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Session Report
SEISMIC RESPONSE CONTROL OF STRUCTURAL SYSTEMS: CLOSURE

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SUMMARY

An overview of the papers, which are relevent to seismic response control of structures, presented at the 9WCEE is given, technical issues are discussed, and recommendations for future research are made.

1. INTRODUCTION

The attenuation of structural response under seismic excitation, long an active area of investigation in the civil engineering field, has been receiving an increasing amount of attention in the recent past due to several factors: advances in technology, successful demonstration projects, and availability of new generations of microprocessors, sensors, devices, etc.

In recognition of the growing interest in, and importance of seismic response attenuation, the 9WCEE Steering Committee decided to organize a special theme session titled "Seismic Response Control of Structural Systems." The session was intended to highlight recent developments of seismic response reduction and control methodologies, with emphasis on seismic load reduction, seismic load isolation and seismic response control.

To accommodate the large number of submitted abstracts dealing with the subject of response control, the Conference Steering Committee planned three poster sessions (P2A, P2B, and P3A) in addition to the special theme session (SE). The organized poster sessions were:

1. Poster session P2A: Base Isolation and Passive Response Control (1); (23 posters)
2. Poster Session P2B: Base Isolation and Passive Response Control (2); (20 posters)
3. Poster Session P3A: Active Response Control and Damping Devices; (23 posters)

In addition, the special theme session SE consisted of two sub-sessions:

- Sub-Theme 1: Base Isolation and Passive Seismic Response; (8 papers)
- Sub-Theme 2: Active Seismic Response Control; (9 papers)

The purpose of this report is (1) to give an overview of the presentations made concerning the seismic response control of structural systems, (2) point out the main technical issues associated with various response control approaches, and (3) make some recommendations for speeding the rate of progress in the field of structural response control under seismic excitations.

2. OVERVIEW OF 9WCEE PAPERS ON SEISMIC RESPONSE CONTROL

One way of broadly classifying the different approaches to controlling the dynamic response of structural systems is to categorize them as shown in Fig. 1:

1. Input Reduction Approach: The objective of this class of methods is to reduce as much as possible the level of excitation transmitted to the primary structure. The main example of this approach is the use of seismic isolation schemes.

2. Damping Augmentation Approach: Techniques relying on this approach aim to increase the inherent damping capacity of the structural system. Typical examples are tuned mass dampers, friction devices, etc.

3. Structural Modifications Approach: The aim of this class of methods is to limit the response of structures by directly modifying their structural properties in such a way so as to (1) detune their natural frequencies from the dominant frequency of the disturbance, (2) reduce the excitation level transmitted to a given structural region, or (3) optimize the amount of mechanical energy dissipation throughout the structure.

An analysis of the 9WCEE posters and papers presented in Session P2A, P2B, P3A and SE, shows that, even though some of the papers and posters overlap the different categories in Fig. 1, the majority of the studies presented (about 60%) are primarily concerned with input reduction methods, about 30% deal with damping augmentation methods, and less than 10% address the subject of structural modification techniques as a means for seismic response control.

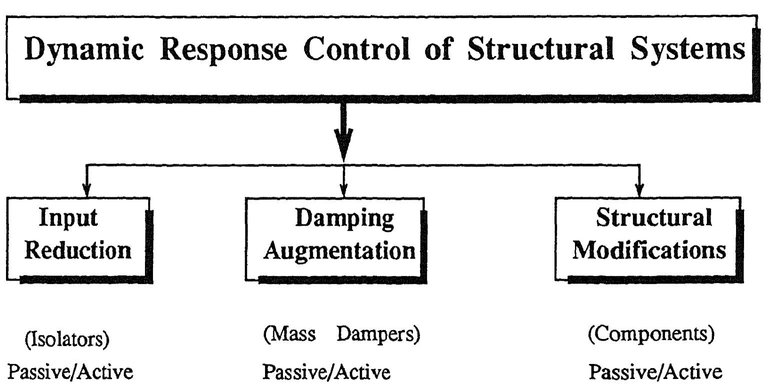

Fig. 1 Classification of approaches for structural response attenuation.

3. TECHNICAL ISSUES

Although it appears that each of the approaches shown in Fig. 1 has some significant benefits for structural systems under seismic loads, nevertheless each of the methods also has associated with it a number of technical issues and concerns that must be investigated and resolved before the full potential of the respective response control method can be exploited.

Input Reduction: Passive Systems

Numerous publications have recently appeared in the engineering literature concerning the use of passive base isolation systems to control the seismic response of large civil structures such as buildings, bridges, nuclear power plants, etc. The advantages and limitations of various passive seismic isolation schemes have been reported in several publications.

A recent study by Hadjian and Tseng (Ref. 1) presented a detailed comparative evaluation of passive seismic isolation schemes. Among the key elements of performance criteria that were addressed in Ref. 1 are: (1) isolation degrees of freedom, (2) structural stability, (3) applicability range, (4) energy dissipation capability, (5) resistance to service loads, (6) reserve capacity, (7) resilience, (8) tolerance for imperfections, (9) survivability in extreme environment, (10) resistance to aging and creep or relaxation, (11) predictability of response and design flexibility, and (12) interaction with adjacent structures and environment.

The main research issues in the dynamic response control of structural systems employing passive base isolation systems are outlined in Fig. 2. Among the key topics requiring further investigation are the long-period effects of earthquake ground motions, the influence of the nonlinearities of the isolation system, and response multi-component interaction effects.

Damping Augmentation: Passive Systems

Since the leading technique for augmenting the damping of seismically excited structures is through the use of auxiliary mass dampers, (such as the tuned mass damper) a considerable amount of research has been devoted to improving the efficiency of these devices. Some of the technical issues confronting the designers of large scale tuned mass dampers are discussed in Ref. 2.

The passive auxiliary mass dampers that have so far been installed in several buildings, bridges and other civil structures throughout the world, have been primarily linear in nature. However, some preliminary studies have shown that certain classes of nonlinear auxiliary mass dampers may furnish superior performance, regarding seismic response attenuation, compared to their linear counterparts. One such nonlinear device uses sliding friction, plastic deformation, and momentum transfer to achieve vibration reduction. Another promising class of auxiliary mass dampers relies on the sloshing of fluids to generate vibration neutralizing forces. Mechanical devices (such as braces) that directly augment damping by plastic deformation, sliding friction or viscous effects are receiving increasing attention and are starting to be used in actual structures.

Much research is still needed into the dynamic response of three-dimensional nonlinear structure/damper systems under strong earthquake ground motion. The main research needs concerning this field are listed in Fig. 2.

Input Reduction and Damping Augmentation: Active Systems

More attention has been given to passive than active control techniques as the primary means for seismic response control of large civil systems. Among the factors which tend to favor inherent passive control approaches over active control techniques in the earthquake

RESEARCH ISSUES

Passive Base Isolation Systems

Analytical Studies:

- Three-Dimensional Nonliear Structure/ Isolator Models with large Deformations.
- Long-Period Effects.
- Nonlinearities in Rubber and Sliding Bearings.
- Effects of Randomness in Parameters.
- Differential Settlements.
- Interaction Effects Between Horizontal Seismic Motions and Vertical, Torsional and Rocking Modes.
- Preliminary Design Procedures.

Experimental Studies:

- Validation Tests.
- Material Properties.
- Overturning and Stability.
- Configuration and Orientation.
- Large Scale Tests.
- Specialized Component Design.

Passive Damping Augmentation Systems

Analytical Studies:

- Nonlinear Mass Dampers.
- Damping Friction Devices.
- Stability Analyses.
- Three-Dimensional Nonlinear Structure/ Damper Systems.
- Innovative Design for Local Members (e.g., Bridge Cables).

Experimental Studies:

- Validation Tests.
- Aging Effects.
- Material Properties.
- Reliability.
- New Concepts.

Active Response Control Systems

Analytical Studies:

- Three-Dimensional Nonlinear Structure/Actuator Models.
- Stability Bounds.
- Optimum Location of Sensors and Actuators.
- Instrumentation/Measurement Errors.
- Time Delay in Control Systems.
- Control Algorithms.
- Degrading Structures.
- Randomness in System Parameters.
- Development of Reduced-Order Nonlinear Math Models for Control (System Identification).
- Retrofitting Problems.
- Cost/Benefit Studies.
- High-Speed Parallel Processors.
- Failure-Tolerant Control Procedures.
- Multi-Direction Control.
- Parameter Control.
- Reliability Issues.

Experimental Studies:

- Validation Tests.
- "Smart Building" Tests.
- Instrument Development.
- Actuator Development.
- Control Energy Sources.
- Measurement Errors.
- Variability in Actuators.
- Reliability Studies.
- Simplified Algorithms.
- Efficient Computer Codes.
- Aging Effects.
- Retrofitting Tests.
- Damage-Tolerant Control Tests.
- Full-Scale Tests.

Fig. 2 Major research issues in the dynamic response control of structural systems.

engineering field is that active seismic response control systems would have to remain in a standby mode for many years without being activated. The reliability of infrequently used equipment then becomes a serious liability which must be addressed by any active control design. In addition, the peak power requirements of conventional actuators can be extremely large. Furthermore, the time at which the control power is most needed often coincides with the time at which failure of most public utility systems can be expected. Thus, the availability of adequate power and energy sources is an additional concern for active control systems. Finally, there may be important psychological factors for the occupants of large civil structures and the public at large which may need to be addressed before acceptance of the concept of active seismic response control is accomplished.

The concept of active control is of course not new; for many decades it has been routinely used by electrical and control engineers to successfully handle challenging problems that arise in a variety of engineering disciplines. Even though the theoretical foundations of modern control theory are well established, the application of active control techniques to large civil engineering structures poses many unique problems and challenges that will require a considerable amount of analytical and experimental investigations by many engineers for an extended period of time.

A detailed survey of research activities in, and the many unique technical issues associated with, active vibration control of civil structures are reported in two recent papers by Miller et al. (Ref. 3) and Soong (Ref. 4).

Since the subject under discussion is not as mature a field as the passive seismic response control field, it is not surprising to find that the list of research topics needing further advancement in Fig. 2 is much longer for active control than for passive control methods. In fact, the list of topics in the right-hand-side of Fig. 2 is much more extensive than it appears to be because many of the outlined topics are in fact composites of many sub-topics each one of which offers many challenging research opportunities. Such example topics are: design of large capacity actuators, development of practical active control algorithms, and system identification procedures for dealing with nonlinear systems of the type encountered in civil structures.

Space limitations preclude a detailed listing, much less discussion, of the myriad research issues concerning the topic under discussion which still await investigation. By consulting Refs. 3 and 4, the interested reader can locate many useful reference articles dealing with this subject matter.

Structural Modifications: Active Parameter Control

As pointed out in the preceeding section, one of the main hurdles along the path of practical implementation of active seismic response control approaches is the potentially excessive control energy and power demands. This has motivated researchers to explore the possibility of using "semi-active" control approaches whereby the control actuators are used to actively modify the parameters of the structure (rather than using control forces to directly counteract the seismic response) according to a prescribed on-line control algorithm. One of the pioneering studies using such a concept is reported in the work of Kobori et al. (Ref. 5) where the approach of "Dynamic Intelligent Building" is employed in conjunction with adjustable structural components to reduce the seismic structural response. Another study exploring the potential of this approach through analytical and experimental investigations of semi-active nonlinear mass dampers is reported in the work of Masri et al. (Ref. 6).

4. SUMMARY AND CONCLUSIONS

Even though a considerable amount of progress has been achieved in the field of seismic response control using various passive and active approaches, additional studies are needed in virtually all aspects of this field. The major research issues are summarized in Fig. 2, and their distribution and nature reflects the fact that the field of passive seismic control is more mature than its active counterpart.

Many serious technical challenges need to be overcome before wide-spread acceptance and implementation of passive, active, semi-active and hybrid seismic response control approaches. In order to speed the rate of progress in removing the serious impediments encountered in this field, extensive cooperative efforts are needed along two paths: (1) multidisciplinary efforts among various engineering fields, together with material science, architecture and psychology; and (2) multi-national efforts involving world-wide collaborative research efforts, exchange of personnel, jointly organized tests, and exchange of data and technical information.

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