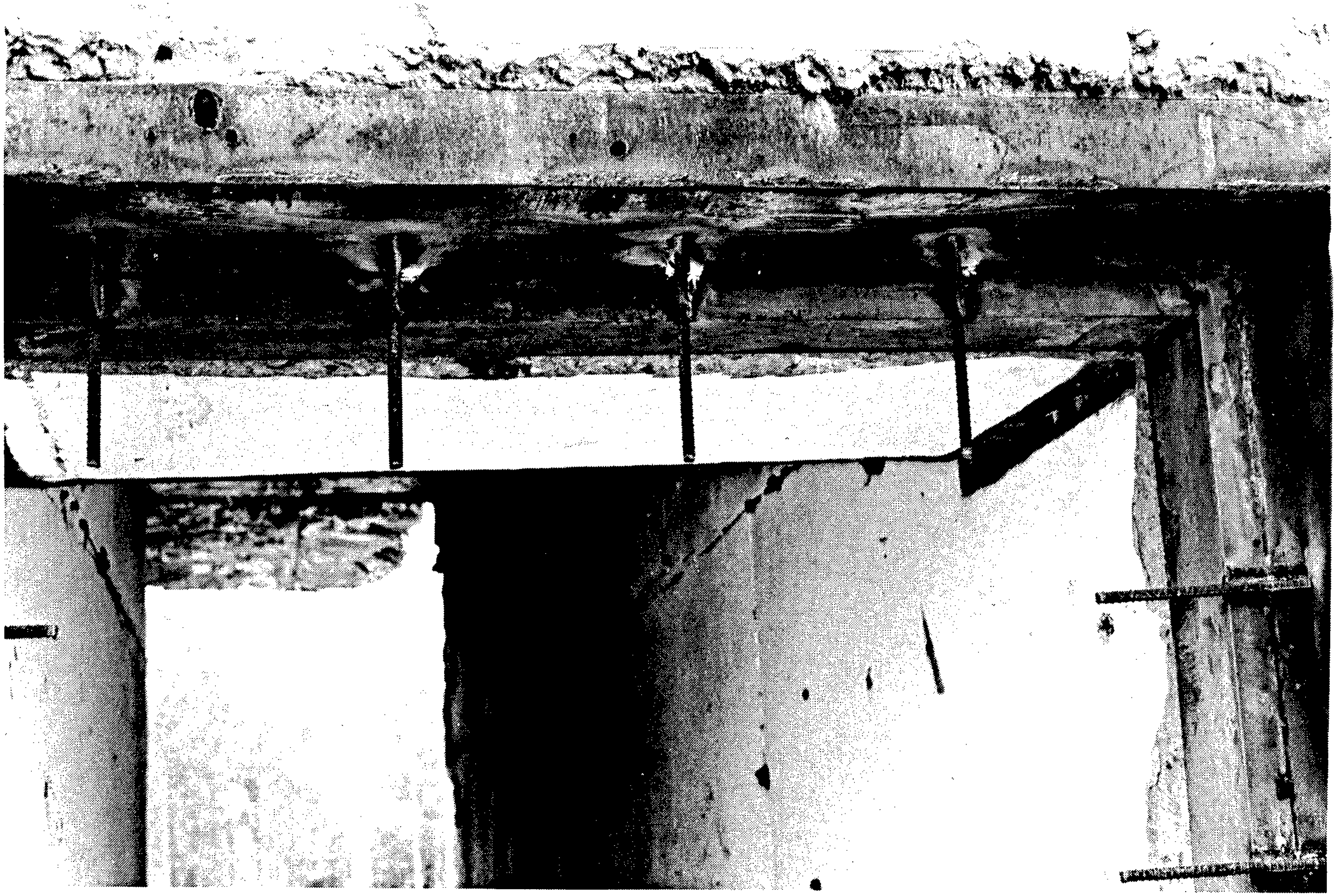


Figure 58. Rebar Welded Along the Top, Bottom, and Sides of the Door Opening.

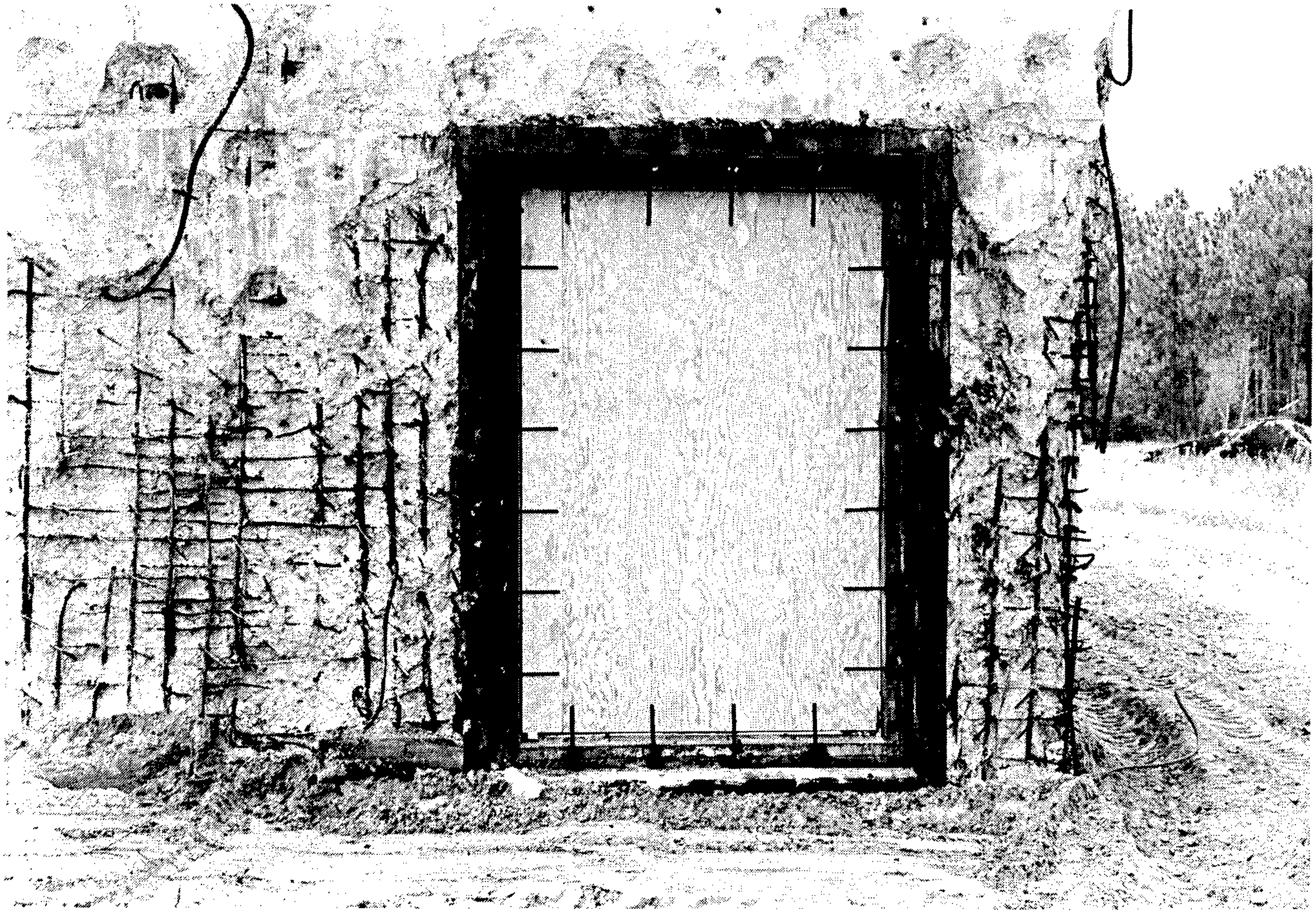


Figure 59. View 1 of Plywood Backing in the Door Opening.

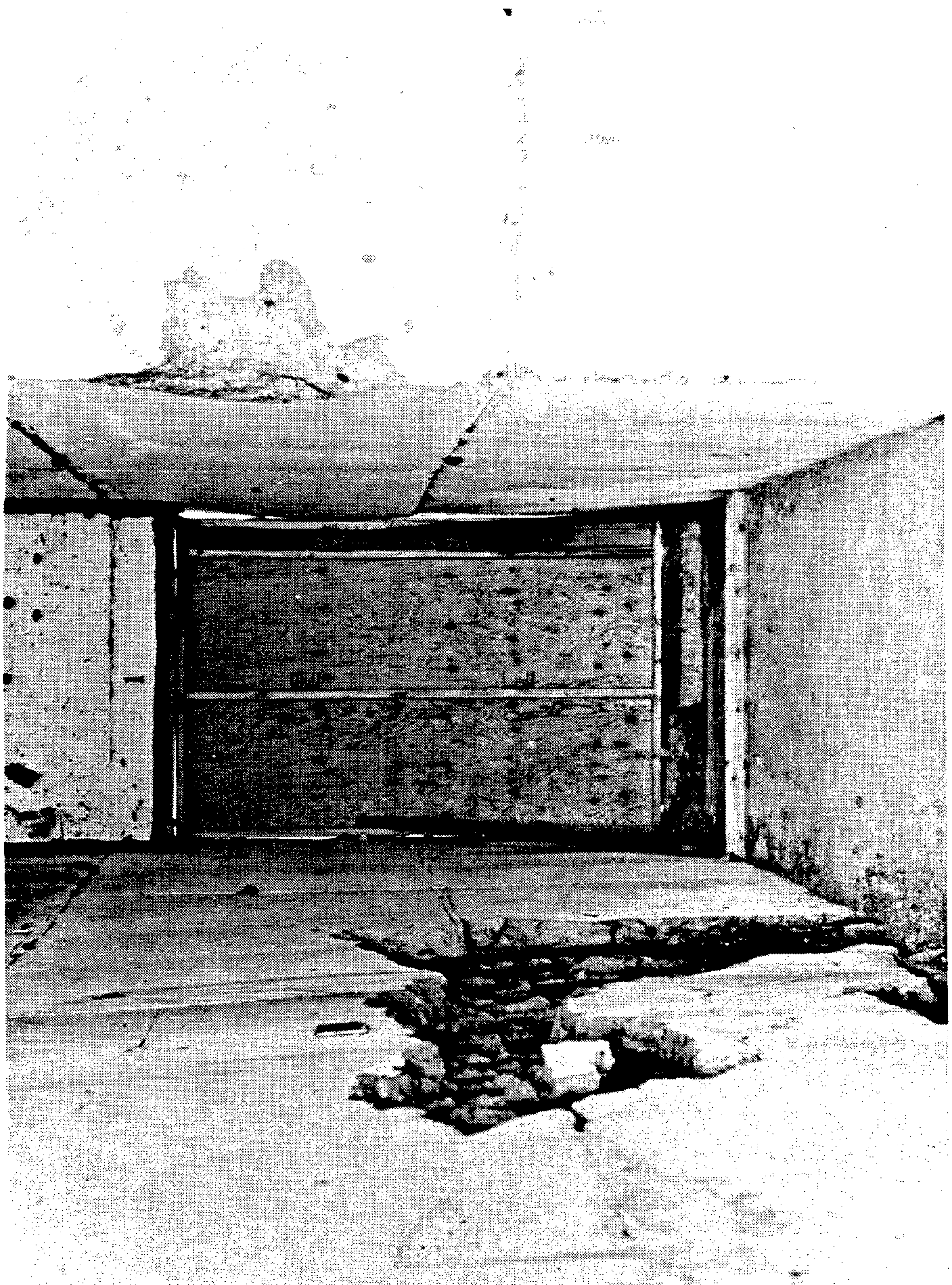


Figure 60. View 2 of Plywood Backing in the Door Opening.

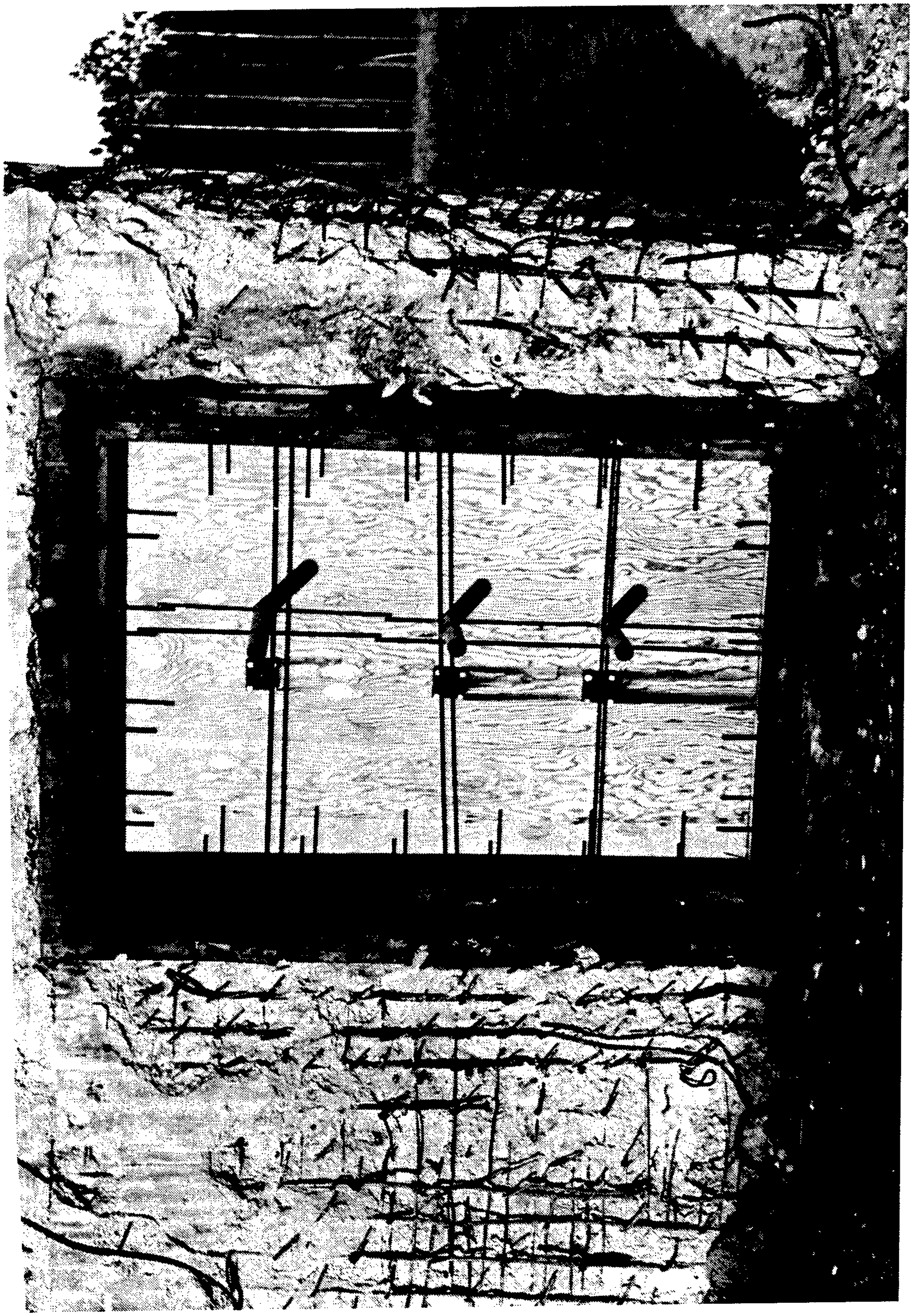


Figure 61. Instrumentation Conduits in the Plywood Backing.

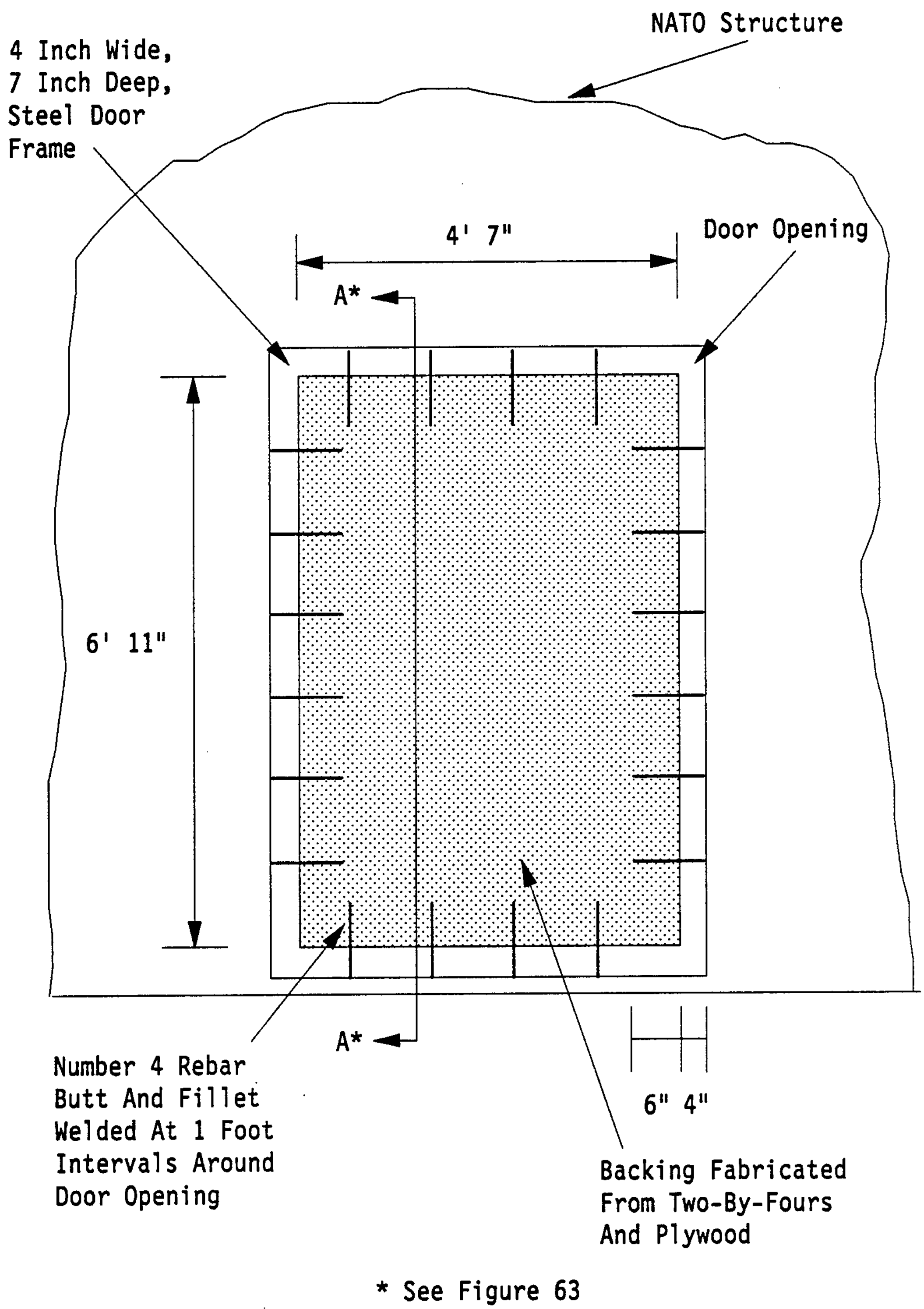
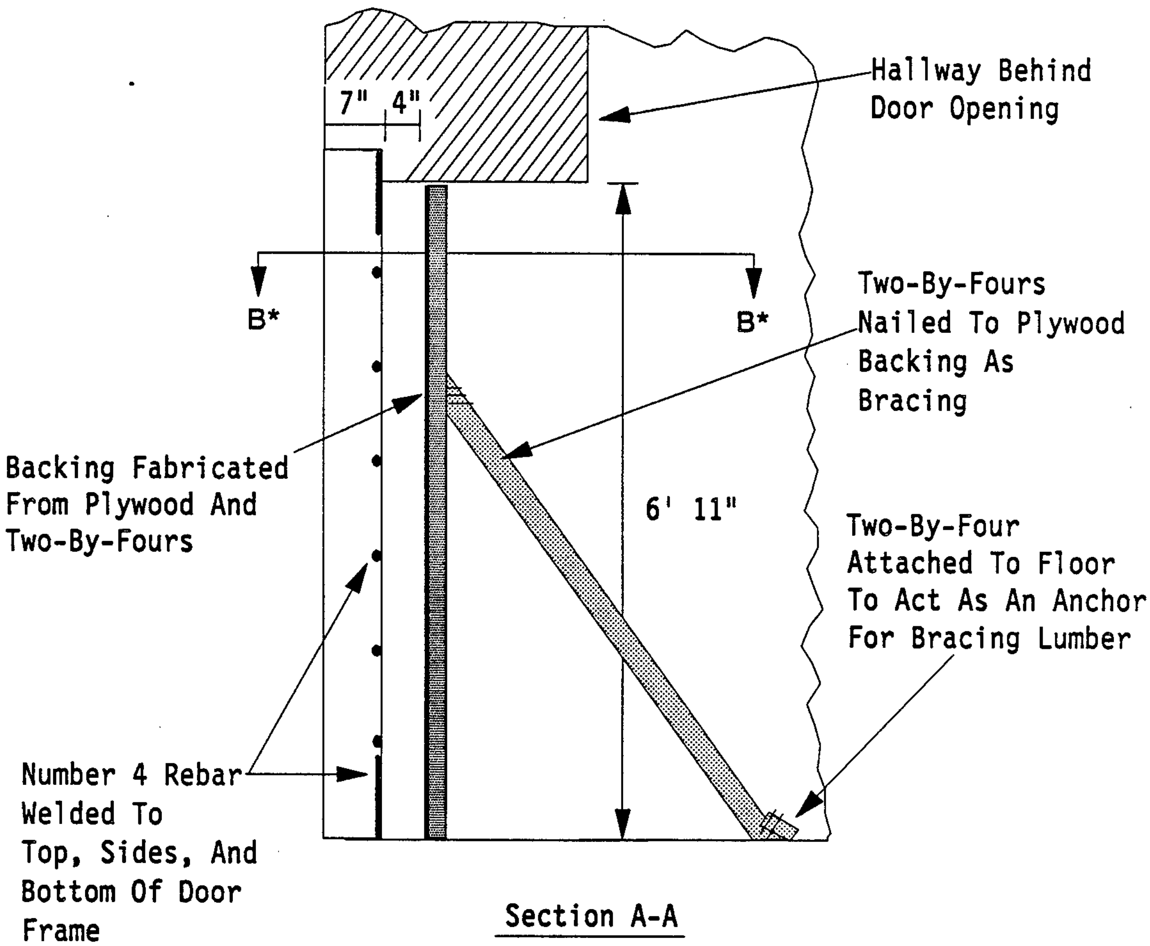
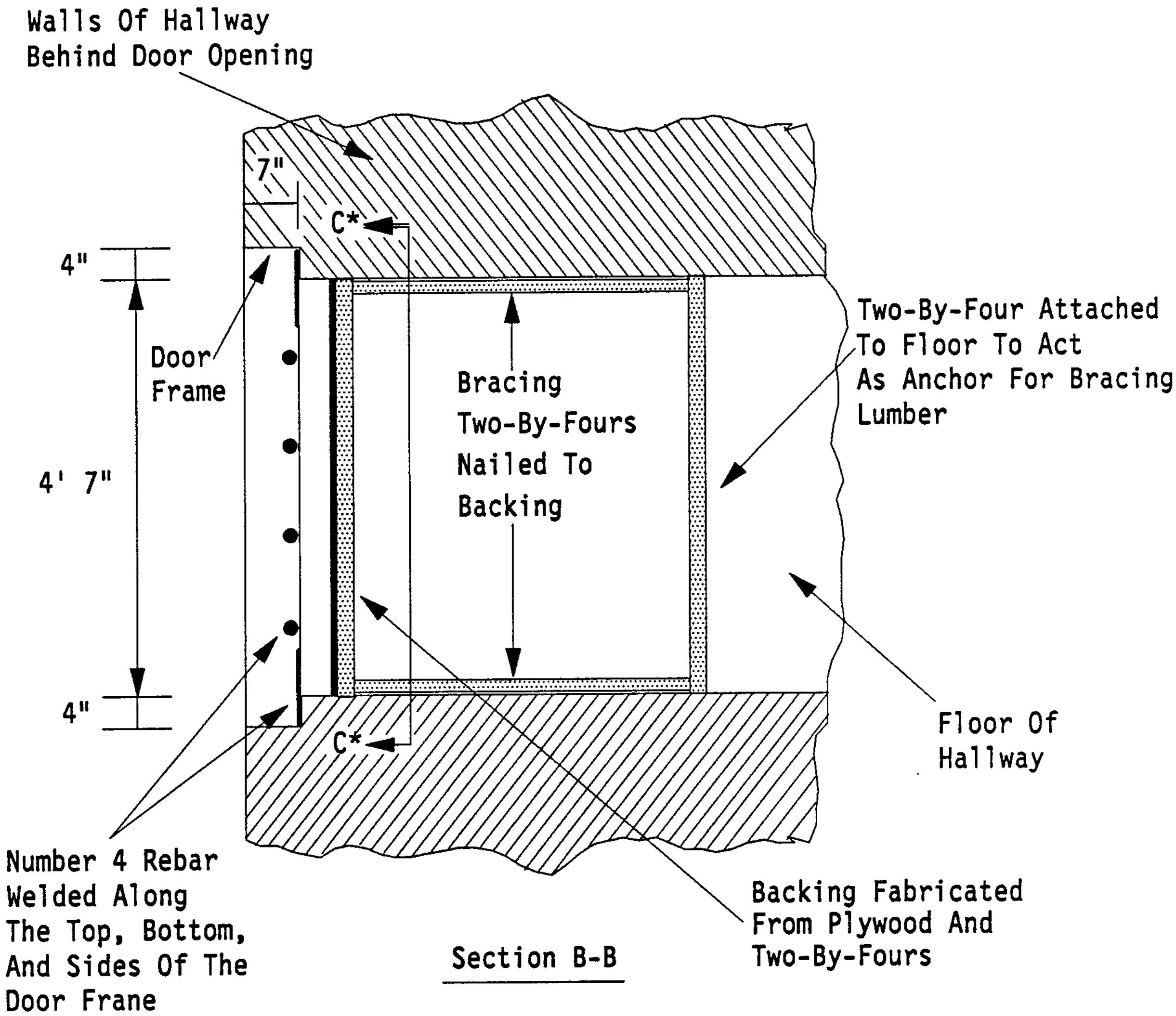


Figure 62. Engineering Drawing 1 of Prepared Door Opening.



* - See Figure 64

Figure 63. Engineering Drawing 2 of Prepared Door Opening.



* See Figure 65

Figure 64. Engineering Drawing 3 of Prepared Door Opening.

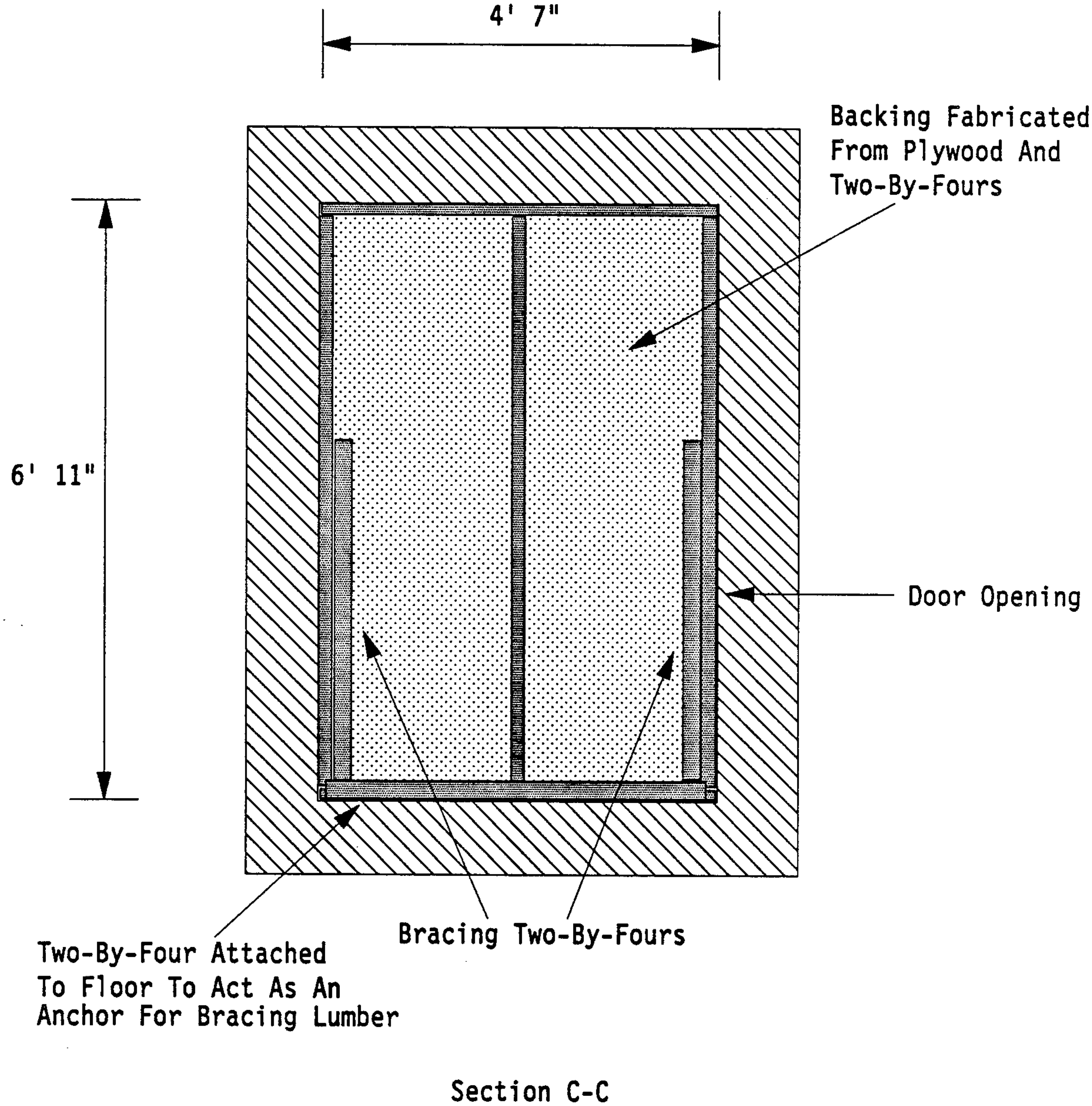


Figure 65. Engineering Drawing 4 of Prepared Door Opening.

RapidSet™ cement (22.8 percent), builder's sand (22.8 percent), steel fibers (5.7 percent), silica fume (2.7 Percent), and an accelerator called Scamper-16 (0.42 percent). During laboratory and initial field testing, this material developed compressive strengths of over 4,500 psi within 1 hour. Additionally, the steel fibers make the material very tough and resistant to spalling and cracking. See Reference 18 for a more detailed discussion of this material.

To accomplish the demonstrations, 15,000 pounds of the material described above was ordered in late August 1990 from PFP, Inc., Atlanta, Georgia. Because of the steel fibers, the material proved difficult to bag. As a result, the material arrived in late September in 55-gallon drums with plastic liners and clamped lids, rather than in supersacks as ordered. Emptying the drums into the hopper of the shotcrete gun proved difficult, not only because it required a special drum-tilting device, but also because the plastic drum liners were dragged into the hopper and had to be dug out by hand. Additionally, the material did not meet the compressive strength of 4,500 psi within 1 hour verbally agreed upon by PFP, Inc. and AFESC/RDCM. It attained compressive strengths of only 3,000 to 3,500 psi within 1 hour. However, ARA decided to use the material in order not to delay the demonstration, and because its compressive strength still met the 3,000 psi ERSF concrete design strength goal.

c. Shotcrete Process Overview

(1) Equipment

The shotcrete equipment used in these demonstrations consisted of 6 basic pieces of equipment: (1) an air compressor, (2) the shotcrete unit, called a gun, (3) a shotcrete nozzle, (4) a 55-gallon water drum with a drum pump, (5) an electricity source for the drum pump, and (6) a concrete bucket attached to a crane.

A MEYCO Piccola 020 shotcrete gun was used in this demonstration. This gun is manufactured by the Shotcrete Division of Master Builders Technologies. The hopper capacity of the gun is 2.5 cubic feet. The maximum shotcrete output of the gun is 74 cubic feet per hour.

All that was required to use the shotcrete gun was water from the 55-gallon drum, the airflow supplied by the air compressor, shotcrete material fed from the concrete bucket into the gun hopper, and various connection hoses. The compressed air propelled the dry shotcrete material from the gun through a hose to the nozzle, where the material was mixed with water and sprayed onto the repair area. The amount of water mixed with the material was controlled at the drum by a preset digital flow meter attached to the drum pump.

(2) Process

Two to four 55-gallon drums of shotcrete material were placed in the concrete bucket, using a specially fabricated drum lift and all-terrain fork-lift, as shown in Figure 66. The crane then positioned the bucket over the shotcrete gun hopper, as shown in Figure 67. In some instances, a wooden funnel was placed in the gun hopper to aid in feeding shotcrete into the hopper. Shotcrete material was fed into the gun hopper by depressing a lever on the concrete bucket as shown in Figure 68. The shotcrete material then fed into a mixing chamber by gravity, from which compressed air propelled it through a hose to the nozzle, where it was mixed with water. The nozzle operator spayed the shotcrete on the ground until the water/material mixture was acceptable and had stabilized. The nozzle operator then sprayed the mixture onto the repair area as shown in Figure 69.

2. Demonstration Results

a. Wall Breach Repair Demonstration

The wall breach repair demonstration was conducted on the morning of Friday, 19 October 1990. This demonstration was treated primarily as an equipment and material check-out for the larger-scale wall replacement demonstration scheduled for that afternoon. Consequently, a complete repair was not attempted, and no video coverage was done.

The concrete bucket was filled with two 55-gallon drums of shotcrete material. The filling process took 28 minutes to complete, including positioning the bucket over the shotcrete gun hopper. While

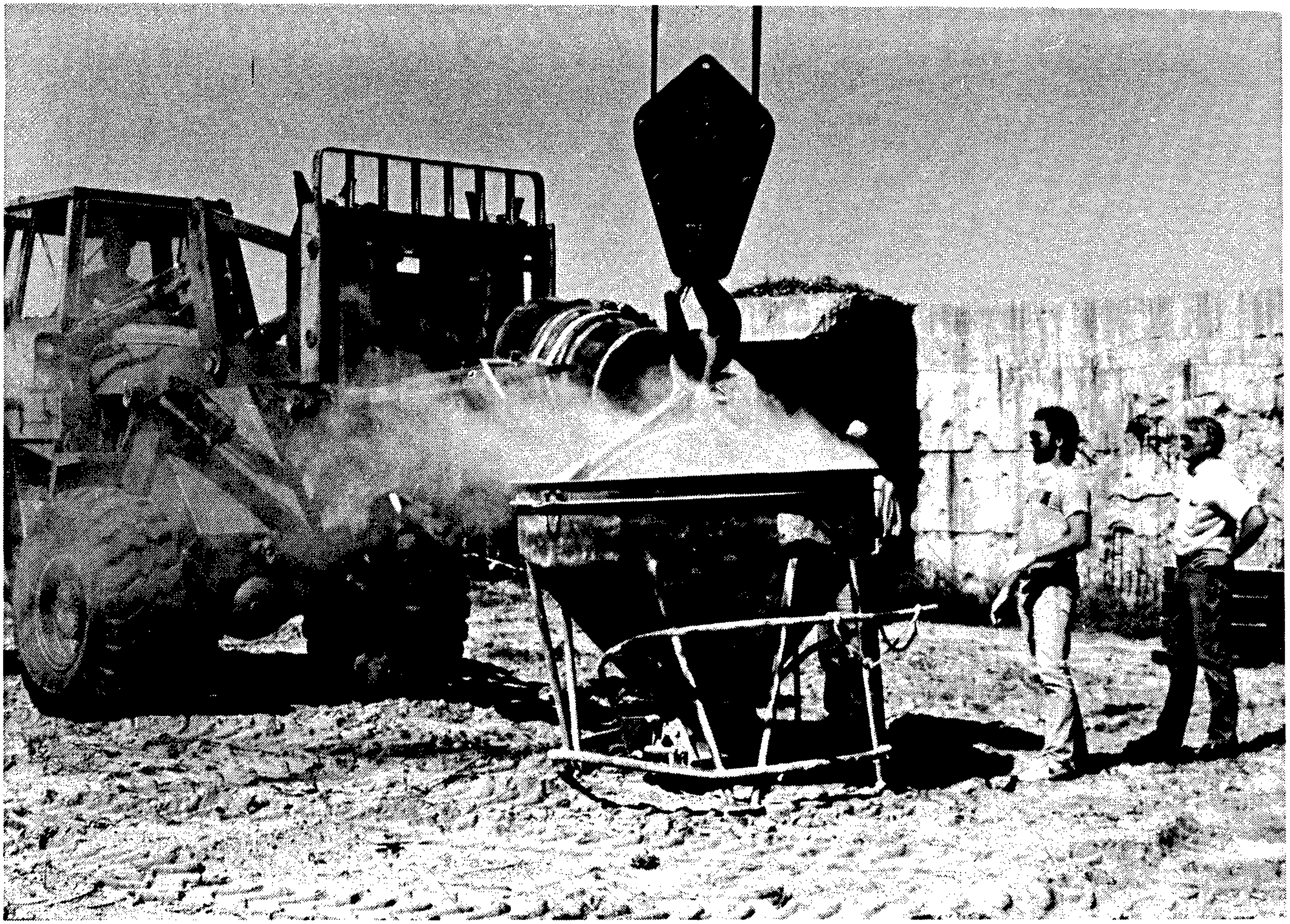


Figure 66. Placing Shotcrete Material in the Concrete Bucket.

Figure 67. Positioning Concrete Bucket Over the Shotcrete Gun Hopper.

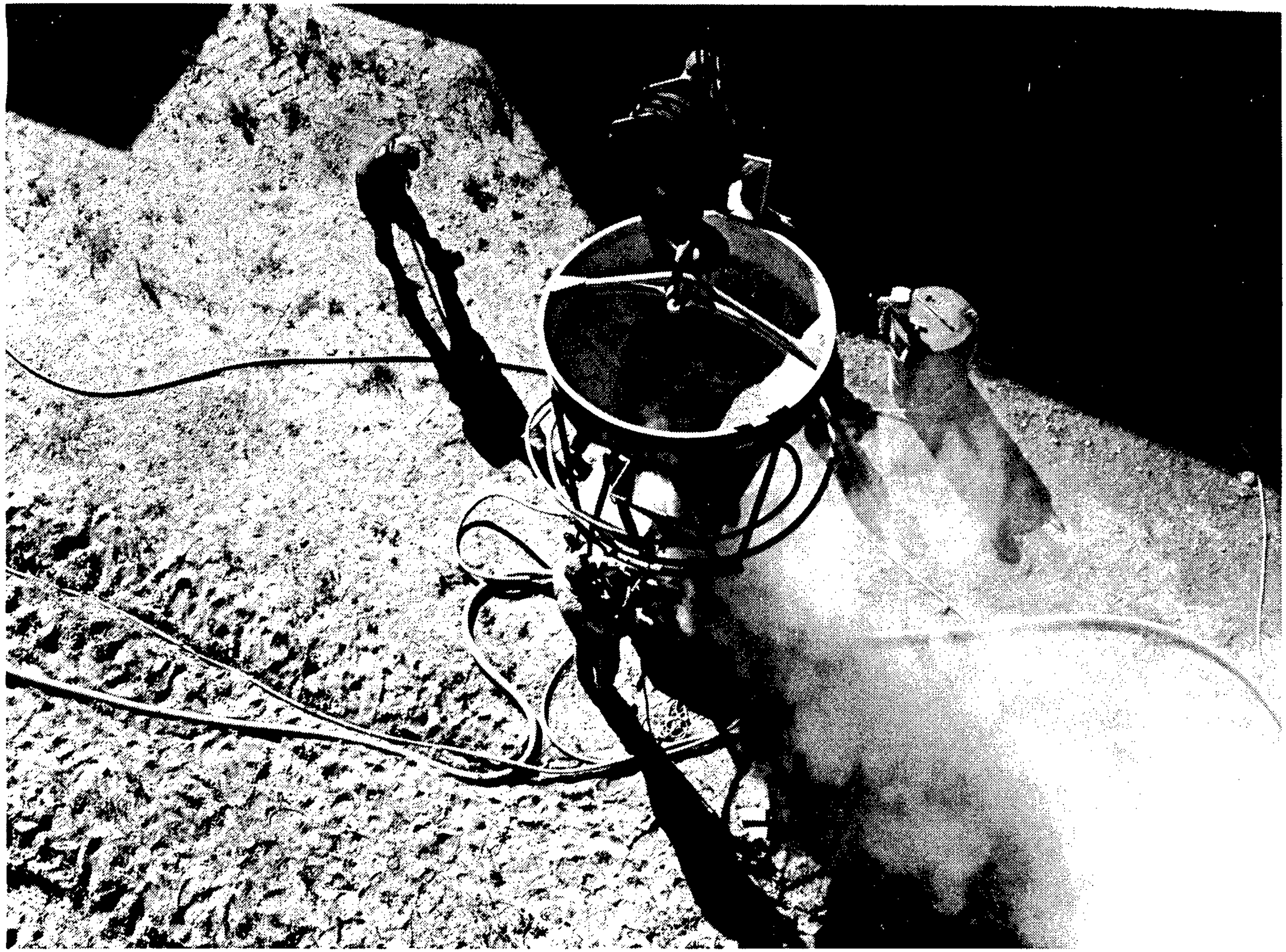


Figure 68. Feeding Shotcrete Material into the Shotcrete Gun Hopper.

Figure 69. Spraying Shotcrete Material into Repair Area.

emptying the first drum into the bucket, the plastic drum liner came out with the material. Removal of the liner added approximately 8 minutes to the filling time.

After a 12 minute delay caused by a stone jamming one of the shotcrete gun's pullies, the repair of the spall area was started. The water flow rate from the 55-gallon drum was set at 1 gallon per minute. Initially, the repair process went well, but after 20 minutes the feed cylinders at the bottom of the shotcrete gun hopper clogged, and the repair process had to be stopped. Since this demonstration was primarily an equipment check-out, the demonstration was terminated.

The repair area after shotcreting is shown in Figure 70, while the clogged feed cylinders of the shotcrete gun are shown in Figure 71. Upon investigation, it was determined that clogging of the cylinders was caused by having too large a surcharge of material in the gun hopper and wood feed funnel above the hopper. To alleviate this problem, the wood funnel was discarded, and only 3 or 4 inches of material was maintained in the hopper. Consequently, continuous monitoring of the shotcrete hopper was required, with frequent small feedings of material from the concrete bucket into the hopper. These new procedures were used during the wall replacement demonstration described below.

b. Wall Replacement Demonstration

The wall replacement repair was conducted during the late morning and afternoon of Friday 19 October 1990, and carried over into the afternoon of Monday, 22 October 1990. Two days were required, because of problems encountered during the first day. Each problem, including the time delay it caused, is described below.

(1) Day 1

The concrete bucket was filled with three-and-one-half 55-gallon drums of shotcrete material. The filling process took 44 minutes to complete, including positioning the bucket over the shotcrete gun. The wooden feed funnel was not used over the hopper.

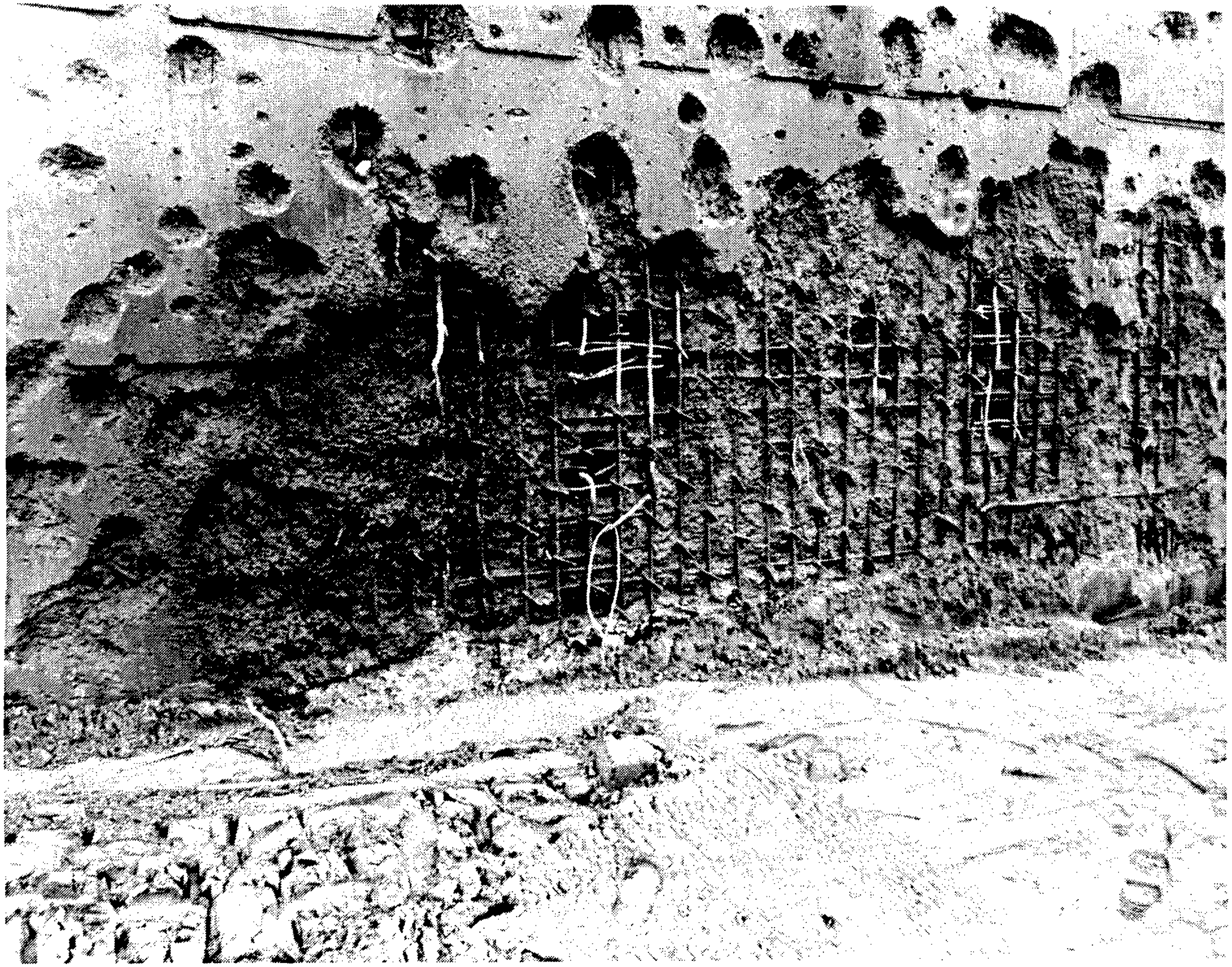


Figure 70. Completed Simulated Shotcrete Wall Breach Repair.

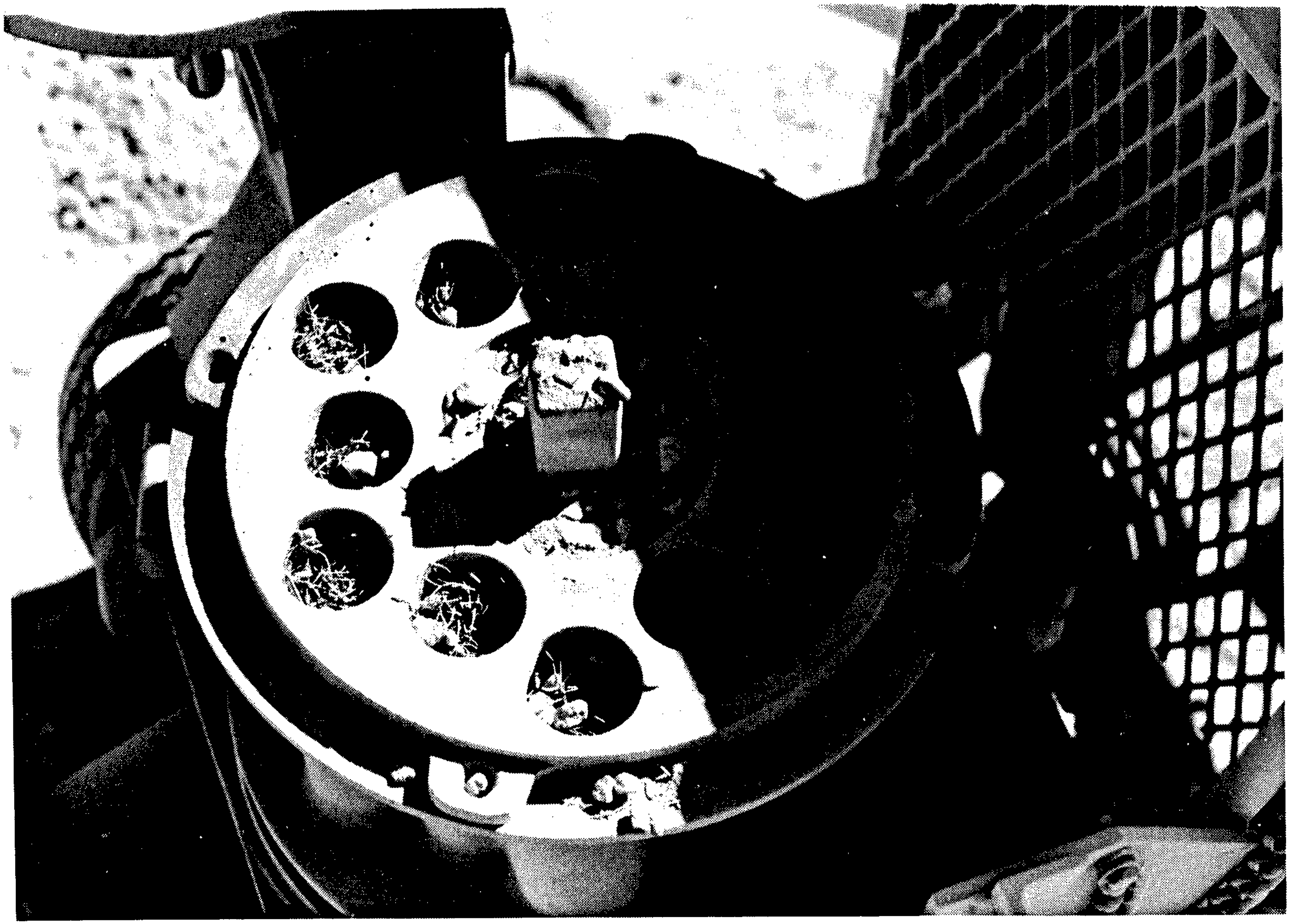


Figure 71. Clogged Shotcrete Gun Feed Cylinders.

The water flow rate was set at 1 gallon per minute, and shooting of shotcrete was started. After shooting for 9 minutes, the repair process had to be stopped for 10 minutes, to adjust the water flow rate to 1.3 gallons per minute, and unclog two shotcrete gun feed cylinders. The water flow rate was increased because the material on the repair surface appeared to be too dry.

The repair process was resumed and continued for 9 minutes, when it had to be stopped again to clear the shotcrete nozzle feed hose, which took 11 minutes. The repair process was resumed and continued for 13 minutes, until it had to be stopped to unclog the shotcrete nozzle water ports, which took 10 minutes. The repair process was resumed and continued for 9 minutes, when it had to be stopped to refill the concrete bucket. Filling the bucket with four drums of material, and repositioning it over the shotcrete gun, took 43 minutes. Additionally, oil had to be added to the shotcrete machine, causing an additional delay of 25 minutes.

The repair was resumed and continued for 19 minutes, when it had to be stopped because the water feed hose began to leak at the nozzle. Fixing the leak took 3 minutes. Also during this time, the water flow rate was adjusted to 1.6 gallons per minute. The repair was resumed and continued for 20 minutes, when it was stopped because the end of the work day had passed and it was obvious the repair could not be completed before dusk.

Total shotcrete repair time on Day 1, excluding delays, was 79 minutes. Total delay time, excluding the time required to fill the concrete bucket, was 59 minutes. The total time required to fill the concrete bucket twice, and position it over the hopper of the shotcrete gun was 87 minutes. Total demonstration time on Day 1 was 225 minutes.

(2) Day 2

On this day (22 October), a change in the shotcrete equipment setup was tried. A pre-dampening hose was attached to the shotcrete nozzle. This attachment allowed the nozzle operator to control the water content of the shotcrete material. The pre-dampening attachment is shown in Figure 72. With this new arrangement, the exact water content of the material was not known, but the nozzle operator could visually determine the quality of

Figure 72. Pre-Dampening Attachment for the Shotcrete Nozzle.

the material and adjust the water flow as needed. The water flow rate from the drum to the nozzle was set at 0.4 gallons per minute.

The concrete bucket was filled with four 55-gallon drums of shotcrete material. The filling process took 43 minutes to complete, including positioning the bucket over the shotcrete gun. The repair process was started and continued for 20 minutes, until it was stopped because the concrete bucket was thought to be empty. Two more drums of material were added to the bucket. Filling and positioning the bucket took 22 minutes. This delay turned out to be unnecessary, because while refilling the bucket it was determined no more material was needed.

The repair was resumed and continued for 14 minutes, until it was stopped because it started to rain. By this time a sufficient amount of material had been applied to the repair area to fulfill the purpose of the demonstration, and the demonstration was terminated.

Total shotcrete repair time on Day 2, excluding delays, was 34 minutes. The total time required to fill the concrete bucket twice, and position it over the shotcrete gun hopper was 65 minutes. Total demonstration time on Day 2 was 99 minutes. The completed wall replacement repair is shown in Figure 73. Due to shotcrete rebound, a large ramp of material was formed at the bottom of the repair, as shown in Figure 74.

3. Explosive Testing

Explosive testing of the shotcrete wall replacement repair was conducted on 8 December 1990 and 10 January 1991. On 8 December, Windsor Probe testing indicated the repair's compressive strength was 4,200 psi.

On 8 December, a Mark 83 1,000-pound bomb, in a nose-tangent configuration, was exploded 50 feet from the repair. Figure 75 shows the appearance of the repair after the blast. Fragments from the bomb impacted the repair, and penetrated several inches, but none passed completely through. Some minor cracking could be seen at the backside of the repair, as is shown in Figure 76. Due to problems with the instrumentation system, no blast pressure or acceleration data was recorded.

On 10 January, another Mark 83 bomb, in the same configuration as before, was exploded 25 feet from the repair. Severe damage to the repair occurred, as is shown in Figure 77. The center section of the repair was

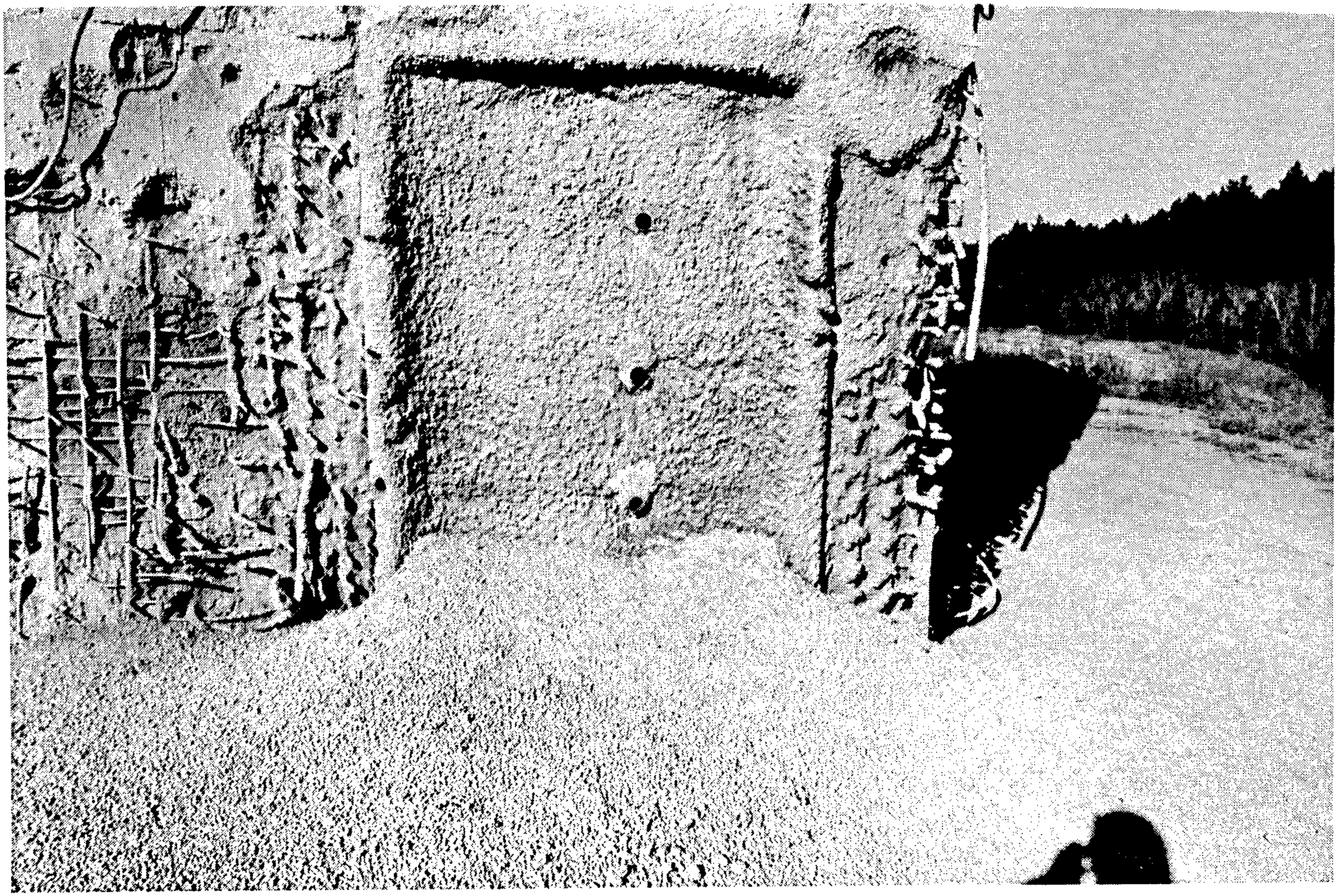


Figure 73. Completed Shotcrete Wall Replacement Repair.

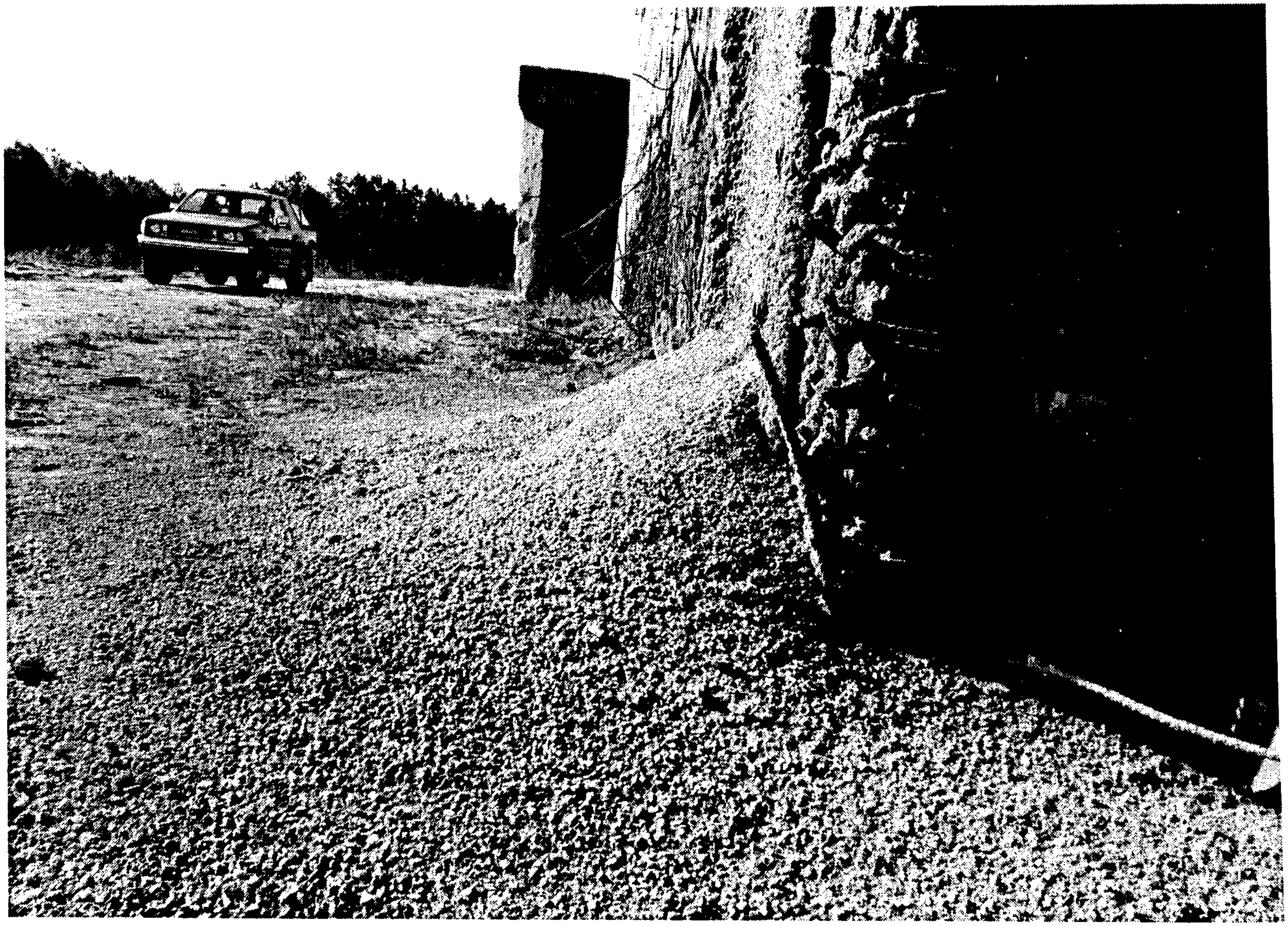


Figure 74. Ramp Caused by Material Rebound During Shotcrete Wall Replacement.

Figure 75. Repair Area After the Explosion of a Mark 83 Bomb at 50 Feet.

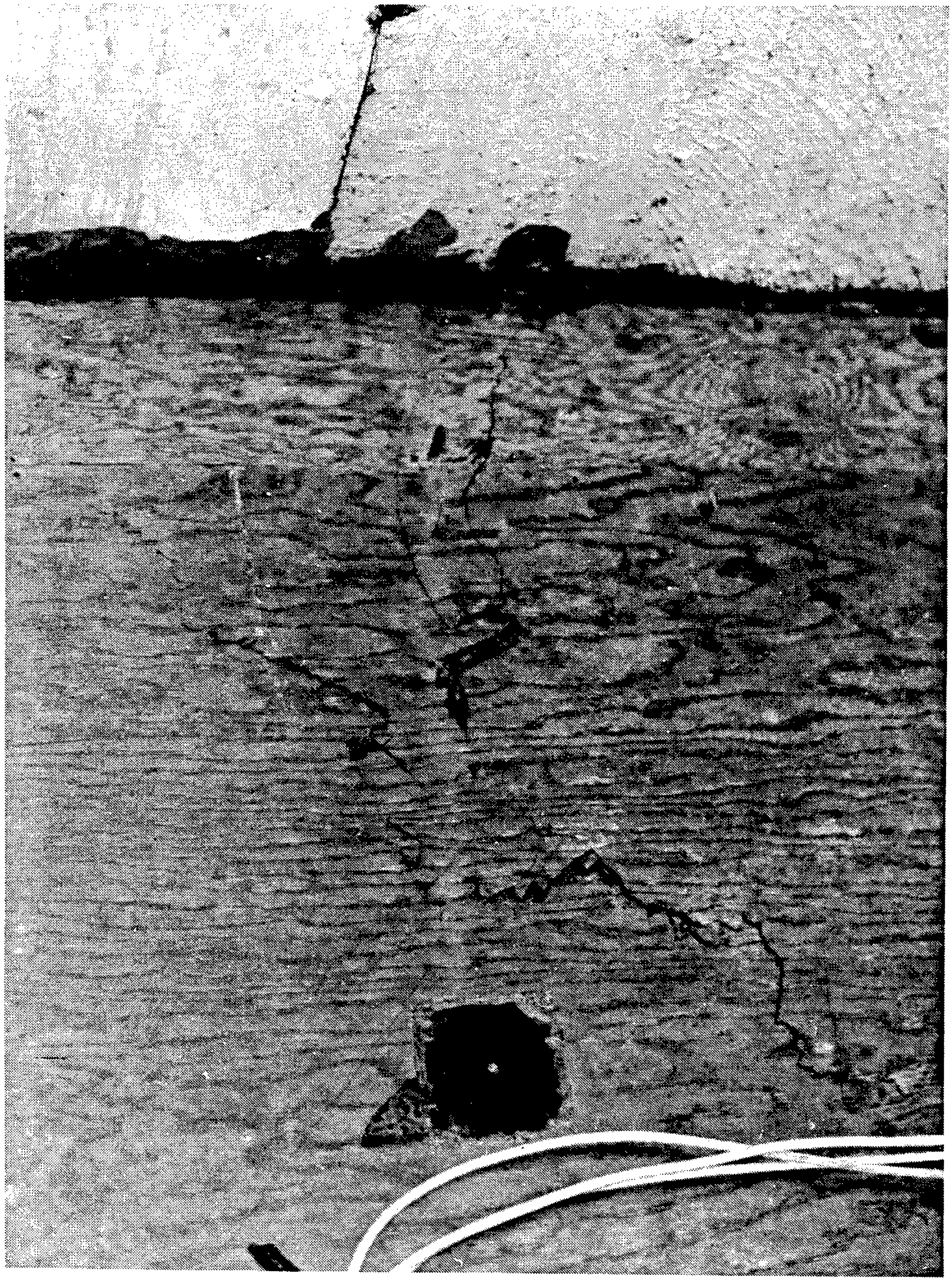


Figure 76. Damage to the Backside of the Repair from the Explosion of a Mark 83 Bomb at 50 Feet.

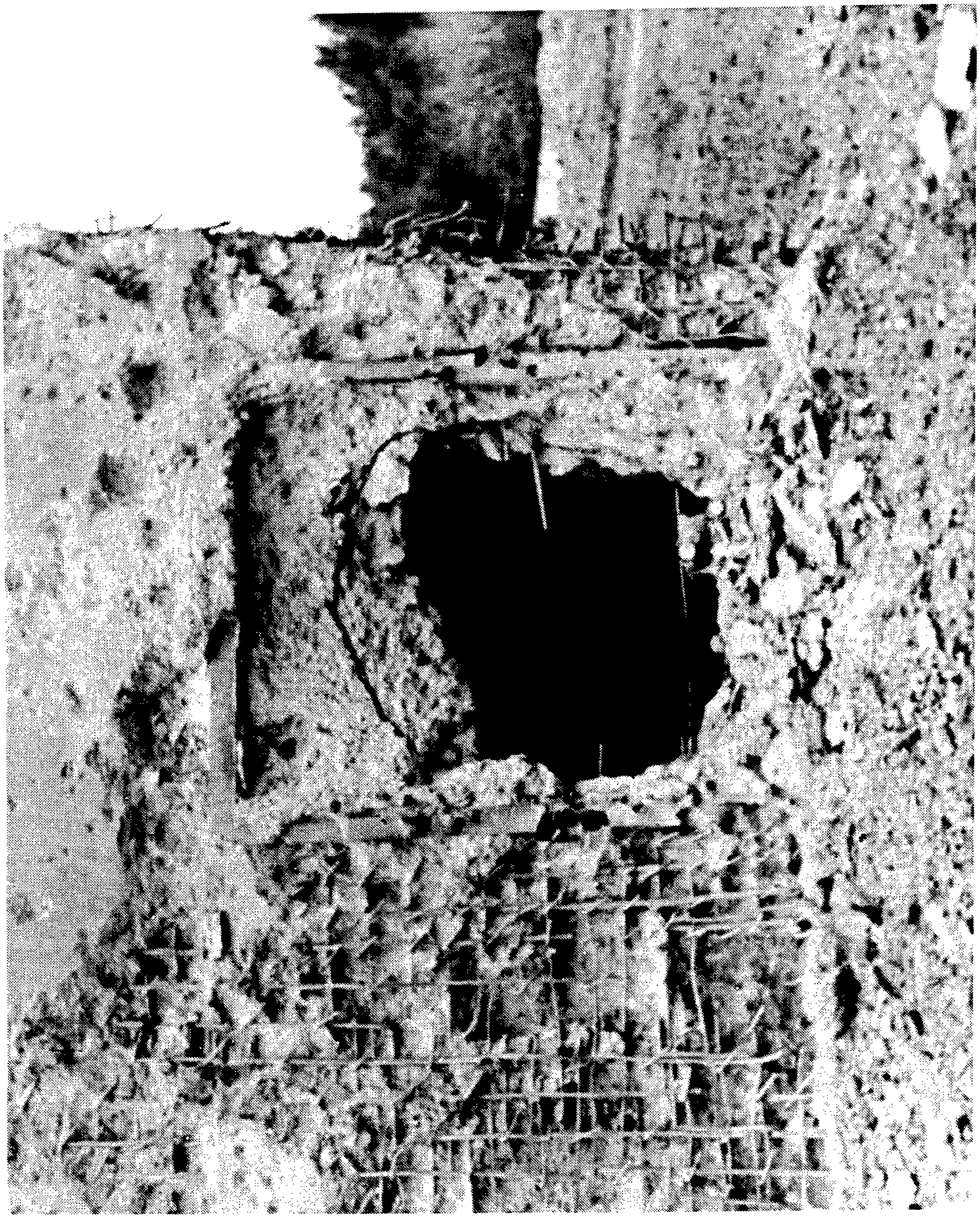


Figure 77. Repair Area After the Explosion of a Mark 83 Bomb at 25 Feet.

completely demolished, and a large amount of rubble was created. The peak pressure recorded during the blast was 660 psi. No acceleration data was measured during the test, due to instrumentation problems.

Measurements taken after this last test indicated repair thickness varied from approximately 11 inches immediately above the ramp formed by material rebound to approximately 8 inches 2 feet from the top of the repair.

For additional details on these explosive tests see the report, Explosive Testing of a Dry-Mix, Rapid Setting, High Strength, Steel Fiber Reinforced Shotcrete Material for Expedient Structural Repair (1991), prepared by AFESC/RDCM (Reference 23).

4. Conclusions

The shotcrete wall replacement demonstration took a total of 5 hours and 24 minutes to complete. Of this time, 1 hour and 53 minutes were spent actually applying material to the repair area. The remaining time was spent coping with equipment problems and filling the concrete bucket. Most of the equipment problems were caused by the size of the shotcrete gun, which was known to be too small for the demonstration, even through it had been quite adequate for the shotcrete material development effort (Reference 18). Its small size resulted in the clogging problems described above. Repair time was also increased by the low material flow rate of the shotcrete equipment. If the correct size of equipment had been used, the repair would have been much faster and more efficient. However, the equipment used had been leased to conduct the shotcrete material development effort, and was the only shotcrete equipment readily available for the demonstration. The decision to use the shotcrete gun on hand was an economic one, and deliberate.

Another factor that increased repair time was the large amount of shotcrete rebound (see Figure 74). The ramp of material at the bottom of the repair was caused solely by material rebound. It also proved difficult to fill in the top portion of the repair. As a result, the repair had to be done from the bottom up, which aggravated the ramp problem.

The demonstration was hindered by the shotcrete material being packaged in 55-gallon drums. The drums were very difficult to handle and empty into the concrete bucket. In the future, the material should be packaged in supersacks. A supersack contains 2,500 pounds of material, can be lifted by a crane, and has a draw-string spout at the bottom, through which the flow rate of the material into a shotcrete gun hopper or material storage tank can be controlled.

A potential problem discovered during the demonstrations is the storage requirements of shotcrete material. When the material was left out in the open in sealed, plastic-lined 55-gallon drums at the demonstration site over the weekend (20 and 21 October), the material appeared to have absorbed moisture from the air. This caused some of the material to become lumpy. Consequently, containers used to store shotcrete material at FOBs must be highly impermeable and puncture resistant, such as supersacks (see above). If possible, the material should be stored in a controlled environment without extremes in temperature and moisture. The cost of such storage facilities is an economic problem. In addition, space constraints at FOBs may make construction of special storage facilities difficult.

While many problems were encountered during the shotcrete repair demonstrations, and actual repair time was too long, the shotcrete repair concept proved viable. Personnel with little or no experience with the method, and using equipment that was too small for the job, were able to accomplish the repairs. Work is required to define shotcrete material storage requirements with respect to containers, environment, and shelf-life. Additionally, an appropriate shotcrete equipment setup must be identified and evaluated for use in ERSF systems. The shotcrete equipment setup should be in a single, self-contained unit that is highly mobile, holds the shotcrete material in a closed system, has a robotic nozzle arm for shooting the material, but with provision for manual shooting from a standard hose nozzle arrangement when necessary, be easily refillable with more material, and require a maximum of two personnel to operate. The hose/nozzle arrangement is required because it will not always be possible to position the shotcrete unit next to the repair area, for example inside a structure.

F. SUMMARY

Demonstrations of the column splint and column replacement ERSF systems proved they are viable ERSF systems, and require only minor additional development. The shotcrete wall replacement and wall breach repair demonstration, while proving the general concept of using shotcrete for ERSF is viable, also showed significant additional development of the system is needed. Once the appropriate shotcrete equipment is identified, and adequate material storage procedures developed, the shotcrete ERSF system should be evaluated again through another large-scale field demonstration. This demonstration will allow the suitability of shotcrete-based systems for ERSF to be determined.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Viable ERSF systems were identified for a wide range of damage modes, and are summarized in Table 17. In this table, the best ERSF system for a particular damage mode is shown first, followed by systems that should be viewed as backups or supplements. However, personnel at each FOB should select the method(s) they feel are most suitable for their situation.

All identified systems are relatively simple, and have simple training requirements. With the exception of the shotcrete-based system, storage requirements for all the systems can easily be met. The shotcrete system is the most costly and difficult to store, especially the material, but its flexibility and the strength and durability of its repairs justify the increased complexity, assuming suitable equipment can be identified and material storage problems overcomed. By fielding a shotcrete-based ERSF system, the number of different ERSF systems required at a FOB, and the associated logistic and training requirements, will be minimized.

B. RECOMMENDATIONS

With the exception of the shotcrete system, the identified ERSF systems are ready for full-scale development. This report is a starting point for developing an ERSF system users manual. Volume II of this report describes the equipment, supplies, materials, and procedures needed to implement each ERSF system. Additionally, training criteria are outlined. However, Volume II does not go into detail with respect to sources for required equipment and materials, nor does it describe the process by which a FOB develops and supports an ERSF capability. These issues must be addressed in an ERSF user's manual, along with command and user responsibilities. Additionally, the manual should define training procedures in detail including facilities.

A follow-on effort has been undertaken to further develop and refine the shotcrete ERSF system with respect to equipment, material, and storage requirements. Once an appropriate shotcrete equipment setup has been

TABLE 17. SUMMARY OF ERSF SYSTEMS VERSUS DAMAGE MODES.

STRUCTURAL DAMAGE MODE	EVALUATED ERSF SYSTEM 1/
DAMAGED STEEL FRAMED STRUCTURE	1) CUTTING AND WELDING
DESTROYED CONCRETE COLUMN	1) INSERT SHORING JACK 2) INSERT GLULAM TIMBER COLUMN 2/
CRACKED CONCRETE COLUMN	1) INSTALL COLUMN SPLINT 2/
DAMAGED BEAM/GIRDER	1) USE VERTICAL SHORING - GLULAM COLUMN - SHORING JACK 2) INSTALL KING POST 3/
DESTROYED NON-LOAD-BEARING WALL	1) ATTACH PLYWOOD PATCH 2) PLACE EARTH BERM COVER 3) PLACE PRECAST SLAB COVER 4) SHOTCRETE REPAIR 2/ 4/ 5) MASONRY BLOCK REPAIR 5/
WALL BREACH	1) ATTACH PLYWOOD PATCH 2) PLACE EARTH BERM COVER 3) PLACE PRECAST SLAB COVER 4) SHOTCRETE REPAIR 2/ 4/ 5) MASONRY BLOCK REPAIR 5/
FLOOR/ROOF BREACH	1) ATTACH PLYWOOD PATCH 2) RAPID SET CONCRETE REPAIR 3) SHOTCRETE REPAIR 4/
SYSTEMS FOR SEALING STAIRS ACCESSING DAMAGED BUILDING STORY →	1) PLYWOOD PATCH 2) SHOTCRETE REPAIR 4/

1/ SYSTEMS LISTED IN ORDER OF MERIT BASED ON EVALUATION SCORES (SEE SECTION V).
2/ SYSTEM WAS DEMONSTRATED IN THE FIELD (SEE SECTION VI).
3/ BACKUP SYSTEM WHEN VERTICAL SHORING CAN NOT BE USED.
4/ SHOTCRETE SYSTEM IS STILL UNDER DEVELOPMENT; ITS RANKING MAY CHANGE.
5/ USE OF THIS SYSTEM IS NOT RECOMMENDED (SEE SECTION V).

TABLE 17. SUMMARY OF ERSF SYSTEMS VERSUS DAMAGE MODES (CONCLUDED).

STRUCTURAL DAMAGE MODE	EVALUATED ERSF SYSTEM [1]
DAMAGED OVER-PRESSURE DOOR SYSTEM	1) INSTALL CANVAS/SHEETING COVERING 2) REPLACE DAMAGED DOOR [2] 3) INSERT THIRD DOOR [2] 4) SEAL DOOR WITH SHOTCRETE [2] [3]
DAMAGED BLAST DOOR - AIRCRAFT SHELTER BLAST DOOR - OTHER BLAST DOORS	1) PRY OPEN DOOR
DESTROYED WINDOW	1) COVER WITH PLASTIC SHEETING 2) COVER WITH ACRYLIC PANELS
RUPTURED AIRCRAFT SHELTER FLOOR SLAB	1) INSTALL RAMP WITH AM2 MATTING 2) INSTALL RAMP WITH RAPID SET CONCRETE [4] 3) INSTALL RAMP WITH SHOTCRETE [3] [4]

1| SYSTEMS LISTED IN ORDER OF MERIT BASED ON EVALUATION SCORES (SEE SECTION V).

2| BACKUP SYSTEM WHEN CANVAS/SHEETING COVERING CAN NOT BE USED.

3| SHOTCRETE SYSTEM IS STILL UNDER DEVELOPMENT; ITS RANKING MAY CHANGE.

4| USE THIS SYSTEM WHEN HIGH RAMP HEIGHTS ARE REQUIRED.

identified, it should be evaluated by a large-scale wall replacement field demonstration.

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