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UPGRADING STRUCTURES FOR HOST AND RISK AREA SHELTERS

FINAL REPORT

for

FEDERAL EMERGENCY MANAGEMENT AGENCY
WASHINGTON, D.C. 20472

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Work Unit 1128A

SCIENTIFIC SERVICE, INC.

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This report presents a summary of the research effort directed toward the development of a Shelter Upgrading Manual for host and risk area shelters in support of Civil Defense planning. Included is a review of the testing, analysis, and data acquisition, by Scientific Service, Inc., and from other sources. Also presented is an overview of the current status of the manual development program, and a discussion of the recommendations for additional research that have become apparent during the four-year conduct of the program.

(DETACHABLE SUMMARY)

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by
Roger S. Tansley

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Scientific Service, Inc.
35 Arch Street, Redwood City, CA 94062

(DETACHABLE SUMMARY)

UPGRADING STRUCTURES FOR HOST AND RISK AREA SHELTERS

FINAL REPORT

Scientific Service, Inc. has completed four years of a five-year program directed at the development of a multi-volume Shelter Upgrading Manual that would be suitable for use by Civil Defense planners in formulating shelter developmental plans in host and risk areas. A revision of the work plan resulted in the deletion of the final program year, and as a result, drafts of only six of the proposed eight volumes were completed.

This purpose of this report is to present a compilation, in summary form, of the research effort directed toward the development of this Shelter Upgrading Manual. The report contains a review of the testing, analysis, and data acquisition, and includes tests conducted and data obtained from related programs and other sources. References to these programs and sources are presented. It presents an overview of the current status of the manual development program, and discusses the development of the charts and worksheets, a number of which are presented in the draft volumes. Also discussed are the recommendations for additional research that have become apparent during the four-year conduct of the program.

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Scientific Service, Inc.
35 Arch Street, Redwood City, CA 94062

Section 1

INTRODUCTION

This contract was initiated at a time when Civil Defense planning in the United States was predicated on the policy of "Crisis Relocation" planning, later called "Emergency Operations Planning" (EOP). This policy assumed that a period of crisis buildup or international tension would permit the time required, a few days or weeks, to evacuate up to 80 percent of the population to host areas. The survival of the evacuated population, and that of the key workers who remained behind to maintain essential industries and services, depended on the provision of adequate shelters for protection from the blast and radiation effects of a nuclear weapons attack. Since neither the host nor the risk areas provided adequate shelter space, a major thrust of the "Crisis Relocation" policy was the upgrading of existing structures, and the provision of expedient shelters, for the purpose of providing this required shelter space.

Since 1975, Scientific Service, Inc. (SSI) has worked, first with DCPA, and then with FEMA, on extensive research relative to upgrading concepts for both structures and industrial equipment. Utilizing a shock tunnel for dynamic testing, and full scale test frames for static load testing, supplemented by small scale tests and analysis, SSI produced shelter upgrading manuals for both host and risk areas, as well as industrial protection manuals. As this work progressed, it became evident that the wealth of data developed by SSI and others with respect to shelter upgrading could best be utilized by Civil Defense planners by incorporating all of these data into a single manual, or set of manuals, that would provide upgrading system flexibility, charts and worksheets, and training materials in a format conducive to the planner's needs. This effort would require additional testing and analysis so that all viable building systems and upgrading configurations were included, and their performance verified.

Scientific Service, Inc. was selected by FEMA to conduct a five-year research program to provide the necessary engineering basis and guidance for the development of a set of manuals covering the upgrading of existing structures. This contract consisted of a basic contract and four one-year options; however, the work plan was modified so as to eliminate the final option year. The end product of this program was to be a set of manuals that would be suitable for use by Civil Defense planners in formulating shelter developmental plans for risk and host areas. Unfortunately, the deletion of the final year of the program eliminated this end product, the promulgation of these manuals in a final and usable form. What has been provided is a compilation of all of the available laboratory and field test data, research and prediction analysis, and basic drafts of ~~only~~ six of the proposed eight upgrading manuals.

The organization of this report is as follows: Section 2 - A review of the testing, research, analysis, and data acquisition used for the development of the manuals, including tests conducted and data obtained from related programs and other sources. Section 3 - Overall view of manual development to date; how charts and worksheets were developed. Section 4 - Recommendations of additional research requirements that became evident during the development of the manual.

Section 2

TESTS, RESEARCH, AND ANALYSIS

INTRODUCTION

The efforts that were required in obtaining the data and information necessary for the development of the shelter upgrading manuals for existing structures in host and risk areas consisted of extensive programs of laboratory and field testing, data analysis, and research and literature reviews. Although the great majority of this effort was executed directly by Scientific Service, Inc. (SSI), valuable support data was obtained from tests and research conducted by other laboratories and organizations. In addition, SSI had a number of concurrent related contracts, and data developed under these contracts was also incorporated into the shelter upgrading program.

In order put this testing, research and analysis effort in its proper perspective, this section of the report will briefly outline the technical input over the last 10 or so years that was instrumental in the development of the shelter upgrading program.

LABORATORY TESTING

In order to determine the performance of various types of as-built and upgraded floor, roof, and wall systems, closure configurations, and shoring systems, over 180 full and small scale laboratory tests were conducted. Testing facilities employed for this effort included the SSI laboratory, Fort Cronkhite shock tunnel, San Jose State University structures laboratory, and several government laboratories.

Tests of Floor and Roof Systems

The selection of floor or roof systems for laboratory testing was predicated on using systems that are commonly in use throughout the country. The test assemblies were constructed from typical "off-the-shelf" materials, using normal construction methods, techniques, and tolerances. In the case of prefabricated systems, the materials were obtained from manufacturers' existing stock, and therefore were not specially designed for the test program.

Within each type of system, a minimum of one test was conducted without upgrading in order to establish an as-built performance base. Subsequent tests were then conducted on identical assemblies using various methods of upgrading. In some cases, based on analysis of the test results, modifications were made to the upgrading configurations, and additional tests conducted in an attempt to obtain optimum results. Many of the full scale tests were supplemented with small scale tests. By judiciously planning the test programs, it was, in a number of cases, possible to predict and/or interpolate performance for similar systems without the expense of additional full scale testing. Following is brief outline of this program:

Timber Systems - Five types of timber systems were investigated by testing. These systems consisted of sawn lumber joists, glulam timber joists and beams, prefabricated manufactured wood joists, panelized wood roof systems and gabled wood roof trusses.

Sawn lumber joists are probably the most common type of construction used for floors and roofs. The initial test program on this system was a series of 11 full scale tests investigating five different upgrading options; i.e., flange stiffener, boxed beam, king-post truss, post shores positioned at midspan and at the one-third points. These tests were conducted to develop base data for prediction theory, and to correlate data with tests conducted by the Waterways Experiment Station (Ref. 1), and are reported in SSI 7719-4 (Ref. 2). These 11 tests were followed by two drop tests on identical assemblies in order to correlate the effects of rapid loading of the assemblies with the hydraulic loading used in the initial 11 tests. The theory and test results for these drop tests are presented in SSI 7910-5 (Ref. 3). Three additional tests on similar lumber joist assemblies were conducted and reported in SSI 8012-6 (Ref. 4). These three tests were used for prediction correlation, and differed in construction from the first 13 in that they employed heavier materials and were designed for a greater live load. One test was conducted without upgrading, while the other two were shored, one at midspan and one at the one-third points.

These timber joist tests were supplemented with an analysis of the material variabilities that affect the design properties in timber. Included in this analytical investigation were factors such as design strength, grading, seasoning, and load duration. This analysis is presented in Refs. 2 and 3.

Glulam timber joists and beams have wide application as both floors and roofs in structures such as motels, offices, theaters, warehouses, retail stores, and manufacturing and commercial buildings. Six full scale tests were conducted on these types of members, three on a size appropriate for floor systems, and three on a size used for roofs. Each set of three had one test without upgrading and two tests with the assembly shored at midspan, each with a shore bearing area of a different size. These tests are reported in SSI 8144-7 (Ref. 5). Because of the many variations in the connectors used for glulam members, a subsequent investigation on these connectors was conducted, and is reported in SSI 8144-12 (Ref. 6).

Prefabricated manufactured wood joists are frequently used as an economical substitution for conventional sawn timber joists in both floors and roofs. Depending on the manufacturer, these joists are supplied in a number of different profiles. As reported in Ref. 6, a series of three full scale tests was conducted on joists constructed in an "I" profile, with parallel laminated veneer lumber flanges and structural plywood webs. One test was without upgrading, one was shored at midspan, and the third was shored at the one-third points.

Panelized wood roof systems are a cost efficient type of construction commonly used on large industrial and commercial buildings. The cost advantage in these systems is a result of prefabrication and speed in erection. The panels are normally constructed in a 4-by-8-ft size, but in some cases may be as large as 8 by 30 ft. Two panel tests were conducted: one without upgrading and the second upgraded by placing 4 by 4 in. timbers on the top surface, spaced apart, to investigate the effects of soil arching on flat roof systems. Additional data with respect to load duration factors of timber systems was also obtained during this investigation. These tests are reported in Ref. 6. A review of the theories of arching in soils may be found in Ref. 3.

Prefabricated wood roof trusses are extensively used for the construction of roofs in single and multiple family dwellings, schools, churches, and agricultural, commercial, and industrial buildings. Four full scale tests were conducted on assemblies built with these trusses. Two of the tests were conducted without upgrading, both loaded to failure, one using hydraulic jacks, the other loaded with sand, to observe if, in these systems, loading methods would affect the results. No discernible difference in the results was observed. The other two tests were upgraded by shoring one at midspan, and the other at the one-quarter points. The data obtained from this test series were compared with that reported by the Waterways Experiment Station Technical Report N-78-1 (Ref. 7). This comparison and the results of the four tests are reported in Ref. 6.

Steel Systems - Two types of steel floor and roof systems were analyzed and tested. These systems consisted of open-web steel bar joists and open-web prefabricated manufactured wood/steel composite joists.

Open-web steel bar joists are widely used in floors and roofs of commercial and industrial buildings. A series of nine full scale and four small scale tests was conducted to investigate and predict the behavior of upgrading techniques of systems utilizing these joists, and to compare results with Ref. 1. The initial series of five tests, as reported in Ref. 2, consisted of one without upgrading, one shored at midspan, and one shored at the one-third points. The final two tests had specially designed "flexible" shores at the one-third points that permitted a controlled amount of joist deflection prior to the shores being loaded. These last two tests indicated that the performance of these types of joists could be enhanced if they were permitted to deflect a given amount prior to being "reverse" loaded by the shores, a concept called "stress control".

An investigation was conducted, and reported in Ref. 3, for the purpose of predicting the amount of "stress control" gap required for various shoring conditions by calculating and analyzing the anticipated resulting stresses in the chord and web members. These predictions were then compared with the results of three full scale tests, one without upgrading, one shored at midspan with a 1/8-in. gap, and one shored at midspan with a 1/4-in. gap.

The data obtained for the first two phases of testing described above indicated test failure loads higher than predicted values, suggesting that the steel decking, which was not considered in the preliminary predictions, contributed significantly to the system's overall performance. As a result, one full scale and four small scale tests were conducted, directed specifically toward obtaining performance data on the decking and its contribution to the system's strength and stiffness. In addition, a failure prediction computer model was developed for open-web steel joists in order that quick and comprehensive analysis might be obtained without extensive additional testing. These tests and a description of the computer model development are presented in Ref. 4.

Another type of open-web joist system in common use is constructed with open-web steel/wood composite joists. Although these joists consist of chords of solid-sawn lumber and open-webs of steel tubing, they are addressed in this report under the heading of steel systems since test results indicated that their modes of failure normally occurred in the steel tubing. Four full scale tests were conducted on assemblies using these members, two were not upgraded, one was shored at midspan, and one was shored at the one-third points. The "stress control" concept developed under the open-web steel bar joist program was used for the shored assembly tests in this program also. These tests are reported in Ref. 6.

Concrete Systems - Tests were conducted on reinforced concrete one-way floor slabs, flat plates, waffle slabs, and prestressed concrete hollow-core slabs. An extensive analytical investigation was conducted on the subject of the punching shear resistance of concrete slabs, and a prediction methodology was developed.

Two series of tests were conducted on reinforced concrete one-way slabs. One series by SSI, Refs. 2 and 3, and one series by the Waterways Experiment Station (WES), Technical Report SL-81-4 (Ref. 8). The SSI series (Refs. 2 and 3) consisted of three full scale tests, one without upgrading, one shored at midspan, and the third shored at the one-third points. The WES series (Ref. 8) consists of three tests, loaded dynamically in their Large Blast Load Generator (LBLG). One test was a typical slab section without upgrading, the second was upgraded with a wooden column system, and the third upgraded with a steel beam column system. All three WES tests were conducted on identical one-way slabs.

An additional series of tests on flat plate and waffle slabs was designed by SSI and conducted by WES. This investigation is reported in WES Technical Report SL-83-7 (Ref. 9). The test program consisted of tests on individual 19 and 30 in. panels taken from waffle slabs, 19 in. panels from one-way joist slabs, two center portions of a full waffle slab bay, and the center portion of a flat plate bay. Also included were tests to determine the punching strength of 4 in. thick slabs-on-grade. The individual 19 and 30 in. waffle slab panels, and the one-way joist and flat plate slab panels were tested statically in the Small Blast Load Generator (SBLG) at WES. The 4-in. thick slabs on grade were tested by driving 7 by 7 in. wooden posts through them with the 200 kip loader. The two center portions of the waffle slabs and the center portion of the flat plate slab were tested in the LBLG. The purpose of these tests was to evaluate the load capacity of the thin pan portion of a waffle slab system, to obtain data on punching capacity of slabs on grade, and to evaluate shoring prediction methodology developed by SSI for waffle slabs and flat plate slabs, both of which require complete perimeter support for realistic test evaluation.

Precast prestressed hollow-core slabs are used extensively as floors in commercial and industrial structures. This topping normally enhances their load carrying capability, and the test program by SSI was conducted without using topping. Initially, 15 full scale tests were conducted covering three thicknesses of slabs, 4, 8, and 10 in. These tests are reported in Ref. 4. Each thickness of slab was tested without upgrading, shored at midspan, and shored at the one-third points, and several of the tests were repeated in order to obtain additional data. In order to supplement the data derived from these static tests, three additional static/dynamic drop tests were conducted on 8-in. thick slabs. These drop tests were similar to those conducted on the sawn lumber joist assemblies discussed previously, and used the theoretical approch outlined in Ref. 3. The concrete drop tests are reported in Ref. 5.

Tests of Wall Systems

The majority of the wall systems were tested in the Fort Cronkhite Shock Tunnel Facility in Marin County, California. This program was conducted over nine years, and is summarized in five volumes in SSI 7618-1 (Ref. 10). Over 100 full scale tests were conducted on walls constructed of various thicknesses of brick and concrete block, and combinations of both. The walls were built as solid walls, window walls, or doorway walls, and were constructed in the test frames as simple, fixed, rigid arched, or gapped arched, beams and plates. Based on these tests, theories were developed on wall panel response and predicted failure pressures.

Tests of Closure Systems

A series of static tests was conducted in the SSI 12-inch shock tube on closures constructed of single, double, and triple layers of 28 gauge (0.0299 in. thick) corrugated steel sheets spanning a 4-ft opening. These tests are reported in SSI 8145-20 (Ref. 11).

The Ballistic Research Laboratory (BRL) conducted a series of seven tests on closures constructed of aluminum I-beams with aluminum skins, wood beams, and wood planks protected with sandbags. The purpose of these tests was to investigate shelter entry structures and non-accessway closures for use at the key worker level of blast pressure. The tests were conducted in the BRL 2.44 m shock tube, and are described in their Memorandum Report ARBRL-MR-03338 (Ref. 12).

Supplemental Tests

In order to provide support to the test data obtained as a result of the structural element tests described above, in was necessary to conduct supplemental testing in particular areas.

One of the most practical methods for upgrading existing structures is by the use or shores. It was found, however, that little data existed on the punching shear capacity of a reinforced concrete slab above, or a slab on grade below, when it was subjected to severe point loading, such as that caused by a shore. An investigation was undertaken that consisted of 16 small scale tests, each loaded to failure with either timber of steel shores. The 5-3/4 in. thick concrete test slabs were either unreinforced, or contained one-way or two-way bottom steel, or one-way or two-way top steel. The results of these tests were later combined with field test data to develop a punching shear prediction method. These 16 small scale punching shear tests are reported in Ref. 4.

To provide for the most efficient use of both equipment and materials for the placement of radiation shielding, a variety of methods, other than soil berming, should be available. In order to investigate alternative shielding methods, laboratory tests were conducted using a full scale timber stud wall. Five different methods were attempted, with the required labor and material resources noted. These tests are reported in Ref. 6.

FIELD TESTING

Although the extensive laboratory testing described above proved to be invaluable, as well as cost effective, in determining the static load capacity of various types of building components under "as-built" and shored conditions, the data developed was somewhat limited with respect to the dynamic load capability of the total structure. Areas that required investigation included loading on basement walls by blast overpressure surcharge, connection integrity, wall upgrading, closure evaluation, continuous floor or roof spans, performance of various shore types, debris translation on shoring integrity, and manpower and resource requirements for various upgrading schemes. Two high explosive tests conducted at White Sands Missile Range in New Mexico by the Defense Nuclear Agency (DNA) provided the opportunity to investigate many of these areas: the MILL RACE event in September 1981, and the DIRECT COURSE event in October 1983. With FEMA support, SSI fielded pertinent experiments in both events.

Experiments at MILL RACE

The experiments at the MILL RACE event that pertain to this program consisted of four structures and three key worker expedient shelters. The four structures were designed using typical current building codes, and constructed by a civilian contractor using methods and materials that he would normally use. Incorporated in these four structures were as many of the desired conditions for evaluation as it was possible to include without having one experiment influence an adjacent one. The three expedient shelters consisted of two buried utility vaults and one dimension lumber buried shelter. These tests are briefly described below and in more detail in SSI 8115-4 (Ref. 13).

Two of the four structures consisted of 24 by 16 ft one-story buildings, constructed on a concrete slab-on-grade, one was a wood frame building and the other masonry with a precast concrete roof. Both contained interior partitions, and exterior doors and windows. The roofs and walls of both buildings were shored, the doors and windows were protected with closures, and the walls bermed and the roofs covered with soil to a minimum depth of 18 in. These two experiments were subjected to approximately 2 psi overpressure during the test, and are designated as DNA No. 5001 and 5002 in Ref. 13.

A third structure was a 24 by 16 ft masonry basement with a wood joist floor above, an interior partition, and no exterior doors or windows. An entry hatch was provided in the floor above for access. One half of the floor above was shored. The entry hatch was covered with a closure, and the entire structure bermed with a minimum of 18 in. of soil. This experiment was also subjected to approximately 2 psi overpressure, and is designated as DNA No. 5003 in Ref. 13.

The fourth structure consisted of a concrete basement 151 ft long and varying in width from 16 to 18 ft. The building was divided into three 18-ft bays, and three sets of two 16 ft bays, each separated by a reinforced concrete wall. The floor above consisted of various construction types; i.e., reinforced concrete flat slab, precast prestressed hollow-core slabs, and reinforced concrete two-way slab, each upgraded with various shoring types and configurations. The exterior and interior walls, with the exception of a portion of one corner that was used to evaluate three different basement wall constructions, were designed to be "non-failing" in order to protect the integrity of the floor upgrading portions of the experiment. The exterior walls contained no openings, and the floor above contained one hatch and one stairway for access. The hatch and stairway were covered with closures, and the entire structured bermed with a minimum of 18 in. of soil.

This objective of this experiment was to evaluate various upgrading methods and closures, the performance of various types of basement walls, obtain data on upgrading methodology and resources, and to observe and evaluate the interaction of different building components, many of which have been individually tested. This experiment was subjected to approximately 40 psi overpressure, and is designated as DNA No. 5201 in Ref. 13.

Two of the key worker expedient shelters consisted of buried concrete utility vaults. The vaults were provided with access by using concrete storm drain pipe, and covered over with 3 ft of soil. One vault was subjected to approximately 20 psi overpressure, and the other to 40 psi. These experiments are designated as DNA No. 5101 in Ref. 13.

The other key worker expedient shelter was constructed of dimension lumber, buried under 30 in. of soil cover, and subjected to approximately a 40 psi overpressure. This structure was of a basic design developed by Oak Ridge National Laboratory as a 50 psi wood pole shelter, described in their "Expedient Shelter Handbook," ORNL-4941 (Ref. 14). This experiment is designated as DNA No. 5301 in Ref. 13.

Experiments at DIRECT COURSE

A number of experiments conducted at the DIRECT COURSE event contributed valuable input to the shelter upgrading program. Pertinent experiments fielded by SSI include an investigation of basic shelter design criteria, model basement wall and shelter tests, and closure tests. These experiments are briefly described below and in more detail in SSI 8306-5 (Ref. 15).

The basic shelter design criteria experiment consisted of two one-fifth scale model buildings, one concrete and the other steel. Both models represented 4-story buildings with a basement. The objectives of these experiments were to obtain experimental data on frame response, develop additional data on basement wall performance, obtain debris distribution data, and to supplement data previously developed under the building collapse program that was currently being conducted by SSI, see SSI 8130-8 (Ref. 16) and SSI 8142-6 (Ref. 17). These experiments were intended to be subjected to 50 psi overpressure (actual overpressure was 70 psi), and are designated as DNA Nos. 4140 and 4145 in Ref. 15.

Eight model basements, each containing three test walls, were tested with the objective of determining the effects of various types of backfill, and to obtain additional data on basement wall collapse. Six of the basements were intended to be subjected to 50 psi overpressure (actual, 80 psi), and two to 18 psi (actual 23 psi). These experiments are designated as DNA Nos. 4150 and 4160 in Ref. 15.

The closure tests involved testing six types of expedient closures consisting of timber, sheet steel, and corrugated sheet steel. These closures were installed horizontally spanning 4 ft, and covered with 18 in. of soil. The thicknesses of the closures were based on the diaphragm theory developed from static loading tests in the SSI shock tube (Ref. 11). The closures were intended to be subjected to 50 psi overpressure (actual 65 psi), and are designated as DNA No. 4170 in Ref. 15.

The model shelter tests consisted of six reinforced concrete basement ceiling slabs. The slabs were installed over non-failing steel boxes flush with the ground surface, and covered with a thin layer of soil. Three were at the expected 50 psi overpressure range (actual 80 psi), and three at the 100 psi range (actual 118 psi). At each range, one slab was unshored, one shored symmetrically at the one-third points, and one shored symmetrically at the one-quarter points. These experiments are designated as DNA Nos. 4180 and 4185 in Ref. 15.

Oak Ridge National Laboratory fielded a set of experiments consisting of three scale models of corrugated blast shelters and three full-size blast door closures for such shelters. The three blast shelters' three blast doors survived blast overpressures up to 225 psi. These tests are reported in ORNL/TM-9289 (Ref. 18). Subsequent tests by ORNL resulted in further refinement of the design of blast doors, and as of this writing, this investigation is presented only in final draft format.

ANALYTICAL STUDIES AND INVESTIGATIONS

In addition to the data developed by laboratory and field tests described above being utilized, to further support the shelter upgrading manual it was necessary to conduct a number of analytical studies and investigations. Following is a brief outline of several analytical programs conducted in support of the manual.

In order to develop a better understanding of the behavior of underground shelters subjected to blast loading, a study of the arching action of soils under loading was conducted. This soil arching action reduces the applied loading on flexible structures, although the exact extent of this reduction is uncertain. A review of the theories of soil arching under static loading provides essential information to the understanding of this subject. This study may be found in Ref. 3.

When a reinforced concrete slab is being shored, it is important to understand the strength and failure characteristics of both vertical and lateral loading of the complete building structure. An analysis conducted on the resistance characteristics of existing slab (flat slab and two-way slab) structures is presented in Ref. 3.

During the large number of laboratory tests conducted on prestressed concrete slabs, a number of different failure modes were observed relative to the position of the shores. Four failure modes were identified, and equations developed to predict the failure loads and the modes of failure, and these predictions were compared to the actual test results. This analysis is presented in Ref. 4.

As a result of the laboratory and field testing of various concrete systems, an analysis was undertaken covering the structural connections and connection systems in concrete construction that most directly affect the performance of potential shelter options. This analysis is presented in Ref. 5.

As previously described, sixteen laboratory small scale punching shear tests were conducted (Ref. 4). Based on these tests, and the results of field tests (Ref. 13), an investigation into providing a method of evaluating the punching shear capacity of shores was initiated. In Ref. 5, a review of SSI test results, and a study of literature by others, resulted in a description of the mechanism of punching shear, and a prediction relationship was developed. This relationship was further refined and used to predict the punching shear capacity of various thicknesses of concrete slabs at different overpressure loadings in Ref. 6.

A discussion of the structural connections used in light timber frame construction is presented in Ref. 6. The lateral load capacity of stud wall construction is examined as it relates to out-of-plane loading (normal to the wall), in-plane loading (parallel to the wall, or shear wall), and diaphragm loading of floor and roof systems.

A factor of considerable importance in the survival of basement shelters is the response of basement walls to the combined effects of static soil loads and the transfer of blast-induced dynamic loads through adjacent soil to the walls. A study in Ref. 6 presents experimental and theoretical data related to basement wall response, which is a complex soil/structure interaction phenomenon. The materials presented include a literature review and summary of existing theory and design methods, a review of data from the MILL RACE tests of full scale walls (Ref. 13), and shock tube tests on laboratory scale models of walls using both static and dynamic loading, conducted to define the relative importance of known parameters (Ref. 6).

Section 3
MANUAL DEVELOPMENT

INTRODUCTION

The development of the manual for upgrading structures in host and risk areas was a concurrent effort with the testing, research, and analytical program outlined in Section 2 of this report. As data from each test became available, they were analyzed, and judgments made with respect to the next test or test program. Additonal small scale tests or research programs were instituted, where required, to supplement the full scale test data. Using these data, charts, graphs, worksheets and tables were drafted, revised, refined, and ultimately finalized for use in the manual. This section of the report will briefly outline the evolution of the manual, its intended use, and the processes and technical approaches that were used in the development of the manual's charts, worksheets, and overall format.

DEVELOPMENT OF PAST MANUALS

Prior to the current contract with FEMA, SSI had conducted extensive research and testing relative to upgrading concepts for existing structures. Based on these early efforts, FEMA determined that existing data were sufficient to develop an upgrading manual limited to host area shelters. The FEMA criteria specified that the manual be limited to the upgrading of shelters in areas where it is assumed blast overpressures do not exceed 2 psi, and radiation protection equivalent to 18 in. of soil is adequate. This manual was completed in a looseleaf format, and issued in March 1980 as SSI 7815-8 (Ref. 19). It was FEMA's concept that this manual would be one of a series of manuals, each covering a different overpressure level and degree of radiation protection, a concept later revised.

As a result of the given fixed parameters; i.e., overpressure and soil loading, the technical aspects of developing this manual were straightforward. A given floor or roof system would either support the load, or it would not, and if not, one upgrading configuration would suffice. The same conditions existed with respect to the closures, the only variables being the material and closure spans. This manual resulted in the initial development of charts and worksheets, an exercise that required investigation of various properties of materials, such as built-in safety factors and load duration factors for timber; these data were used extensively in later manuals. The worksheets used in this first manual became the prototypes for the current manual, as did many of the illustrations.

A second manual in this planned series was also developed for upgrading key worker shelters, the FEMA criteria specifying that it should be limited to 40 psi and radiation protection equivalent to 3 ft of soil. This protection criterion was a compromise between a desire to create shelter designs that could survive very close-in weapon environments, and the reality of what was practical when upgrading existing structures. This manual was also issued in looseleaf format, in May 1981, as SSI 8012-7 (Ref. 20).

As might be expected, the number of existing floor systems that could be upgraded to 40 psi are few. The types of shelter areas included in this manual are essentially limited to basement areas with heavy concrete floor construction above, and all require significant upgrading resources. For that reason, it was necessary to examine a number of expedient shelter options, and those are included in the manual.

DEVELOPMENT OF CURRENT MANUAL

After the promulgation of Ref. 20, FEMA selected SSI to conduct a five-year research and testing program to provide the necessary engineering and guidance for the development of a manual of considerably greater scope. It was decided that this manual should present a number of options to the planner with respect to overpressure and radiation protection, and to some degree, the upgrading scheme he wished to use. This was a much more logical approach than the series of manuals proposed earlier, one for each of six or seven pre-selected overpressures and radiation criteria. A shelter development planner, provided that he has the structures, resources, and time, would probably always upgrade to the maximum possible, even if his exposure is assumed to be host area or less. On the other hand, a planner faced with an assumed higher exposure, but with shortages of structures, resources, and time, requires options and information so that he may make the appropriate decisions. A planner may desire to sacrifice radiation protection for blast protection, or vice versa, and the current manual was designed to provide these options.

This program was also instituted at a time when a series of high explosive tests were being planned by the Defense Nuclear Agency at White Sands Missile Range, and participation in these tests was an important adjunct to the overall shelter upgrading program. Participation in two of these tests (Refs. 13 and 15) resulted in significant data input for use in the manual.

Manual Format

The end product of this program was to be a manual for use by Civil Defense planners in formulating shelter development plans for risk and host areas. The manual was to present a number of upgrading options for consideration by the planner, and was to be written in a clear, concise, and simplified format. Included in the manual were to be sections on predicting the performance of candidate shelters, and completed shelter upgrading examples that were suitable for use in instructional training courses.

At the end of the third year of the program, a draft manual was produced, SSI 8144-17 (Ref. 21), which incorporated all of the program data developed to date in a single publication, and introduced a suggested manual format. This draft manual consisted of eleven chapters and an appendix. It became evident during the compilation of this draft that, in order to present the included material in a usable form, the final manual format would need to consist of a series of individual volumes, each volume presented so that it could be used by itself, or in conjunction with other volumes, as per the planner's individual requirements. The fourth year of the manual development program was directed toward this effort.

The manual was divided into eight separate volumes, and the format of each revised to be consistent with the guidelines outlined above. Six of these volumes were completed in draft form in October 1985, and submitted to FEMA as per contract requirements. The six volumes are reported as SSI 8144B-4, and are titled as follows:

Volume II (Ref. 22) - Methodology for Classifying and Predicting the Performance of Candidate Shelters

Volume III (Ref. 23) - Floor Systems

Volume IV (Ref. 24) - Roof Systems

Volume VI (Ref. 25) - Upgrading Methods and Systems

Volume VII (Ref. 26) - Closures

Volume VIII (Ref. 27) - Training and Survey Procedures

It may be noted that Volumes I and V are not included. Upon completion of the manual, Volume I was to be the "Introduction", describing the manual contents, the basic shelter selection criteria, and the data required for use of the manual. Volume V was reserved for Wall Systems, provided that additional usable data could be developed during the final contract year.

Charts and Worksheets

A large number of charts and worksheets were developed, and many are included within these six volumes. Charts and worksheets were originally developed for use in the Host Area manual (Ref. 19), and although the charts have undergone significant revision, some of the worksheets have progressed through the program relatively unchanged. The following will briefly discuss these upgrading aids.

Upgraded Survival Capability Charts - Throughout Volume III (Ref. 23) are numerous charts that provide the upgraded survival capability for floor systems. Not only is there a chart for each type of floor system, but within a given floor system, separate charts are provided for each level of design loading. For example, a sawn lumber joist floor may have been designed for residential occupancy, 40 psf; from a table provided in Ref. 23, it can be determined that this is considered "light" design loading, and the appropriate chart may then be referred to. On the other hand, the same type of floor system may have been designed for light storage loading, considered "medium" design loading, and therefore a different chart would be appropriate.

Each chart has diagonal lines indicating either as-built or a shoring configuration. The lines slope to the right as the depth of soil, shown on the abscissa, increases. It may be noted that occasionally one or more of these lines will become vertical at a particular soil depth, thus indicating that the assembly will collapse if additional soil, above this depth, is added.

Volume IV (Ref. 24) on roof systems contains similar charts; however, roof loading is approached differently than floor loading. Since roofs are not designed for occupancy loads, but for potential snow loading, or absence of snow loading, geographical categories were developed to assist the planner in this determination.

These charts provide options to the planner as to soil depth and shoring configuration, and are the initial step in the shelter development process. From these charts, the planner will determine the survival overpressure, shown on the chart's ordinate, which will then be entered on worksheets to determine the sizes and types of shoring and closures that may be used. The majority of these charts were developed directly from the test and analytical data presented in Section 2.

Upgrading Shoring Charts - Upon determination of the survival overpressure and shoring configuration for a particular floor or roof system, Volume VI (Ref. 25) is used to determine the size and type of materials required to perform the shoring operations. This volume contains a multitude of charts covering different timber shoring systems, such as stud walls constructed with various size studs and on-center spacing, round timber posts, and sawn rectangular and square timber beams and posts. These charts also take into account the difference in bearing properties between timber and other materials, such as concrete and steel. Each size of beam or post has an individual chart, with the acceptable lengths indicated. The chart's abscissa shows the shore spacing, while the ordinate indicates the supported load.

There obviously are many viable shoring materials and systems in addition to those included; however, the charts and systems in this volume were developed through extensive test programs, both in the field and in the laboratory, and a high degree of confidence may be placed in their anticipated performance. The bending, shear, and bearing stresses, and the buckling methodology used for calculating these charts, were based on sound, as well as conservative, timber engineering technology.

Upgrading Closure Charts - The volume on closures, Volume VII (Ref. 26), contains material charts that indicate the load supported vs. closure span. Materials included are plywood, round, rectangular and square timber posts, steel plates, and plywood and timber joist constructions. These charts cover a number of various material thicknesses, and for the most part, were calculated without the benefit of proof testing.

Worksheets - A number of different types of worksheets are provided throughout the manual. In Volume VI (Ref. 25), worksheets are provided for each of the upgrading systems included. These worksheets take the user through the development of the upgrading plan, assisting in the determination of the load to be supported, shore spacing, and material sizes. Worksheets in Volume VII (Ref. 26) provide the same assistance for closure upgrading. In addition, both of these volumes provide worksheets that assist in determining the quantities of materials required to perform the specific upgrading scheme selected.

Training and Survey Procedures

Volume VIII (Ref. 27) presents instructional materials, using example buildings, in the use of this manual for developing upgrading plans and methodology for providing shelter in existing structures. It also serves the function of providing teaching materials for use in training courses related to shelter upgrading. There are three example buildings, each having a different required level of overpressure and radiation protection. Each uses different upgrading methods (shoring configurations), and all require closing off or windows, doors, or shafts to maintain the integrity of the shelter area. The examples include appropriate charts and filled-in worksheets for reference.

Section 4

RESEARCH RECOMMENDATIONS

The purpose of this section is to highlight the areas in the shelter upgrading program that require further research, discuss what particular data are required, and outline procedures that could be implemented for their acquisition. Following are several of the more important areas in the shelter upgrading program that require additional research and investigation.

WALL SYSTEMS

Of all the major structural building elements, with respect to performance under blast loading and upgrading methodology, the least information is available on wall systems. This paucity of data is the result of a number of factors, paramount among these being the difficulty in testing and the large number of variables associated with walls.

Conducting laboratory tests on wall systems is difficult. Although full scale specimens may be tested at some large laboratories and used to validate dynamic behavior of structural elements, these static tests produce questionable results with respect to defining dynamic behavior involving complexity of soil/structure interaction under blast loading, and are very expensive. An effective and efficient approach is to develop the test methodology in a large shock tunnel using full and small scale prototypes, and to extend and verify this research with full scale experiments at the high explosive tests conducted at White Sands Missile Range (WSMR). SSI began such a program with the shock tunnel wall tests in Ref. 10 and continued at MILL RACE (Ref. 13) and DIRECT COURSE (Ref. 15), testing full scale wood stud, concrete block and brick, and precast concrete walls at MILL RACE, and small scale walls at DIRECT COURSE, resulting in valuable data.

The high explosive tests indicated conclusively that existing data on soil structure interaction with walls was, as best, inconclusive. At the MILL RACE test, precast and masory basement walls were designed to minimum code values and not upgraded. Based on published soil structure interaction data, these walls were fully expected to fail under the blast surcharge load of 40 psi overpressure - but did not. This phenomenon provided the incentive for an SSI research program conducted in the shock tube using scale model walls (Ref. 6). This preliminary investigation attempted to identify the variables associated with soil/structure interaction, such as soil density, soil wall interface, soil saturation, and wall deflection; it produced valuable data and is worthy of continued support.

Other research on wall systems is needed in upgrading methodology. If shelters are to be considered in above-grade structures, even in host areas, most walls will require upgrading - even if only to support soil berms for radiation protection. Several methods were used at the MILL RACE event, all expending considerable upgrading resources. They performed adequately, but certainly were overdesigned. Further tests such as these need to be conducted in order to determine minimum acceptable alternatives.

FLOOR SYSTEMS

Although a large number of typical floor system components have been tested in the laboratory with considerable success, more of these systems need to be field tested in actual buildings so that their interaction with other portions of the building system (walls, columns, connections, etc.) may be evaluated. The high explosive tests at WSMR would provide a good vehicle for these studies and analysis.

Floor systems in common use that are of concern, and that have not yet been evaluated, include post-tensioned concrete slabs and pre-tensioned prestressed concrete single and double tees. Post-tensioned concrete systems have an unfortunate history of catastrophic progressive collapse due to the method of their construction. Many times these slabs contain tendons that have been highly stressed, left ungrouted, and therefore anchored only at their ends. Once a tendon, or several tendons have been severed, either by inadvertently drilling through the slab or by some type of local distress, an entire section of the building slab is left without adequate reinforcement, possibly resulting in a progressive, large scale, collapse. Although this system is widely used, it has not been included in the shelter upgrading manual until such time as further data are available.

Tests at MILL RACE (Ref. 13) on prestressed concrete slabs indicated a problem with the connections associated with these systems, a problem not completely obvious, though suspected, during the conduct of the laboratory tests (Ref. 4). It would be anticipated that prestressed single and double tees, which have been included in the upgrading manual, may have similar problems. It is also believed that these connection problems may, to some degree, be mitigated, but further research and testing are required.

UPGRADING SYSTEMS

The upgrading systems that have been field evaluated are limited. Their full scale performance under actual dynamic loading conditions consists of shores installed at the MILL RACE test (Ref. 13). Other dynamic field tests are required, with the introduction of alternative upgrading methods other than vertical shores. There is a real question concerning the maintenance of upgrading integrity in basement shelters with a several story structure collapsing above. This subject was approached in SSI 8142-6 (Ref. 17).

One practical method of field testing upgrading systems would be to conduct tests in conjunction with existing buildings that are being explosively demolished. With the cooperation of a demolition contractor, basements of condemned buildings could be upgraded, instrumented, and photography obtained, with a minimum of expenditure. In addition, the manpower and resources required to install the various upgrading systems is an area that has been only minimally looked at, and this type of field testing would be an ideal setup for such a study.

CLOSURES

Closures are another area where the investigations are primarily field test oriented. Although significant preliminary data may be developed with small scale testing in a shock tube (Ref. 11), further investigative effort requires testing in the shock tunnel, and finally, during the WSMR high explosive tests. The great majority of materials suggested for closures in the manual have not been proof tested, and while there is high degree of confidence in the performance of these materials, installation and construction methods require full scale verification as a prudent measure.

MANUAL TESTING

Upon completion of the drafts of the manual, extensive field tests were to be conducted on the included materials during the final year of the contract. Because the revision in the contract work plan eliminated the final year, however, these field tests will not be conducted. If the manual is ever to be completed, and if it is intended for to be in any way useful to planners in the field, it must be first tested in the field. The draft manuals submitted to date were carefully written and intended to be as clear and as comprehensible as possible, but until the charts and worksheets have actually been worked through in the field by non-technical personnel, their effectiveness has not been proven.

The manual testing program, as contemplated, consisted of fielding teams in selected geographical areas, possibly in conjunction with concurrent national multihazard surveys, and assigning various manual exercises for solution. As a result of these exercises, it would be possible to obtain written and oral input, and critiques on all phases of the upgrading methodology therein. It was assumed that this input would result in revisions, some significant, to the draft manual's contents.

Section 4

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UPGRADING STRUCTURES FOR HOST AND RISK AREA SHELTERS

Unclassified

December 1985

Scientific Service, Inc., Redwood City, CA
Contract EMW-84-C-1828, Work Unit 1128A

32 pages

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