RESEARCH ON RC/SRC COLUMN SYSTEMS

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SUMMARY

Summarized herein are the motivation, scope and accomplishments of cooperative research by investigators in Japan and the United States on composite moment frames consisting of steel beams and reinforced or encased composite columns. Inspired by innovative applications of composite frame systems in the late 1970's and early 1980's, extensive research over the past ten years has improved our understanding of composite frame behavior and lead to the development of seismic design models and criteria. This research includes testing and analysis of composite beam-column connections and composite columns, nonlinear seismic simulation of composite framing systems, testing of several reduce reduced scale composite frames, and preliminary investigations on performance based design approaches. Aside from the cost effectiveness of composite frames, the research confirms that composite frames can be designed with seismic deformation capacity and toughness at least equal to traditional steel or reinforced concrete construction. Compare to structural steel frames, composite frames avoid many of the problems associated with field welding and fracture resistance of beam-column connections, and compared to reinforced concrete, composite frames have more inherent toughness and reduced problems associated with reinforcing bar congestion and concrete placement.

INTRODUCTION

One of the four research thrust areas of the US-Japan Cooperative Research Program on Composite and Hybrid Structures addresses the seismic design and behavior of frames consisting of Reinforced Concrete (RC) columns and steel (S) beams - so called composite RCS moment frames. Such systems have been constructed since the mid-1980's as cost-effective alternatives to traditional steel or reinforced concrete building systems, but their use in high seismic regions has been hindered by a lack of information on their design and behavior. Among the outstanding issues are many related to the design and detailing of composite elements – particularly connections between structural steel and reinforced concrete elements - and the overall inelastic performance of the systems. The primary objective of the coordinated US-Japan research effort is to enable more effective use of composite RCS systems in high seismic regions through a broad investigation that involves (1) testing and finite element analyses of RCS beam-column connection subassemblies, (2) testing and finite element analyses of RCS moment frames, (3) seismic design studies and analyses of RCS framing systems, and (4) development of design guidelines and recommendations.

Historical Development of RCS Frame Systems: While composite RCS systems built in Japan and the United States bear many similarities, there are significant differences in how RCS systems were developed and are commonly applied in each country. In the United States, RCS composite moment frames evolved during the late 1970's and 1980's as a variation of conventional steel moment frames in mid- to high-rise buildings. The composite frames typically resemble conventional steel frame construction except that the steel columns are replaced by high strength reinforced concrete – the primary motivation being a 10 to 1 cost advantage of concrete over structural steel for resisting compressive column loads (Griffis 1992). Innovative construction staging operations also add to the overall cost and time savings. As shown in Fig. 1, the typical construction sequence utilizes small steel erection columns to advance steel framing several floors ahead of placing

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reinforced concrete columns. Shown in Fig. 2 is a typical beam-column connection for composite frames where the steel beam passes continuous through the joint, thereby eliminating the need to interrupt the beam at the column face. This in turn eliminates the need for welding or bolting of the beam at the point of maximum moment. Concrete column reinforcement also runs continuous through the joint and is spliced near column mid-height.

In Japan, RCS frames were developed as an alternative to conventional reinforced concrete construction for low-rise office buildings and retail stores. Here the incentive is to utilize steel beams for long span floor framing and minimize field labor while still achieving the cost savings provided by reinforced concrete columns. Another contributing factor to the development of RCS systems in Japan was an established tradition of mixing structural

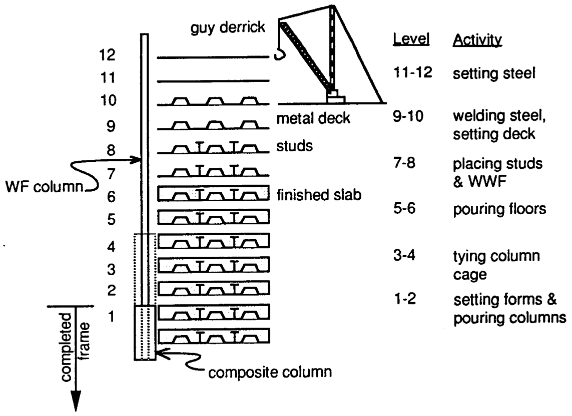


Fig. 1 – RCS Construction Method for High-Rise Buildings (US Practice)

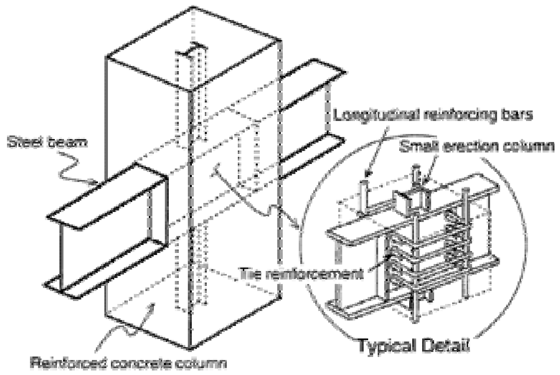


Fig. 2 – RCS Beam-Column Joint (beam through type)

steel and reinforced concrete in Steel Reinforced Concrete (SRC) construction. SRC construction is characterized by full concrete encasement of structural steel frames (beams and columns) – a style of construction dating back to the 1923 Kanto earthquake when such structures were observed to perform well. Modern RCS construction is distinguished by the fact that the steel beams are exposed, i.e., not encased, and the columns are standard reinforced concrete without any encased steel shapes. Thus, the construction methods and design codes for RCS construction are distinctly different from SRC construction. Furthermore, whereas design provisions for SRC structures are well established (AIJ 1987), detailed provisions are not generally available for RCS frames. Shown in Fig. 3 are two examples of RCS frame construction in Japan, Fig. 3a featuring a precast construction method and Fig. 3b a cast in place method where the reinforcing bar cage serves as the erection elements. Note that in both cases, the steel beam is cast integral with the column and field beam splices occur a short distance away from the column.

COMPONENT BEHAVIOR AND DESIGN

In general, the steel beams and reinforced concrete columns in RCS systems are designed following provisions for members in conventional steel or reinforced concrete construction. Much of the challenge lies in designing the composite beam-column joint, and accordingly, research has emphasized the design and behavior of composite connections. Over 70 RCS beam-column connections have been tested as part of the US-Japan Cooperative Research Program, adding to a database of over 400 RCS joint subassemblies previously tested in Japan and 35 subassemblies tested in the United States. Results of these tests (numbering over 500) have been compiled in an electronic database developed by the Building Contractors Society of Japan (BCS 1997, 98).

Summarized in Fig. 4 are examples of the general types of RCS connections that have been tested. As suggested by this figure, one of the challenges to codifying provisions for RCS frames is the great variety of details that have been used for RCS structures. This is particularly the case in Japan where various construction companies have developed their own proprietary details. A basic distinction between the connection types shown in Fig. 4 relate to whether the beam or column is interrupted at the joint. Details 1 to 7 are so-called “through-beam”

(a) precast RCS frame

(b) cast-in-place RCS frame

Fig. 3 – Examples of RCS Construction Methods for Low-Rise Buildings in Japan

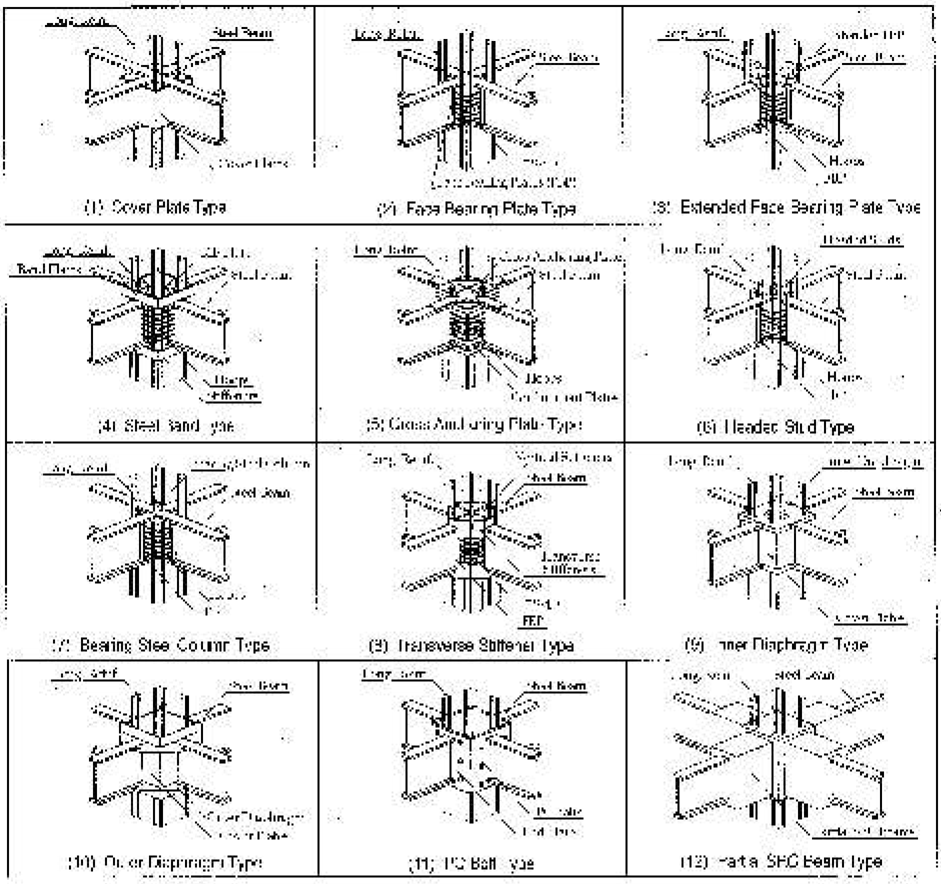


Fig. 4 – Schematic Diagrams of RCS Beam-Column Joint Details

type connections where the beam runs continuous through the joint, like the detail shown in Fig. 2. This type of connection has been used in the United States and by several Japanese construction companies. Details numbered 8 to 11 in Fig. 4 are “through-column” type connections where the beam is interrupted at the joint, the idea being to facilitate concrete placement by minimizing congestion in the joint. Finally, detail 12 is one example of the many unique details that various construction companies have developed which are specific to certain design and construction methods. In this case, the steel beam is encased near its ends, forming an SRC haunch that enhances force transfer through the joint and stiffens the beam. Overall, tests of all these connection types confirm that, when properly detailed to provide force transfer between the steel and concrete, the composite RCS connections can provide sufficient strength to develop the beam plastic moment and reliable hysteretic behavior.

While many RCS connections (over 500) have been tested, less than a third of these have been designed with the goal of investigating and quantifying the internal joint transfer mechanisms in basic through-beam and through-column type connections. The balance have largely been geared towards proof testing of specific systems and details developed by individual construction companies, often with the steel beam yielding outside the joint, thus offering limited insight into the joint behavior. Therefore, the research-oriented tests conducted through the US-Japan cooperative program have contributed greatly to our understanding of force transfer mechanisms and the development of behavioral models for design. The following is a summary of the tests that have been conducted through the program:

- Building Research Institute and Building Contractor Society (Japan) - Ten tests of planar interior joints with through-column joint details were conducted to evaluate joint shear behavior as influenced by various steel details including cover plates, face bearing plates, and the existence of transverse beams and stiffeners. Additionally, four tests of interior three-dimensional joints with concrete slabs have been tested under 3D bi-directional loading (Nishiyama et al., 1997). Three of these were through-column type details and one was a through-beam type detail. Overall, the 3D tests showed that the strength and behavior of the joint under bi-directional loading is not remarkably different than results from planar tests and that design models developed from planar tests are valid for bi-directional loading.

- Chiba University (Japan) - Sixteen tests of through-column and through-beam type joints have been completed to examine force transfer mechanisms. Twelve tests were of exterior joints, one test of interior joints, and three tests of corner joints. Kim and Noguchi (1997) conducted companion finite element analyses of the tests to further examine behavioral aspects (e.g., effective joint widths, etc.) of proposed design equations. Aside from providing the means to extrapolate beyond the available test data, these analyses proved an effective means to visualize (through computer graphics) stress-transfer mechanisms in the joint.

- Osaka Inst. Of Technology (Japan) - Seven tests of interior RCS joints and five auxiliary component tests have been completed to examine shear and bearing force mechanisms in through-beam type details (Nishimura 1998). Results of these tests have been valuable to refine criteria for the various component models used to determine the joint strength.

- University of Michigan (US)- Ten tests of through-column type exterior RCS connections have been completed, including two tests to examine repair to damaged connections and two tests that include fiber reinforced concrete (Wight 1997-98). These have focused on evaluating shear and bearing behavior in exterior joints and requirements for transverse and longitudinal reinforcement in the joint. Tests of repaired connections show epoxy carbon fiber bands wrapped above and below the beam to be very effective in restoring strength and stiffness to the damaged connection.

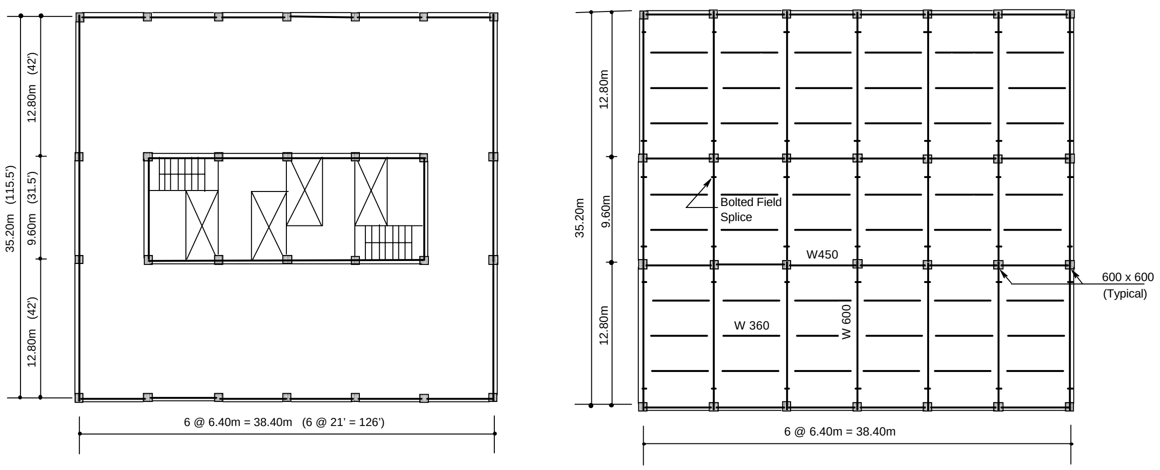
- Texas A & M University (US) - Six tests of through-column type interior RCS connections with concrete slabs and bi-directional beams have been completed (Bugeja 1999). These tests provide unique data on the effect of the concrete slab on composite joint behavior. Additionally, the test program examined the development of steel encasement plates to facilitate construction of low-rise RCS space frames.

- Univ. of Calif. at San Diego (US) - Three tests of have been conduced to examine connection details between steel beams and SRC (encased composite) columns. Included is the application of a reduced beam section detail to limit the force and inelastic deformation demands on the joint (Uang 1998).

FRAME BEHAVIOR AND SYSTEM ANALYSIS

Frame Tests: Prior to the US-Japan program, reduced scale RCS frame tests were conducted in Japan by the Tokyu Corporation (1 test), the Nishimatsu Corporation (2 tests), the Okumura Corporation (1 test). More recently, a two-bay two-story RCS frame test with through-beam type connections has been completed at the Osaka Institute of Technology (Baba and Nishimura 2000). The frame was designed such that the plastic strength of the beams were nearly equal to the ultimate shear strength of the joints, so as to provide information on the interaction between frame and connection response. The frame withstood story drift ratios in excess of 0.05 without significant strength or stiffness degradation, thus confirming the reliable seismic behavior of RCS framing systems. Subsequent finite element analyses of the frame (Noguchi and Uchida 2000) showed that the analytical model can predict the frame behavior and progression of damage fairly well.

System Analysis: Several groups of investigators have developed trial designs of RCS frames modeled after the building theme structure for the US-Japan Program shown in Fig. 5 (Mehanny and Deierlein 2000, Bugeja 1999, Noguchi 1998). These trial designs have been an effective mechanism to exercise proposed seismic design provisions for RCS systems and then, through nonlinear analyses, to evaluate the performance of these systems. In general, most of the trial designs employ a space-frame concept where there are seismic moment resisting frames on all column lines, i.e., where all columns participate in resisting lateral loads. Shown in Fig. 5b is a framing layout for a six-story structure designed according to U.S. codes (Mehanny and Deierlein 2000) where RC columns are 600 mm square and W-shape steel beams are about 600 mm deep. In general, these investigations have shown that the inelastic dynamic response of the RCS frames is similar to comparably designed steel moment frames.



(a) Architectural Layout (b) RCS Framing Plan (6 story)

Fig. 5 – RCS Theme Building for US-Japan Project

DESIGN GUIDELINES

The overall objective of the research is to provide the basis for developing improved design criteria and provisions for composite RCS buildings so as to facilitate their use in high seismic regions. In the US, seismic design criteria for RCS frames are available, but owing to the traditional separation of steel and reinforced concrete construction, design provisions are distributed between several codes and standards. Deierlein (2000) provides a review of the development of US seismic design provisions for composite structures. General seismic loading and design requirements are included in the International Building Code (ICC 2000) which, in turn, adopts Part II of the AISC Seismic Design Provisions (1997) for specific detailing requirements for RCS frames (composite special moment frames). The AISC seismic provisions then reference underlying requirements for reinforced concrete and steel structures (ACI 318-95 and AISC-LRFD 1993). Beyond these general requirements, specific guidance on the design of RCS beam-column connection design is available in published guidelines by ASCE (1994).

In Japan, requirements for SRC structures have been available for several years (AIJ 1987), but as noted above, SRC structures are sufficiently different from RCS structures to require new provisions for RCS structures. Currently, work is underway in Japan to finalize new recommendations for RCS structures to be published by the AIJ, entitled "Seismic Design Guidelines for Composite RCS Structural Systems". These provisions will include requirements that outline material requirements, overall design principles, detailed models and requirements for beam-column joints, general principles for analysis and design, and then a two-step design procedure (an allowable stress and ultimate design check). This two-stage design check follows similar methods currently employed for other materials and framing systems. Work is also underway to develop a performance-based design approach that employs nonlinear pushover analysis and capacity spectrum concepts (Kuramoto et al. 2000).

RELATED STUDIES

Related to, but not directly dealing with RCS frames, are several research projects conducted through the US side of the US-Japan Cooperative Research Program. These projects include: (1) tests of SRC beam-columns to evaluate shear critical behavior of members built with high strength concrete (Xiao et al. 1998), (2) tests and analyses of frames with composite partially restrained moment connections (Leon et al. 1998), (3) development of nonlinear analysis models for composite beams (Salari et al. 1998), and (4) tests of simple shear connections acting composite with the concrete floor slab (Liu and Astaneh 1999). While not specifically related to the design/behavior of RCS elements themselves, these projects provide relevant information for the design of complete hybrid building systems.

CONCLUSIONS AND FUTURE WORK

Research conducted through the US-Japan program on RCS structures has provided valuable information regarding the behavior of composite connections, members and systems. Using this information, efforts are now underway in Japan and the US to developed improved seismic design requirements for composite structures. The ultimate goal of this effort is to better enable engineers to apply composite steel-concrete structures as as cost-effective and reliable alternatives to conventional steel construction. Beyond these immediate goals, several of the analytical and system design research projects have served as a vehicle to explore improved performance-based seismic design and engineering concepts.

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