HYBRID WALL SYSTEMS: US-JAPAN RESEARCH

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SUMMARY

The focus of the fifth phase of the US-Japan cooperative earthquake research program is hybird and composite structural systems. One aspect of this program involves the study of buildings with concrete core walls surrounded by a steel frame, which is referred to as a hybrid wall system (HWS) in the US-Japan research program. Research projects were undertaken to investigate the following areas: reinforced concrete (RC) and steel reinforced concrete (SRC) core walls; steel frames with RC infill walls; RC, steel, and hybrid coupling beams, and steel frame connections to core walls. Development of analytical models and performance-based design guidelines were also addressed. A overview of the program is provided, along with brief summaries of the research projects.

INTRODUCTION

The fifth phase of the US-Japan co-operative earthquake research program was initiated in 1993 to investigate composite and hybrid structures. Research conducted in this program has been organized into four general areas: (1) concrete-filled tube systems, (2) reinforced-concrete and steel reinforced concrete systems, (3) reinforced concrete and steel reinforced concrete hybrid wall systems, and (4) new materials, elements, or systems. The focus of this paper is to summarize research in the reinforced concrete (RC) and steel, reinforced concrete (SRC) hybrid wall systems (HWS). Companion papers outline research in the other areas.

HYBRID WALL SYSTEMS

Hybrid wall systems involve the use of RC or SRC walls to provide the lateral-force resisting system for earthquake ground motions. The walls provide substantial lateral strength and stiffness, as well as the inelastic deformation capacity needed to meet the earthquake ground motions. In hybrid wall systems, RC or SRC “core walls” are commonly used, where the walls are concentrated at the center of the building. A steel frame system with either simple or moment connections is commonly used to resist the gravity forces, and floor system also serves as a collector for the core walls. For taller buildings top hat or belt trusses are commonly used to provide effective coupling between the core walls and the steel frame.

The use of hybrid wall systems presents a number of challenging research and design issues. For RC and SRC walls, adequate detailing must be provided to resist the inelastic deformation demands at critical locations, and the influence of the coupling beams and floor slabs on the wall and system behavior must be assessed. Anchorage and detailing issues, and the influence of the embedded structural steel section on potential failure modes, are important research topics for SRC walls. The coupling beams, constructed of either reinforced concrete or structural steel, impact the lateral stiffness of the system as well as the distribution of axial and shear forces among the core walls. Embedment of the steel coupling beams within the core wall and connection of the structural steel frame system to the core wall also requires attention.

Alternative composite systems include the use steel frames with rc or steel plate infill panels. The interaction and connection between the steel frame and the infill panel are important issues. Shear studs are commonly used at the

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interface of the structural steel section and the rc infill panel. The behavior of the shear studs embedded in narrow rc infill panels subjected to cyclic loads is not well understood.

Analytical studies are an effective means to study the interaction between the core walls and the steel frame; however, analytical models capable of capturing the important characteristics of the walls, coupling beams, steel frame, and the connections need to be developed and implemented. Three-dimensional behavior of the core walls and the combined core wall, steel frame system are also areas of interest.

A series of research projects were undertaken to address the spectrum of topics associated with the behavior and use of hybrid wall systems. A summary of these projects, as well as important findings are outlined in the following sections for research conducted in both the US and Japan. More detailed information is available in summary project papers presented at the Fourth (Monterey, CA in October 1997) and Fifth (Tokyo, October 1998) Joint Technical Coordinating Committee meetings of US-Japan Cooperative Earthquake Research Program on Composite and Hybrid Structures, and US Technical Coordination meeting (San Francisco, August 1999). The papers are available from the individual researchers, or through the NISEE (http://www.eerc.berkeley.edu/).

HWS RESEARCH – US

Research projects are being conducted at seven different universities in the US to address HWS research topics (Table 1). These projects are organized into four topic areas and summarized in the following subsections.

Composite Wall Systems

Research is underway at the University of Minnesota, UCLA, and UC Berkeley to provide essential data on the performance of composite wall systems. The work underway at the Minnesota involves studies of structural steel frames with rc infill panels, whereas the work at UCLA is focusing on reinforced concrete walls with embedded steel sections at the wall boundaries (Fig. 1). Studies at UC Berkeley aim to develop an innovative steel plate shear wall system.

A major focus of the work on steel frames with rc infill panels is the interaction and connection between the steel frame and the infill panel. Monotonic (6 specimens) and cyclic (2 specimens) tests of shear studs with thin rc panels have been conducted to assess the behavior of studs under cyclic shear and axial tension (Fig. 2). Primary variables included slip displacement history, axial tension magnitude, and configuration of confining reinforcement. The confining reinforcement is used to mitigate the effects of concrete cracking adjacent to the interface with the steel frame members. Cyclic shear loading was found to have a modestly detrimental effect on stud strength, but a large impact on deformation capacity. Axial tension stress on the studs affects both shear strength and deformation capacity of the studs in a dramatic manner. Providing confining reinforcement around the stud served to mitigate much of the damaging potential of axial tension stress. Additional tests are being conducted to investigate the use of a ductility-enhancing device (DED) on the studs. The device is a polymer insert placed around the base of the studs to improve the shear displacement ductility under reversed cyclic loading. Based on the results of the stud tests and analytical studies, two approximately one-third scale, two-story, one-bay frames are being constructed for testing. The primary variable between the two test structures is the degree of composite action, which is controlled by the number of shear connectors and confining reinforcement scheme, or the ductility capacity of the stud connections, which is dictated by the use of the DEDs.

The research project at UCLA on SRC walls is designed to address strength, detailing, and construction issues. Flexural strength depends on the degree of composite action between the embedded steel sections at the wall boundaries and the surrounding concrete. The tests will address whether full composite action can be expected. Although shear strength is not a primary concern for slender walls, the level of shear stress developed at the flexural capacity may influence the deformation capacity of the wall. This is being addressed by varying the size of the embedded structural steel section. ACI 318-99 and UBC-97 provisions for transverse reinforcement are being used as a basis for assessing detailing issues at the wall boundaries. An axial stress of $0.1f_c^{'}$ to $0.2\ f_c^{'}$ will be maintained on each specimen for the duration of each test, although variation of axial load may be considered for one or two specimens. Construction issues include the anchorage of horizontal web reinforcement and the orientation of the embedded steel section at the wall boundary. The specimens will be approximately 1/3 scale, with a thickness of approximately 150 mm, a length of 1220 mm, and a height of 4877 mm. Testing of the first three specimens is expected in the fall of 1999.

The objective of the study at UC Berkeley is to further develop the steel plate shear wall system where the steel plate is reinforced out-of-plane by concrete panels. In the new proposed system, the concrete panels are separated from the steel frame by rubber shims such that the concrete wall panels come into bearing against the steel-framing members only for strong shaking. This project was initiated in late 1998; therefore, only limited results are available at this time.

Coupling Beams

RC coupling beams commonly employ diagonal reinforcement to enhance shear resistance and toughness; however, relatively deep beams are required to effectively utilize the diagonal reinforcement and reinforcement congestion poses a significant construction issue. To address these problems, work at the University of Cincinnati has been conducted to investigate the use of steel coupling beams between rc core walls. Additional studies are being conducted at the University of Michigan and the University of Notre Dame to develop innovative coupling elements. Summaries of each project are provided in the following paragraphs.

Primary objectives of the University of Cincinnati research was to determine the length of embedment of the steel coupling beam into the rc core wall needed to ensure inelastic deformations occur within the coupling beam in a controlled manner, as well as to assess appropriate stiffness values to use for analysis. Based on the research, a design model to determine the depth of embedment for steel coupling beams was developed. The primary variables in the equation are the concrete strength, wall thickness, flange width, and the beam span. Test results also indicated that the steel coupling beams displaced vertically at the coupling beam-wall interface; therefore, the coupling beam stiffness was only 30 to 45% of the value corresponding to the case where the coupling beam is fixed at the face of the wall. Based on a review of the experimental data, the effective fixed point is approximately one-third of the required embedment length from the face of the wall.

At the University of Michigan, the potential to use a coupling beam-damper element (CBDE) made using high-performance fiber reinforced cement composite (HPFRCC) is being investigated (Fig. 3). The underlying concept is to connect the steel frames with a story deep coupling element specially designed to dissipate energy in a controlled manner. Energy is dissipated in the notched section of the coupling element, which develops well-distributed micro cracking. Additional experimental and analytical studies are being conducted in this research project, which was initiated in the fall of 1998.

Development of an unbonded post-tensioned hybrid coupled wall system is being studied at the University of Notre Dame. The system (Fig. 4) relies on gap opening along the beam-to-wall connections to dissipate energy within the angles during structural response to earthquake ground motions. Varying the post-tensioning force, beam depth, or beam length can control the degree of coupling between the walls. The main objectives of the research are to develop analytical models for the coupled wall system and to verify the models based on subassemblage tests, as well as to perform parametric studies to assess expected building performance. Preliminary analytical studies have been conducted to develop moment-rotation relationships for the system that capture the progression of damage (i.e., gap opening, cover plate yielding, angle yielding, post-tensioning strand yielding, beam flange yielding), as well as to examine the influence of the major design variables on beam moment-rotation behavior.

Structural Steel Connections

The use of hybrid wall systems involves the use of rc or src core walls with a surrounding structural steel frame. Because significant coupling cannot be developed between the steel frame and the core walls (given the relatively large spans and beam sizes), simple connections between the steel frame and the core wall are most likely to be used. Because the floor system also serves to "collect" the seismic forces generated in the floor system and "deliver" them to the core wall, connections between the steel beams and the core wall are required to resist both shear and tension. For taller buildings, where coupling is needed to reduce displacements, "top hat" trusses or story level trusses are efficient. Connection forces between the truss and the core wall are required to resist both shear and tension.

Experimental studies were conducted at the University of Cincinnati to investigate steel frame core wall connections. The testing is being conducted in two phases. Phase I will investigate the behavior of plate/connections subjected to combined shear and tension. Seven, approximately one-third scale specimens have been tested to investigate the role of concrete strength, number of studs, plate thickness, as well as the influence of wall boundary reinforcement on the connection strength and ductility. Based on prior research and the test results, a design model for the plate/stud connection was reviewed. The model provided reasonable agreement with test results for cases where the studs were embedded into a lightly reinforced wall. For the specimen with substantial wall boundary longitudinal reinforcement (specimen 4), failure occurred at the stud/plate connection and the design model substantially under-predicted the connection strength. In Phase II, a complete wall specimen with two stud/plate connections will be tested to address the influence of concrete cracking on connection behavior.

Analytical Models

Analytical models are being developed within each of the experimental research programs as well as within other projects to improve the analytical tools available for evaluation of hybrid wall systems. Specific models being developed and/or calibrated against experimental data include: (1) a steel plate/stud connection model at the University of Cincinnati, (2) an unbonded post-tensioned coupled wall model at UND, (3) a coupling beam damper element at the University of Michigan, (4) a wall macro-model (multiple-vertical-line) at UCLA, and (5) a wall macro-model (beam-column) at UCF. The wall macro-models include a single beam-column element with stiffness and strength degrading behavior (UCF) and a multiple-vertical-line element (UCLA). The objective of these studies is to provide a robust toolbox for analytical studies of various hybrid wall systems. The analytical studies will investigate various parameters (e.g., optimal coupling between core walls and steel frame, economical floor plans for various systems, the influence of soil-foundation-structure interaction). Various platforms are being used for current development work (e.g., DRAIN-2DX, DYNAMIX, FEAP, MATLAB); however, the long term goal of the HWS program is to implement the models in a common format, such as the new analytical platform being developed by the Pacific Earthquake Engineering Research Center (http://peer.berkeley.edu/).

Detailed nonlinear finite element formulations are also under development at University of Central Florida, UCLA, and University of Minnesota. At UCF, a plane stress, smeared fixed-crack model is being implemented in DYNAMIX. Work at the University of Minnesota is directed towards developing both a refined and macro model for steel frames with infill panels, whereas work at UCLA will extend prior research on steel tube models with nonlinear material and geometry to core wall systems. Currently (August 1999), most of this detailed work is in the early stages of development.

HWS RESEARCH – JAPAN

Hybrid wall system research in Japan was based on a prototype structure with a reinforced concrete core wall surrounded by a steel frame. The main areas of study include: (1) seismic behavior of coupled walls, (2) shear and flexural behavior of 3D walls, (3) coupling beam and steel frame core wall connection behavior, (4) bi-directional earthquake ground motion, and (5) development of performance-based design guidelines. Major research projects are identified in Table 2 and a brief overview of the projects is provided in the following sections.

Core Walls (Kabeyasawa)

Research on core wall behavior has been conducted to address confinement and shear issues as well as to study three-dimensional effects and develop models. Each of these areas a discussed in the following paragraphs.

Displacement-based approaches were used to assess confinement requirements at boundaries and corners of core walls for serviceability, damage control, and ultimate limit states. A pushover analysis is used to determine appropriate levels of wall moment, shear, and axial load to use in assessing required details for each performance state. Experimental results were used to review and refine plastic hinge estimates for walls. The wall strain gradient is then estimated and used to assess detailing requirements. The influence of shear on the wall neutral axis depth is then evaluated and detailing requirements are revised. The approach has been verified using experimental data that includes tests on rectangular-, T-, and L-shaped wall cross sections (Kabeyasawa, et al., 1995; 1996; 1998). Skewed earthquake loading was considered to evaluate the need for confinement reinforcement at the corners of T- and L-shaped walls.

For analytical modeling, a new wall macro element was developed. The model uses nonlinear axial springs at the wall edges to capture flexural response and a nonlinear panel element for shear response. The panel element was developed based on finite element concepts and very good correlation was obtained between analytical and experimental results for isolated and coupled walls provided the level of axial load and shear was not too large. Simulation of concrete shear response as a function of wall axial load, and estimation of tangent stiffness are areas where additional development work is needed. A method to predict wall shear under dynamic loads was also studied. The proposed method involves superposition of the shear forces obtained from pushover analysis under lateral loads (first mode distribution) with higher mode shears obtained from a linear acceleration response spectrum.

Coupling Beams (Kobayashi)

Behavior of coupling beams with diagonal reinforcement and shear span ratio between approximately 0.5 to 2 was studied. The load-displacement relationship was evaluated for cracking, yielding, and ultimate limit states. Cracking strength is defined as the smaller of the load for flexural cracking or shear cracking. For yield strength, a strut and tie model or a model based on flexural strength is used. The flexural strength mode uses equilibrium requirements and geometry of the beam, and accounts for both diagonal and parallel steel. Ultimate strength assessed using standard approaches. Yield deformation is determined based on one of several approaches depending on the case. The ultimate deformation in the post-peak loading range is defined at 90% of peak load. Comparison with data from 70 experiments indicates that the trilinear envelop predicts the load-displacement relation reasonably.

Coupled Walls (Teshigawara, Sugaya, Kato, and Matsushima)

Tests of a one-third scale twelve story coupled wall system were conducted at BRI under lateral and vertical loads. T-shaped wall cross sections were used Tests were conducted to drifts of approximately 1/25. Buckling of the girder reinforcement and spalling of concrete occurred at drifts around 1/50. The coupling girders elongated as a result of cyclic plastic excursions resulting in an increasing compression load in the coupling girders. An analysis of the specimen was carried out using a multi-spring model for the walls and coupling girders. Reasonable correlation between analytical and experimental results was obtained with the fiber model, including the transfer of shear from the tension to compression wall. The multiple-spring model also did a reasonable job predicting the influence of axial load on wall stiffness, the impact of wedge action of coupling beams, and the residual compressive axial load in the coupling beams. Analytical studies were conducted to address the importance of the floor slab on the behavior of the specimen. Results of these studies suggest that the influence of the floor slab may not be as significant as expected.

Structural Steel Connections (Kei, Yamanobe, and Kobayashi)

Research work on steel frame connections to rc core walls has focused on developing economical semi-rigid connections because use of moment connections of steel beams to the rc core walls requires special detailing and efficient coupling is hard to achieve with moment connections (belt or hat trusses are more efficient). Design aids have been developed to determine what level of moment capacity and detailing should be provided at beam-to-wall connections. A capacity design approach is used to force the weak link to be the connection at the beam end versus the connection to the wall (various connection types, including shear tabs or beam seats anchored to the wall with studs or anchor bolts). Design charts have also been developed to aid in selecting the connection stiffness to use for analysis.

Design Requirements (Tsukatani; Teshigawara and Matshushima; Nakano; Kabeyasawa; Wada)

Considerable effort has been expended to develop design guidelines for hybrid wall systems consisting of a reinforced concrete core wall (with coupling) and a perimeter steel frame. Relevant studies include work to define performance and damage levels (Tsukatani), develop detailed design guidelines (Teshigawara and Matshushima; Kabeyasawa; Wada), and develop detailed example applications (Nakano). Each of these projects is outlined in the following paragraphs.

Performance levels were defined for earthquake recurrence intervals of 20, 100, 500, and 1000 years (L1 to L4, respectively). In addition to an essentially undamaged state (D0), damage states corresponding to the elastic limit (operational, or D1), repairable damage (D2), and ultimate limit (D3) have been defined as appropriate for each performance level. Specific element damage information has been assigned for each damage level. For example, a rc coupling beams would be assigned damage state D2 if yielding occurs in the diagonal reinforcement (versus partial yielding for D1) and the joint rotation is between 1/50 and 1/100. Although strength deterioration is allowed for damage level D2, repair work would be required. Other elements covered include bearing walls, perimeter steel frames, and footings.

Design guidelines have been proposed that define the earthquake demand, the analysis method, and the performance assessment. A capacity spectrum approach is used where a performance point is defined on a plot of spectral acceleration versus spectral displacement. A substitute or equivalent damping factor for the structure is determined assessing the damping contribution on an element-by-element basis, and summing the element damping contribution to determine the global damping factor for the structure. The damping contribution for each element is a function of the element cyclic load-displacement response and the element ductility demand; therefore, substantial computational effort is required. Teshigawara and Matsushima (1998) apply the overall approach to the twelve-story coupled wall test structure. Nakano (1998) provides a very detailed example application for a complete structure (hws theme structure for the US-Japan program).

ACKNOWLEDGMENTS

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Table 1 US HWS Research Projects

UNIVERSITY	RESEARCH TEAM	RESEARCH TOPIC
California, Berkeley	Astaneh-Asl	Composite wall tests and modeling
California, Los Angeles	Wallace, Conte, Stewart	SRC wall tests, wall modeling, system studies
Central Florida	El-Tawil, Kunnath	Wall modeling and system studies
Cincinnati	Shahrooz	Steel coupling beams, core wall connections
Michigan	Naaman	HPFRCC coupling beams
Minnesota	Schultz, Hajjar, Shield	Steel frame, concrete infill tests and modeling
Notre Dame	Kurama	Unbonded PT coupling beam tests and modeling

Table 2 Japan HWS Research Projects

AFFILIATION	RESEARCH TEAM	RESEARCH TOPIC
Univ. of Tokyo	Kabeyasawa	Wall modeling, detailing, and shear
Fujita, Sato Kogyo, Zenitaka, Taisei	Sasaki, Yanagisawa, Igarashi, Kobayashi	Strength and deformation capacity of diagonal reinforced coupling beams
Takenaka, Shimizu, Taisei	Kei, Yamanobe, Kobayashi	Steel frame connections to core walls
NTT	Nakano	Design examples
BRI	Teshigawara, Sugaya, Kato, Matsushima	12-story coupled wall test and evaluation
BRI Tokyo Inst. of Tech. Univ. of Tokyo	Teshigawara, Matsushima Wada Kabeyasawa	Seismic design guidelines for HWS structures
Mitsubishi	Tsukatani	Performance Levels for HWS structures

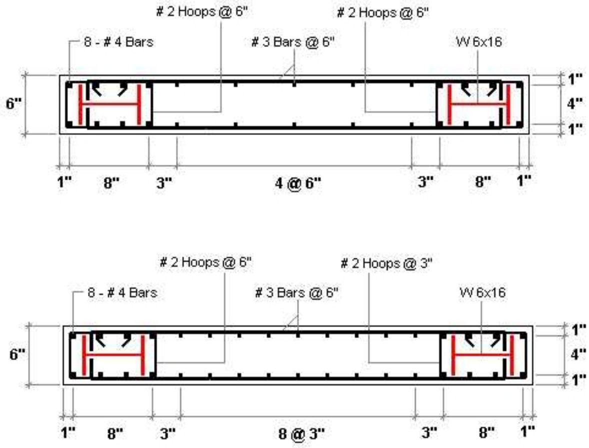

Fig. 1 Geometry and Reinforcement for SRC Wall Test (Specimen SRCW-2)

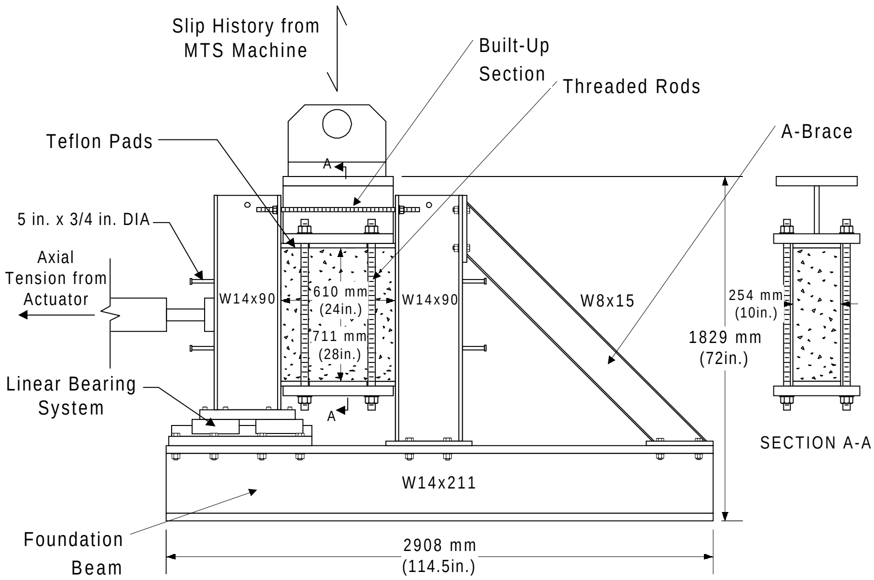

Fig. 2 Shear Stud Connection Tests

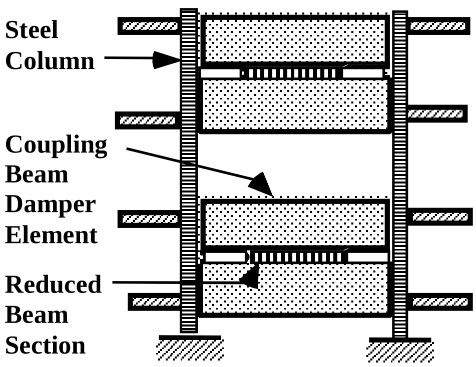

Fig. 3 Coupling Beam Damper Element

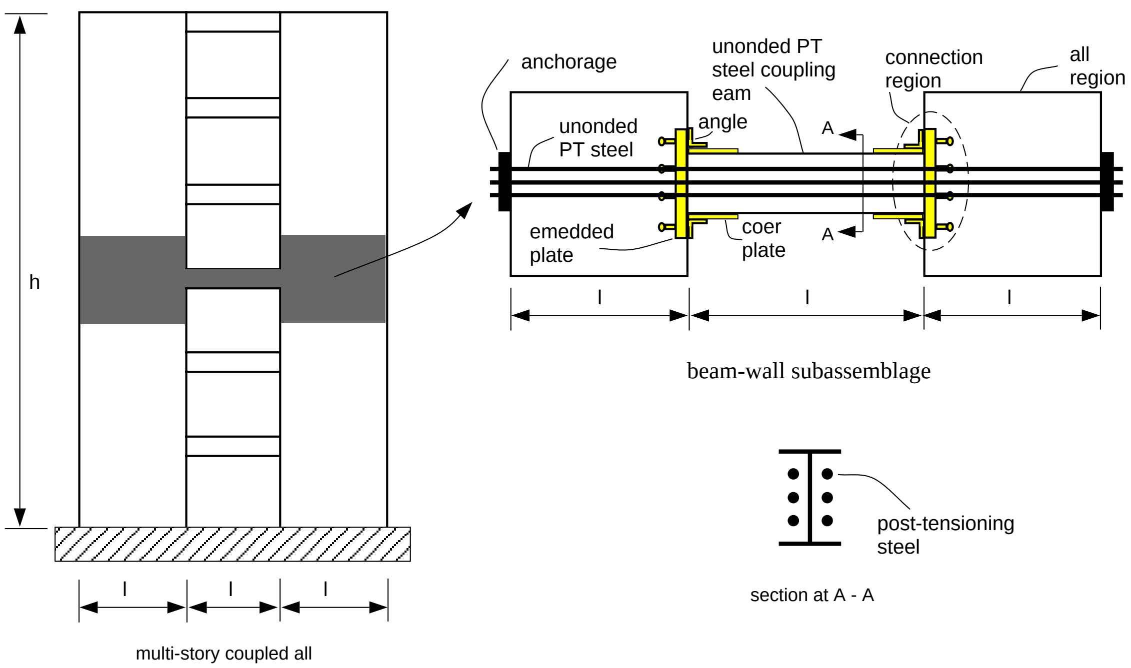

Fig. 4 Unbonded Post-Tensioned Wall Coupling Beam

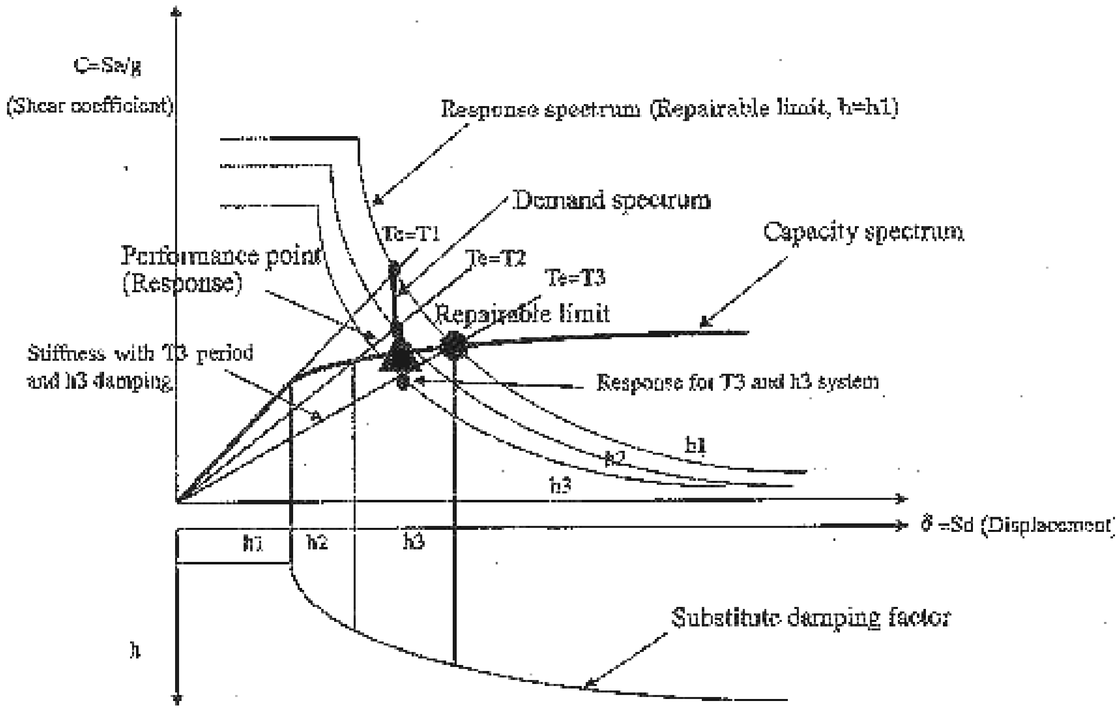

Fig. 5 Performance Spectrum – Repairable Limit