DEVELOPMENT OF THE ENHANCED LOAD-TREE APPARATUS FOR STRUCTURAL RESISTANCE MEASUREMENT OF MODERN LOAD-BEARING CONSTRUCTION TECHNIQUES (PREPRINT)

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Development of the Enhanced Load-Tree Apparatus for Structural Resistance Measurement of Modern Load-Bearing Construction Techniques (PREPRINT)

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Department of Defense (DoD) structures worldwide are threatened by a number of increasing conventional and non-conventional threats. The architectural-engineering industry is simultaneously meeting new cost efficiency demands by creating structures that make more efficient use of energy and materials. Although these more efficient structural systems could save the DoD billions of dollars annually in direct construction cost and in long-term energy savings, their deployment in structures that must be designed for blast threats face obstacles. The lack of data pertaining to modern structural systems subjected to blast loads and subsequent conservative structural codes is the main obstacle preventing many DoD construction projects using the cost-efficient structural systems. The Engineering Mechanics and Explosive Effects Research Group (EMEERG), located at Tyndall Air Force Base, is the blast research arm of the Air Force Civil Engineer Center and has been involved in the study of several types of modern structural and non-structural systems, including cold-formed steel stud framing and precast/pre-stressed concrete façade construction. In the past for non-load bearing applications, a load-tree apparatus was used to provide structural resistance for a variety of construction techniques. In order to study load-bearing construction techniques statically in the laboratory, EMEERG developed the enhanced load-tree, a research apparatus that allows the application of axial loads to structural elements while applying the pseudo-uniform load of a traditional load-tree apparatus. This paper describes the development, construction, and initial testing of the enhanced load-tree apparatus, along with future research plans for load-bearing construction subjected to blast.
Development of the Enhanced Load-Tree Apparatus for Structural Resistance Measurement of Modern Load-Bearing Construction Techniques

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Abstract
Department of Defense (DoD) structures worldwide are threatened by a number of increasing conventional and non-conventional threats. The architectural-engineering industry is simultaneously meeting new cost efficiency demands by creating structures that make more-efficient use of energy and materials. Although these more-efficient structural systems could save the DoD billions of dollars annually in direct construction cost and in long-term energy savings, their deployment in structures that must be designed for blast threats faces obstacles. The lack of data pertaining to modern structural systems subjected to blast loads and subsequent conservative structural codes is the main obstacle preventing many DoD construction projects’ using the cost-efficient structural systems. The Engineering Mechanics and Explosive Effects Research Group (EMEERG), located at Tyndall Air Force Base (TAFB), FL is the blast research arm of the Air Force Civil Engineer Center (AFCEC) and has been involved in the study of several types of modern structural and non-structural systems, including cold-formed steel stud (CFSS) framing and precast/prestressed concrete façade construction. In the past, for non-load bearing applications, a load-tree apparatus was used to provide structural resistance for a variety of construction techniques. To study load-bearing construction techniques statically in the laboratory, EMEERG developed the enhanced load-tree, a research apparatus that allows the application of axial loads to structural elements while applying the pseudo-uniform load of a traditional load-tree. This paper describes the development, construction, and initial testing of the enhanced load-tree apparatus, along with future research plans for load-bearing construction subjected to blast.

Keywords: blast loading; load-bearing; protective design; structural resistance; levels of protection; load-tree

INTRODUCTION

Background
The Department of Defense needs to improve structural design codes related to blast effects due to increasing conventional and non-conventional (i.e., terrorism, IEDs, etc.) threats. Geopolitical pressures have risen globally and exported terrorism is becoming an ever-increasing danger to national security on the home front. During the Cold War, research of structures subjected to blasts and the subsequent development of corresponding design codes were based on the threat of large nuclear detonations. This research is not only still relevant today, but a cornerstone of understanding structural response to shock waves. Modern construction techniques along with both smaller conventional and non-conventional threats to DoD and other US government infrastructure have forced the research civil engineering community to develop techniques and capabilities to research these emerging infrastructure scenarios.
An explosion is a thermochemical detonation that creates a shock front with peak pressures orders of magnitude higher than non-explosive load scenarios familiar to most designers. To properly design structures for blast, designers need a reliable methodology to describe the plastic behavior that is needed to resist such large-pressure, short-duration loading events. [1] The structural resistance and the mass of a structural component (e.g., walls, roofs, windows, doors, etc.) counter the dynamic force imposed by a blast. Modern construction techniques frequently lead to both energy- and materially-efficient structures. However, this material efficiency tends to produce structures with less mass. To enable the architectural-engineering industry as a whole and the DoD specifically to design for blast, research of modern structural systems must be performed to better understand the plastic behavior of such systems subjected to blast loads.

**Past Research**

AFCEC, located at TAFB, has been involved in the research of such systems including CFSS [2] and precast/prestressed concrete facades [3][4]. The past research has provided insight into the way these systems respond to blasts and produced data used to change the codes dictating the design of such systems. For instance, prior research identified and studied various failure mechanisms and determined the use of deeper tracks in CFSS systems allowed for multiple connection screws, providing the CFSS walls with significantly increased blast resistance (Figure 1) [2]. All prior research has been on non-loadbearing systems — infill walls in the case of CFSS and façade panels in the case of precast/prestressed concrete.

![Figure 1](image)

**Load-Bearing Requirements**

Response levels are measured as either a support rotation or a ductility ratio. The overarching goal of structural/blast research is to harden facilities economically by relaxing current response limits or to create design methodology with new response limits. Acceptable maximum component response levels for DoD Antiterrorism/Force Protection (AT/FP) applications are defined by the U.S. Army Corps of Engineers (COE). Levels of Protection (LOP) are specified for buildings and for each of three structural component framing categories (i.e., secondary, primary, and non-structural). The COE shows five building component damage/performance levels in the PDC TR-06-01 [5] criteria, ranging from blowout (the most severe) to superficial damage. They also explain how these damage levels are associated with building LOP. A primary structural component is defined by the PDC-TR 06-08 [6] criteria as “members whose loss would affect a number of other components supported by that member and whose loss could potentially affect the overall structural stability of the building in the area of loss.” Therefore, any load-bearing structural component would be considered primary. When determining the building LOP, the predicted damage to primary structural components is weighted heavier than that of secondary and non-structural components. Understanding the response of load-bearing components is important because of the critical

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role they play in mitigating collapse. There is insufficient information available to develop response limits specifically for members in combined flexure and compression. For this reason, more-conservative limits are placed on the allowable level of flexural response [5]. Also, the limits for load-bearing members are restricted so that they do not exceed a moderate level of damage. Therefore, when systems such as CFSS are selected for use, the response limits become extremely stringent, essentially eliminating their use in many DoD facilities. The DoD is currently restricted on the use of more cost-effective AT/FP solutions by lack of confidence in the nonlinear response and residual load-bearing capacity of primary (i.e., load-bearing) structural elements exposed to blast.

Research and development programs will shed light into the load-bearing capacities of many different types of components (e.g., steel stud, precast concrete sandwich panel, concrete masonry units, etc.) and aim to relax response limits prescribed by COE by increasing the understanding of how different load-bearing components perform under a range of loading conditions. Such lab tests are useful in characterizing response at a fraction of the cost needed to evaluate load-bearing components through full-scale blast testing.

**APPROACH**

**Traditional Load-Tree Apparatus**

The enhanced load-tree apparatus is an addition to the current traditional apparatus located at TAFB. The traditional load-tree apparatus (Figure 2) consists of a 65 kip (289 kN) actuator that provides a load which is broken into 16 total point loads on a test specimen by a series of balanced arms and fulcrums. The distributed 16 point loads simulate a uniform load across the specimen. Specimens are mounted horizontally with appropriate boundary conditions fastened to the existing strong floor. The actuator applies load to the specimen until failure. Load versus midspan deflection provides the structural resistance of the system. This structural resistance (Figure 3) correlates with how the system will respond to uniformly applied blast pressures and can be used in single-degree-of-freedom prediction models.

![Current load-tree test apparatus with CFSS specimen.](image-url)
Enhanced Load-Tree Design and Installation

The main component for applying axial load to load-tree specimens was the addition of a horizontally installed second actuator. AFCEC/EMEERG installed a 328-kip (1,470-kN) actuator (shown in Figure 4), with sufficient capacity to meet requirements for future research efforts. The actuator is designed to be mounted to a concrete mounting block with an equivalent mounting block on the opposite side of the load-tree. A steel box with 10 mounted rails (five top and bottom) is designed to attach to the strong floor with an interior carriage block sliding on rails (Figure 5). The actuator is attached to this carriage block and the test specimen. The opposite side of the test specimen is attached to the equivalent opposite mounting block. The design and fabrication of the system met many obstacles. The most prevalent obstacle is the introduction of large moments in the system induced by actuators working in different planes. For actuators to function properly, a design had to be both very robust and very exact, due to the moving parts of the horizontal actuator mounted to the rail and carriage system. Also, all load-tree expansions had to fit within the existing layout of the load-tree and overall materials characterization laboratory (e.g., strong floor). This required an extensive study performed by Protection Engineering Consultants (PEC), focused on mounting block reactions, possible testing failure mechanisms, and system safety.

The horizontally placed actuator will apply a continuous axial load while the vertical actuator of the existing load-tree apparatus applies the simulated uniformly distributed lateral load to the specimen. The lateral-load-applying actuator will be programmed to run in deflection control, while the axial load applying actuator will be programmed in force control, simulating gravity loads. Force is measured through a load cell for the vertical actuator and the applied axial force is measured directly through the differential pressure sensor of the horizontal actuator. Lateral displacement will be measured through string potentiometers at various lengths along the span of the specimen, and overall axial displacement will be measured through the installed displacement transducer of the horizontal actuator. The enhanced load-tree, similar to the original load-tree apparatus, can test specimens with spans of 10 ft (3.05 m), 12 ft (3.66 m), and 14 ft (4.27 m).
ft (4.27 m). Although the system was designed for measurement of blast structural resistance, the large axial load can be applied using the horizontal actuator. This could lead to other forms of structural component testing such as typical component buckling studies with the vertical actuator providing only a single perturbation force instead of the simulated uniform lateral load as in blast research.

Figure 4. Installed horizontal actuator for enhanced load-tree.

Figure 5. Finalized design of the enhanced load-tree apparatus.
Future Research with Enhanced Load-tree

A test program is ongoing at AFCEC to study load-bearing CFSS resistance in both the enhanced load tree and with numerical modeling performed by PEC. Preliminary numerical modeling will provide a basis for identifying influential parameters and will help update the initial static test matrix. Finite element models will parametrically look at increased attachment screw spacing for sheathing, bridging/blocking for increased lateral support, and various track-to-stud connections. Initial parameters for the static testing portion of the research program will consist of stud gauge, sheathing materials (gypsum, plywood, sheet steel), and approximated axial loads for one- to three-floor structures. Based on results, numerical modeling may influence the finalized static test matrix. Modeling is ongoing during summer 2015 with static testing slated in the following fall. Subsequent full-scale dynamic testing will be performed on the Sky X test range located at TAFB. An apparatus used for dynamic testing that would provide axial loading to full-scale specimens was designed by Jacobs Technology with testing tentatively scheduled for summer 2016. A precast/prestressed concrete program is also being developed by EMEERG to continue with previous work on energy-efficient sandwich panel designs, leading ultimately to include structural resistance measurements of load-bearing designs using the enhanced load-tree apparatus.

CONCLUSION/SUMMARY/RECOMMENDATIONS

The blast response limits used in several modern construction techniques by the architectural-engineering industry for design are often either too conservative or nonexistent. The most efficient procedure for validating new response limits is a research and development program that relies on a three-part approach of numerical modeling, static laboratory testing, and full-scale dynamic validations. AFCEC/EMEERG has been a leader in this research field for several years using a wide range of construction techniques including precast/prestressed concrete and CFSS systems. Numerical modeling ensures efficient experimental
procedures and is used in conjunction with static and dynamic testing. Static laboratory testing of structural resistance has been studied in the past by EMEERG with the load-tree apparatus. This past testing has been limited to non-load-bearing construction techniques. This gap in capability has been closed with the design and ongoing enhancement of the existing load-tree apparatus located at TAFB. The enhanced load tree apparatus will have the ability to test structural resistance of load-bearing elements with the typical simulating uniform lateral load and an axial load upwards of 300 kips (1330 kN).

REFERENCES