NOTICE

Active Bracing System: A Full Scale Implementation of Active Control

by

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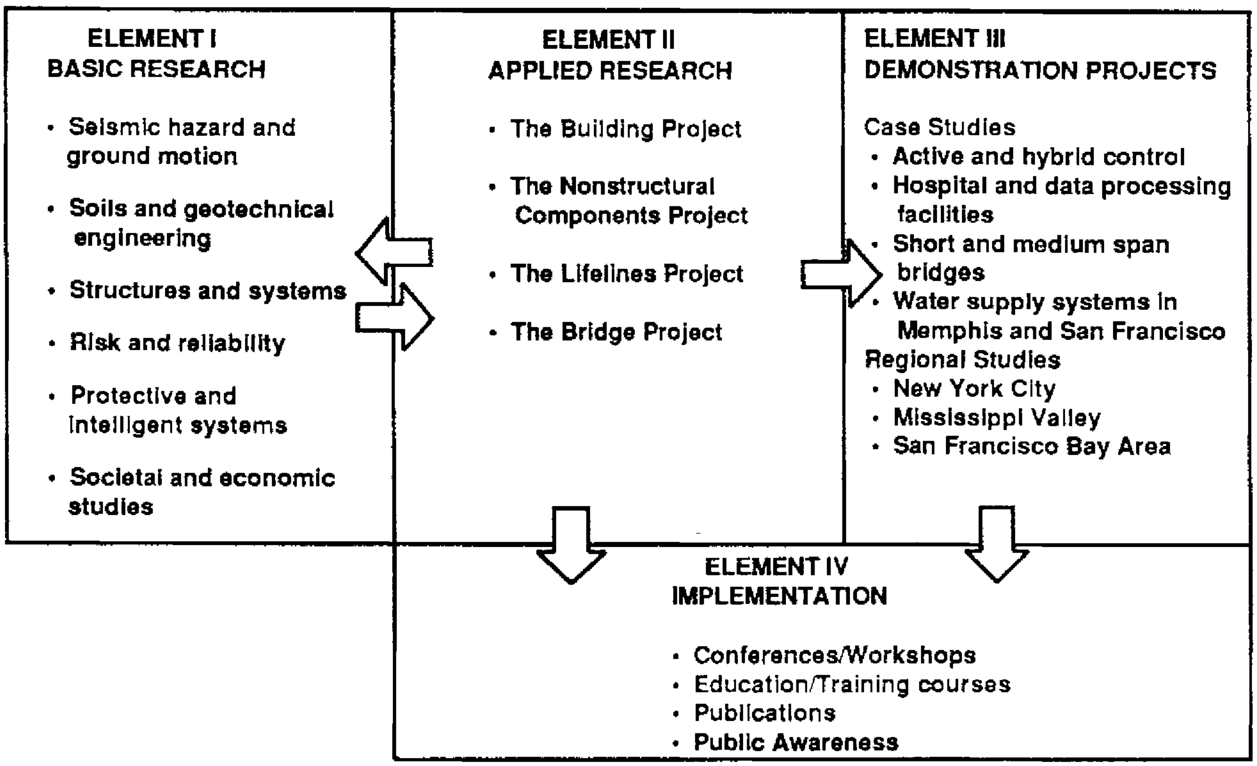
PREFACE

The National Center for Earthquake Engineering Research (NCEER) was established to expand and disseminate knowledge about earthquakes, improve earthquake-resistant design, and implement seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures in the eastern and central United States and lifelines throughout the country that are found in zones of low, moderate, and high seismicity.

NCEER's research and implementation plan in years six through ten (1991-1996) comprises four interlocked elements, as shown in the figure below. Element I, Basic Research, is carried out to support projects in the Applied Research area. Element II, Applied Research, is the major focus of work for years six through ten. Element III, Demonstration Projects, have been planned to support Applied Research projects, and will be either case studies or regional studies. Element IV, Implementation, will result from activity in the four Applied Research projects, and from Demonstration Projects.



Research in the **Building Project** focuses on the evaluation and retrofit of buildings in regions of moderate seismicity. Emphasis is on lightly reinforced concrete buildings, steel semi-rigid frames, and masonry walls or infills. The research involves small- and medium-scale shake table tests and full-scale component tests at several institutions. In a parallel effort, analytical models and computer programs are being developed to aid in the prediction of the response of these buildings to various types of ground motion.

Two of the short-term products of the **Building Project** will be a monograph on the evaluation of lightly reinforced concrete buildings and a state-of-the-art report on unreinforced masonry.

The **protective and intelligent systems program** constitutes one of the important areas of research in the **Building Project**. Current tasks include the following:

1. Evaluate the performance of full-scale active bracing and active mass dampers already in place in terms of performance, power requirements, maintenance, reliability and cost.
2. Compare passive and active control strategies in terms of structural type, degree of effectiveness, cost and long-term reliability.
3. Perform fundamental studies of hybrid control.
4. Develop and test hybrid control systems.

NCEER's research efforts in the active control area has led to the development of a full-scale active bracing system, which was installed in an experimental structure in Tokyo. This report describes design, fabrication, and operational aspects of this system, together with its observed performance under three actual earthquakes and other artificial loadings. We note that, while several active mass dampers have been implemented in full-scale structures over the last few years, the active bracing system described here represents the first full-scale active system of this type developed and tested under actual ground motions. The experience gained through the development of this system can serve as an invaluable resource for the development of active structural control systems in the future.

ABSTRACT

An active bracing system has been designed, fabricated, and installed in a full-scale dedicated test structure for structural response control under seismic loads. This report presents (i) a description of the constructed system, (ii) design specifications for the control system along with simulation studies for the design earthquake, and (iii) observed performance of the system under three actual earthquakes and other artificial loadings. Detailed design and analysis of the active system are carried out with respect to hardware development, control force constraints, and power and energy requirements. It is shown that a full-scale efficient active structural control system can be developed within limits of current technology. Simulation results provide information on performance bounds that can be expected of active systems in structural control under seismic loads and under constraints imposed by practical considerations. Installation details of the system in the building structure are presented along with the selections for fail-safe shutdown operations in case of malfunctions. Also presented are the procedures for proper maintenance and self testing which ensure continuous control with minimal resources. The observed performance under artificial loadings and actual ground motions is compared with the estimated analytical response. It is shown that the performance of the active bracing system is predictable by simple analytical procedures and efficient within the design limitations.

ACKNOWLEDGEMENTS

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SECTION 1

INTRODUCTION

The possible use of active control systems as a means of structural protection against seismic loads has received considerable attention in recent years. It has now reached the stage where active systems have been installed in full-scale structures (Soong 1990). The focus of this report is on the development of an active bracing system and it's implementation to a full-scale dedicated test structure whose performance could be assessed under actual ground motions.

Active control using structural braces and tendons has been one of the most studied control mechanisms. Systems of this type generally consist of a set of prestressed tendons or braces connected to a structure, their tensions being controlled by electrohydraulic servomechanisms. One of the reasons for favoring such a control mechanism has to do with the fact that tendons and braces are already existing members of many structures. Thus, active bracing control can make use of existing structural members and thus minimize extensive additions or modifications of an as-built structure. This is attractive, for example, in the case of retrofitting or strengthening an existing structure.

Active tendon control has been studied analytically in connection with control of slender structures, tall buildings, bridges and offshore structures. Early experiments involving the use of tendons were performed on a series of small-scale structural models (Roorda 1980), which included a simple cantilever beam, a king-post truss and a free-standing column while control devices varied from tendon control with manual operation to tendon control with servo-controlled actuators.

More recently, a comprehensive experimental program was designed and carried out in order to study the feasibility of active bracing control using a series of carefully calibrated structural models. As Fig. 1.1 shows, the model structures increased in weight and

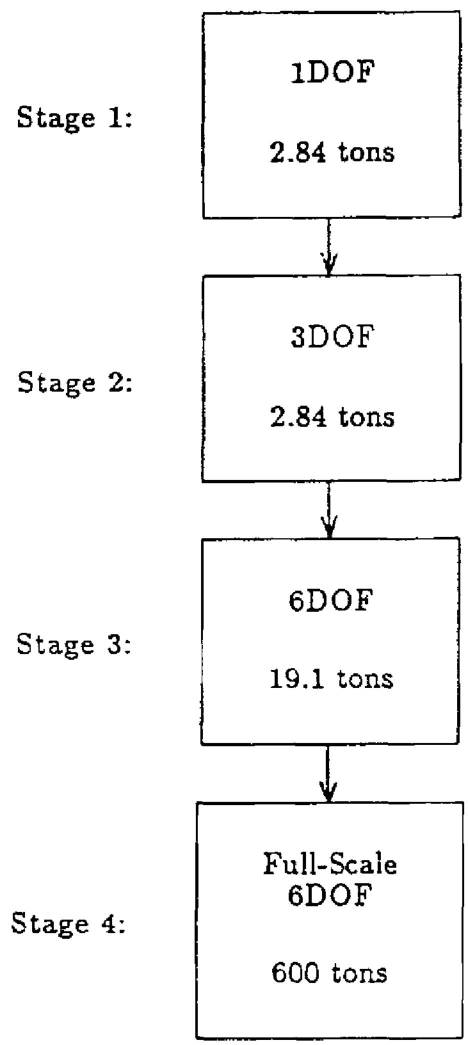

Fig. 1.1 Experimental Stages of Active Bracing Control

complexity as the experiments progressed from Stage 1 to Stage 3 so that more control features could be incorporated into the experiments. At Stages 1 and 2, the model structure was a three-story steel frame modeling a shear building by the method of mass simulation. At Stage 1, the top two floors were rigidly braced to simulate a single-degree-of-freedom system. The model was mounted on a shaking table which supplied the external load and the control force was transmitted to the structure through two sets of diagonal prestressed tendons mounted on the side frames.

Results obtained from this series of experiments are reported in (Chung et al. 1988, Chung et al. 1989). Several significant features of these experiments are noteworthy. First, they were carefully designed in order that realistic structural control situations could be investigated. Efforts made towards this goal included making the model structure dynamically similar to a real structure, working with a carefully calibrated model, using realistic base excitation, and requiring more realistic control force. Secondly, these experiments permitted a realistic comparison between analytical and experimental results, which made it possible to perform extrapolation to real structural behavior. Furthermore, important practical considerations such as time delay, robustness of control algorithms, modeling errors and structure-control system interactions could be identified and realistically assessed.

Experimental results show significant reduction of structural motion under the action of the simple tendon system. In the single-degree-of-freedom system case, for example, a reduction of over 50% of the first-floor maximum relative displacement could be achieved. This is due to the fact that the control system was able to induce damping in the system from a damping ratio of 1.24% in the uncontrolled case to 34.0% in the controlled case (Chung et al. 1988).

As a further step in this direction, a substantially larger and heavier six-story model structure was fabricated for Stage 3. It was also a welded space frame utilizing artificial mass simulation, weighing 19.1 metric tons and standing 5.5 m in height. In this series of experiments, multiple tendon control was possible and the results again show that simple tendon arrangements can produce significant motion reduction under simulated earthquake excitations (Reinhorn et al. 1989).

Another added feature at this stage was the testing of a second control system, an active mass damper, on the same model structure, thus allowing a performance comparison of these two systems. Furthermore, control requirements and control efficiencies realized in this series of experiments were extrapolated to the full-scale case, leading to a preliminary design of the full-scale active bracing system for Stage 4. The feasibility of implementation was analyzed, followed by the design and simulation study in order to assess its performance capabilities when installed in an actual structure (Soong et al. 1991).

The active bracing system has since been fabricated, installed in a full-scale test structure, tested using artificial excitations, and subjected to actual ground motions (Reinhorn et al. 1992). The objectives of the full-scale implementation are (i) to verify the complex electronic-digital-servohydraulic system under actual strong motions, (ii) to verify the capability of the system to operate or shutdown under prescribed conditions, and (iii) to validate simplified analytical procedures used to predict actual system performance. This report provides information on the detailed design and analyses of the full-scale active bracing system. The performance of the system under simulated excitations and actual ground motions is described and compared with predicted performances using simple analytical procedures.