STUDY OF THE CYCLIC INTERACTION IN STEEL FRAMES WITH COMPOSITE RC INFILL WALLS

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SUMMARY

This paper summarizes progress made during the first three years of a research project on the design of steel frames with RC infills walls as composite systems for seismic resistance, and which is sponsored by the National Science Foundation (NSF) under the auspices of the U.S.-Japan Program on Composite and Hybrid Structures (CHS). The steel frame-RC infill system offers the potential for ample lateral strength and stiffness and low construction costs, particularly for low- to moderate-rise structures, but uncertainty exists concerning its seismic performance. The project includes a shear stud connection test program, a prototype building design study, and a test program on the seismic resistance of infilled frames. To date, a beneficial effect on deformation capacity was noted during the stud connection tests with the use of "confining reinforcement" in the vicinity of the studs. However, low-cycle fatigue fracture of the studs becomes the dominant failure mode under cyclic shear loading. The prototype building design enabled the formulation of draft design guidelines for steel frames with RC infill walls. Finally, two one-third scale frame tests have been planned around specimens that represent the two lowest stories in a mid-rise prototype frame. The test structures and setup have been fabricated, and test results are forthcoming.

INTRODUCTION

The steel frame-RC infill wall (SRCW) system, with steel frame members resisting gravity loads and overturning and RC infills serving as shear-resisting webs, offers the potential for large lateral strength and stiffness and low construction costs. Another advantage of this system is that damage during a “design” level earthquake can be focused on the RC infill walls as distributed cracking, yielding of wall reinforcement, and crushing of concrete along compression struts (Fig. 1). Repair to the infill following the seismic event can be effected without interruption of building service, even in the case of infill replacement .

Optimum performance of the composite wall depends on the transfer of stresses along the interface between steel members and RC infills. Headed shear studs are the most common means of connecting the steel and concrete components and are adopted in this research, but the cyclic behavior of shear studs under axial tension and fully reversed shear is not well known. Premature loss of shear stud capacity may result in excessive damage or undesirable failure modes, and the relative strengths and stiffnesses of the steel frame and RC infills required to ensure a ductile mode of response to seismic loading are not known.

The project combines three coordinated tasks to answer some of the questions surrounding the seismic behavior and design of SRCW frame buildings. First, cyclic shear tests of stud connection specimens are underway to quantify the strength of studs under cyclic shear and axial tension, and to investigate potential details for reinforcement near studs in RC infills. Second, a design study has been completed to determine preliminary sizes for prototype SCRW structures, and to formulate draft guidelines for seismic design. Third, simulated seismic load testing of two one-third scale, two-story, one-bay frames will be conducted to evaluate the seismic behavior of SRCW systems.

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PREVIOUS RESEARCH

Static and dynamic tests of small-scale multistory SRCW frames conducted by researchers in Hong Kong [Liauw, 1979; Liauw and Kwan 1985] have revealed the importance of shear connectors along the steel-concrete interface for improving both strength and deformation capacity. Unfortunately, due to the small-scale of these tests (1:12), square steel bar stock was used for the frame members, and J-shaped or semi-circular steel wire loops were used for the shear connectors. Japanese researchers have also studied the seismic behavior and design of this system [Makino et al., 1980; Hayashi and Yoshinaga, 1994] using one-third scale models of steel portal frames with RC infills that were constructed using typical building materials (i.e., rolled steel sections, commercial shear studs, normal concrete and hot-rolled rebar). This research indicates that the orientation of the steel shapes has a significant impact on behavior, with strong-axis bending of these members being conducive to better cyclic load performance, and that there is a minimum threshold for the ratio of steel column to RC infill cross-sectional areas. Studs were used in these tests to prevent out-of-plane collapse of the RC infills, therefore, the number of studs was minimal, and their spacing quite large.

Some of the questions regarding the use of RC infill panels as lateral load resisting elements for seismic design arise from an incomplete understanding of the behavior of shear studs. Repeated loading has long been known [e.g., Slutter and Fisher, 1966] to reduce the load capacity of shear studs in composite beams below that which has been observed for studs under monotonic loading [e.g., Ollgaard et al., 1971]. Recent research [Hawkins and Mitchell, 1984; McMullin and Astaneh, 1994; Bursi and Ballerini, 1996] indicates that fully-reversed, cyclic loading produces even larger reductions in strength and stiffness of stud connections. But, a complete description of the response of shear stud connections to cyclic loading remains elusive, and the orientation of the studs relative to the plane of the concrete element for RC infill panels differs from that for composite beams. The proximity of shear studs to the edges of concrete in an infill panel introduces failure modes that are likely to differ over those in composite beams. These include cracks in the mid-plane of RC infill walls, as noted by Goel and Mahin [1993] following recent earthquakes in the west coast of the U.S. Due to these uncertainties, the NEHRP [1995] guidelines apply a 25% deduction in stud shear strength for infilled frames subjected to seismic loading.

SHEAR STUD CONNECTION TESTS

An experimental program on the strength of shear stud connections is underway using the test setup and specimen configuration shown in Fig. 2. This setup is intended as an idealization of the force and deformation conditions near the proximity of shear stud connections in RC infill panels. Cycles of slip displacement are applied in the vertical direction by a 2700-kN (600-kip) universal testing machine to a concrete panel through a system of steel plates and threaded steel rods. To reduce eccentricity of shear force, pressure from the steel plates is taken by 152 x 254 x 25 mm (6 x 10 x 1 in.) bearing plates which are placed at both edges of the concrete panel. Sheets of teflon between the plates and the concrete serve to prevent lateral restraint. The concrete panel is connected to steel wide-flange column sections along vertical edges by means of two headed studs per column. The steel sections are attached to either a steel foundation beam or a linear bearing, the latter of which is attached to the foundation beam. The linear bearing allows unrestrained in-plane horizontal movement of the column. Thus, this column can be loaded laterally to simulate axial tension in the studs.

Two reinforcing schemes are included in the present study. The first one, the “perimeter bar” scheme, is an adaptation of a detail proposed by Makino [1984]. In addition to the usual reinforcement in concrete walls, this scheme includes a pair of reinforcing bars placed on either side of the single line of studs along the perimeter of the panel. These bars serve to anchor the wall steel, as well as to arrest concrete crack growth normal to the bars. The "reinforcing cage" detail (shown in Fig. 3 for the concrete infills in the two-story frame specimens that will be tested as part of this project) features a more complex arrangement of steel reinforcement along the perimeter of the panel. Steel cages with reinforcing bars along three axes serve to confine the concrete surrounding the studs and to arrest crack growth along orthogonal directions. A total of eight specimens are included in the stud connection test program, with four specimens each for the “perimeter bar” detail (Specimens 1-4) and the “reinforcing cage” scheme (Specimens 5-8). For each reinforcement detail, three monotonic loading tests were conducted, including pure monotonic shear (Specimens 1 and 5), pure monotonic axial tension (Specimens 2 and 6), and monotonic shear combined with 127 kN (28.5 kips) of constant axial tension (Specimens 3 and 7). The cyclic shear test for the “perimeter bar” scheme (Specimen 4) was conducted with no axial tension, while Specimen 8 (“reinforcing cage” scheme) was subjected to cyclic shear while it resisted 127 kN (28.5 kips) of constant axial tension.

Specimen strengths, and deformation capacities and failure modes are listed in Table 1 for the shear stud connection specimens, and some load displacement relations are given in Fig. 4. The type of confining reinforcement detail can be seen to have a dramatic impact on specimen behavior, increasing strength and deformation capacity for monotonic loading because it changes the failure mode from concrete cracking to ductile fracture of the studs. Under pure monotonic shear loading (Fig. 4a), the observed increase in strength (Specimens 1 and 5) is attributed to better distribution of stud shear forces as highly stressed locations in the concrete can continue to carry load beyond initial crushing by virtue of the confining effect of the reinforcement. For the pure tension tests (Specimens 2 and 6), as well as for those combining monotonic shear and tension (Specimens 3 and 7), highly beneficial effects are seen with the use of the reinforcing cage (Table 1). The reinforcing cage enables the formation of reliable compression stress paths from the heads of the studs to the corner bars in the reinforcing cage.

Less strength improvement is associated with the reinforcing cage for the specimens subjected to cyclic shear loading (Fig. 4b), because the failure mode under fully reversed cyclic shear loading is brittle fracture of the studs from low-cycle fatigue. Yet, even with this shift in failure mode, the specimen with reinforcing cage (#8) enjoys an enhanced ability to carry axial load under fully reversed cycles of shear. In fact, the weakness under tensile loading of specimens loaded in monotonic shear (Specimens 2 and 3) was so severe that the perimeter bar specimen subjected to cyclic shear (#4) was not loaded in axial tension as initially planned. Ongoing activities in this phase of the research include additional shear stud connection tests that are planned to evaluate the efficacy of a ductility enhancing device (DED) proposed by the authors for cyclically-loaded shear studs. The DED comprises a plastic cone that is placed around the base of studs, which serves to increase the deformable portion of the stud shank so as to simultaneously increase deformation capacity and reduce fatigue strains in the studs. McMullin and Astaneh [1994] investigated a similar concept for composite beams.

In addition to measured strengths, Table 1 also contains strengths calculated according to the AISC specification [AISC, 1993] and PCI design handbook [PCI, 1985] for both concrete and stud failure mechanisms using nominal strengths for the studs and concrete and excluding any resistance (ϕ) factors. Comparison of failure modes and strengths leads to the following conclusions. The AISC and PCI design formulas were able to predict the correct mode for failure for only cases of monotonic loading of specimens with the perimeter bar reinforcing detail. The AISC design formulas were able to provide a reasonable estimate of strength only for Specimen 5 with the reinforcing cage detail. Finally, the PCI design formulas were better able to approximate measured strengths than the AISC formulas. However, the difference between measurements and strengths estimated using the PCI design formulas can be as large as 30%.

DESIGN STUDIES

Idealized SRCW Frame Behavior

The behavior of SRCW frames was idealized such that “design” intensity loads would mobilize distributed cracking of the RC infill panels, as well as distress and failure of shear studs. The latter are more likely to occur at or near corners along the beam-infill panel interface, where shear force demands are coupled with large axial tension demands from overturning. Subsequent loading is expected to generate localized crushing of concrete and yielding of reinforcement in the RC infills, particularly along the diagonals near panel corners. Under increased loading, the steel frame and RC infill may no longer act as a composite system, due to deterioration of tension and shear stress transfer along the frame-panel interface. After sufficient deterioration of composite action, the steel frame is expected to develop plastic hinges as it responds to increased drift.

Linear analyses of SRCW frames reveal that beams in SRCW frames carry little bending at initial stages of loading, and that pin connections are just as effective as fully restrained (FR) connections. For later stages of loading, it is advisable to use partially-restrained (PR) connections because the moment restraint at beam-to-column joints greatly improves frame strength and deformation capacity even if composite action is seriously undermined or the RC panels lose all load capacity. At the “ultimate” limit state, plastic hinges are expected to develop in the PR connections of the steel frame, thus converting the system into a mechanism which can still undergo inelastic drifts.

This idealized sequence of behavioral events described above was targeted during the prototype design studies, and it was used to draft seismic design guidelines for SRCW frames with PR connections. The draft guidelines include strength design provisions applicable to “design” intensity loads, as well as capacity design provisions at “ultimate strength” conditions.

Prototype Design Studies

Design studies for prototype SRCW frames were carried out for 3, 6 and 15-story building elevations, assuming a constant story height of 3.96 m (13 ft). The principal goal of the prototype designs was the determination of reasonable component sizes for the frame tests, the latter of which are intended to represent infilled frames at or near the bottom of a prototype building. Other objectives of the design exercise included: 1) investigation of overall composite system behavior, 2) estimation of force demands on the shear studs, and 3) verification of the potential of using pin or partially-restrained (PR) connections for the girders instead of fully-restrained (FR) connections. Composite system behavior was judged in terms of drift response, relative contributions to lateral resistance of steel members and concrete infills, and effect of girder connection restraint.

The floor plan of the prototype structure (Fig. 5) is a modification of a floor plan proposed by Shahrooz [1996] for use in the NSF-CHS program and it is intended to include features that are common and desirable for low-to mid-rise office buildings in the U.S. Three SRCW frames are oriented in the North-South direction, while six shorter SRCW frames are arranged in the East-West direction. These infilled frames create a core which can be used for elevator shafts, stairwells, and equipment rooms. The SRCW frames are assumed to resist all lateral force, while the remaining steel framing carries only gravity loads. Only the central infilled frame in the North-South direction was analyzed, and the contribution to lateral resistance in the North-South direction from SRCW frames oriented in the East-West direction was neglected.

Four types of lateral-load resisting frames were considered, including SRCW frames with either pin or FR beam-to-column connections, or SRCW frames coupled with outriggers (i.e., in-plane moment frames, with either pin or FR connections for the perimeter columns of the outriggers). Seismic loading was defined according to NEHRP [1995] for seismic area 7, including response modification factor R = 5.5; soil profile type D; effective peak acceleration A_a = 0.4; effective peak velocity-related acceleration A_v = 0.4; seismic coefficients C_a = 0.44 and C_v = 0.64, and deflection amplification factor of C_d = 5. Initial member sizes were determined from the gravity loading, and the bare steel frame was assumed to carry all gravity loads. Grades 36 and 50 steel were assumed for the beams and columns, respectively, and normal-weight concrete with a compression strength of 28 MPa (4 ksi) was assumed for the RC infill panels.

The frames were analyzed using linear finite element analysis with beam elements representing the frame members, and membrane elements representing the RC infills. The simplest technique to model fully-composite action between the steel frames and the RC infills is to have membrane and beam elements share nodes along the steel-concrete interface of the infilled panels. This assumption implies shear stud connections of infinite stiffness, so more realistic modeling techniques were also investigated. By representing the studs as linear elastic elements in the slip and axial directions, peak values of shear and axial stresses were reduced by approximately 50% over the values calculated assuming the rigid connection assumption for the 6-story elevation. The design objectives included the NEHRP drift limit of 2% of story height, and, for the 15-story frame with this floor plan, column sizes had to be increased substantially beyond strength requirements in order to satisfy this criterion. Second-order effects were determined to be negligible.

Drift response for the SRCW frames was found to be satisfactory for the 3 and 6-story elevations, but column sizes had to be increased substantially beyond the gravity load requirements for the 15 story frames in order to meet the drift limit. The RC infills were found to carry 90% or more of story shear forces, and, the steel frames resisted a significant portion of the overturning moment (30%, 40%, and 60%, respectively, for the 3, 6 and 15-story elevations). Infilled frames with pin connections were found to be as effective in resisting seismic forces as those with FR connections. The outriggers were found to improve drift control, but FR connections were required in exterior beam-to-column joints making the outriggers a costly solution. For the 15-story elevation, alternate floor plans are recommended in which SRCW frames are located on the perimeter of the structure. Compression and shear stress demands along the steel frame-RC infill interface were found to be acceptable for all three frame elevations. However, large tensile stress demands were generated along the beam-infill interface from overturning. For the 15-story elevation, these stresses were deemed to be unacceptably large, even when outriggers were used.

Limit Analyses

A limit analysis model was defined for the steel frame-RC infill building system with PR beam-to-column connections, based on prior work by Liauw and Kwan [1984]. This previous formulation includes the contributions to strength at the ultimate limit state from 1) the flexural resistance of the steel frame, 2) the compression resistance of the concrete panel, and 3) the shear resistance of the headed studs. However, several important modifications were made in the present study, including the treatment of multistory frames, the formation of plastic hinges in the PR connections, and consideration of the influence of axial tension and cyclic loading on stud shear strength.

Four different mechanisms were postulated by Liauw and Kwan [1984] for SRCW frames, and these include plastic hinge formation in the frame members, crushing of the concrete compression struts along their vertical boundaries, and shear yielding of the stud connections. However, due to the lower flexural strength of the PR connections relative to the beams and columns, the controlling mechanism for the frames in the present study invariably included plastic hinging of the PR connections. Thus, a fifth mechanism is recognized in the present study for the case of frames with PR connections in which plastic hinges form in these connections.

Limit analyses of the two-story, one bay test structures were conducted to investigate the influence of stud spacing and panel geometry. In all cases, the limiting mechanism included plastic hinging of the PR beam-to-column connections, as expected, because less energy is required to form plastic hinges in the PR connections than in either beams or columns. These analyses indicate that stud spacing can be expected to have a marked influence on predicted lateral strength, with base shear capacity increasing by 33% as stud spacing decreases from 254 mm (10 in.) to 76 mm (3 in.). The final configuration selected for the first test structure has studs at a 102-mm (4-in.) stud spacing and an estimated lateral load capacity of 781 kN (176 kips).

INFILL PANEL FRAME TESTS

Construction of two-story, one-bay SRCW frame specimens which represent two adjacent stories at or near the bottom of a low to mid-rise building is currently underway. The two-story configuration was chosen over a simple portal frame because the latter minimizes overturning and potential interaction effects in the steel connection region. The SRCW portal frames tested in Japan [Makino et al., 1980; Hayashi and Yoshinaga, 1994] featured frames with a square aspect ratio, which is unrealistic for modern steel construction. The test specimen and setup chosen in the present investigation (Fig. 1) is expected to generate behavioral information at the system level that currently does not exist in the technical literature. Lateral load will be applied only at the top of the second story, because the first-floor contribution to base shear is small for multistory buildings.

Preliminary dimensions for the frame members of the first specimen include W200x19 (W8x13) girder sections and W130x28 (W5x19) column sections. These sections insure strong-column/weak-beam behavior, and are sufficient to permit connections (Fig. 6) designed according to seismic design standards in the U.S. [NEHRP, 1995]. At a one-third scale, these sections represent girders and columns on the order of Group 3 or Group 4 wide-flange sizes [AISC, 1993], which are common for both girders and columns in bare-steel moment-resisting frames. The RC infills (Fig. 3) will be cast from 28-MPa (4-ksi) normal-weight concrete, and will have enough horizontal and vertical reinforcement to meet ACI recommended provisions [ACI, 1995]. The 89-mm (3.5-in.) thickness of the infills represents a 254-mm (10-in.) thick wall at a 1:3 length scale. These infills will be connected to the steel frames using 9.5-mm (3/8-in) diameter studs, which represent a full-scale diameter of 19 mm (3/4 in.) at the 1:3 scale. The first SRCW frame specimen will feature studs at a 102-mm (4-in.) spacing and complete reinforcing cages along panel perimeters to ensure a high level of composite action. The second SRCW test structure will not be completely detailed until completion of the first test. However, it is likely to feature studs at twice the spacing for to investigate more economical stud spacing, and it may feature DED's to enhance stud ductility under cyclic loading.

Both specimens will be instrumented with an array of strain gages, LVDT's, pressure transducers and other sensors to capture SRCW frame response to cyclic loading. In addition to the lateral load history and drifts at the top of both stories, the measurements will be used to define local response as well. For the steel frame, this includes beam-to-column connection rotation, panel zone shear deformation, and plastification of top and seat angles. For the RC infill panel, shear deformation, distribution of compression stresses (i.e., development of compression struts), straining of wall reinforcement, and crack formation are sought. For the studs, axial strain and slip demands, and fracture, are needed throughout the loading history. These local response measurements are deemed essential to monitor changes in load transfer between steel frame and RC infill panels. Finally, a suite of eight acoustic emission sensors will be placed strategically on the specimens to identify and locate concrete cracking damage and steel stud fractures.

CONCLUSIONS

Progress during the first three years of an NSF CHS research project on the use of steel frames with RC infill walls as composite systems for seismic resistance is presented. The research project comprises three separate thrusts which include a testing program to evaluate the resistance of shear stud connections for RC infills under simulated seismic loading, a building studies component to address analysis and design issues, and an experimental program on the seismic resistance of infilled frames.

The shear stud connection test program has revealed that axial tension loading can seriously undermine shear strength and deformation capacity. Thus, confining reinforcement in the vicinity of the studs is needed retain integrity and extend the deformation capacity of stud connections, especially when axial tension stress is applied to the studs. The tests have also demonstrated that low-cycle fatigue fracture is the dominant failure mode for cyclic shear loading, and an effort to develop a ductility enhancing device (DED) for this application is underway. Existing design equations for estimating shear stud strengths were found to be inadequate for identifying failure modes, and errors in strength estimates can be as large as 30%.

The building studies have shown that RC infills carry most of the story shear forces, but, they also resist a significant portion of the overturning moment. The 15-story frames were found to be too flexible, and seismic drifts exceeded code limits. However, this excess flexibility can be solved economically by changing wall placement from the central core to the perimeter of the building. Larger than expected overturning effects for frames taller than 6 stories were observed to generate large tension forces in the stud connections along the steel beams in the lowest floors. The assumptions made in modeling the studs were found to have a large influence on stress demands, and the "flexible stud" approach is believed to give more realistic estimates.

Finally, two one-third scale frame tests are planned using infilled frame specimens that represent the two lowest stories in a mid-rise frame (3 to 6 stories). The frames feature steel members with proportions similar to those selected for the prototype building, and the geometry of the RC infill panels was scaled from those for the prototype. The first frame will feature studs at a spacing conducive to a high level of composite action, and the stud configuration of the second frame specimen will not be finalized until the first test is completed.

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Table 1: Strengths of Shear Connection Specimens

Test No.	Failure Mode	Deformation Capacity[1], mm (in.)	Measured Shear Strength kN (kips)	AISC Calculated Shear Strength, kN (kips)		PCI Calculated Shear Strength, kN (kips)	
				Concrete	Steel	Concrete	Steel
1	concrete	11.7 (0.461)	400 (89.9)	470 (106)	470 (106)	346 (77.9)	352 (79.2)
2	concrete	3.84 (0.151)	142 (31.9)	------[3]	------[3]	186 (41.9)[2]	211 (47.5)[2]
3	concrete	1.91 (0.075)	241 (54.2)	------[4]	------[4]	254 (57.1)	282 (63.4)
4	fatigue	2.08 (0.082)	375 (84.4)	470 (106)[5]	470 (106)[5]	346 (77.9)[5]	352 (79.2)[5]
5	stud	9.19 (0.362)	503 (113.1)	470 (106)	470 (106)	346 (77.9)	352 (79.2)
6	stud	28.0 (1.102)	281 (63.2)	------[3]	------[3]	186 (41.9)[2]	211 (47.5)[2]
7	stud	5.89 (0.232)	306 (68.8)	------[4]	------[4]	254 (57.1)	282 (63.4)
8	fatigue	1.63 (0.064)	255 (57.2)	------[4]	------[4]	254 (57.1)[5]	282 (63.4)[5]