SEISMIC RESISTANT CONNECTIONS FOR MIXED CONSTRUCTION

C.W. Roeder[I]

SUMMARY

This paper describes a study into the seismic resistance of connections between steel frames and concrete walls. In this study, a series of prototype structures are designed and analyzed. The analyses define the behavior requirements for these connections under several different conditions. Previous research is then reviewed to determine which connection details are suitable, and design procedures are developed for these connections. Finally, experiments are performed to verify the effectiveness of the design procedures and generally evaluate connection behavior. The results indicate that seismic resistant frame-wall connections can be attained, but there are a number of potential problems which must be avoided.

INTRODUCTION

Steel frame structures and reinforced concrete shear walls are both widely used in seismic resistant design. Both structural systems are well understood, and they are known to offer distinct advantages in seismic behavior. Steel frames are very ductile and they exhibit superior inelastic behavior during severe earthquakes. However, these frames are flexible, and they may not economically satisfy stiffness requirements. Reinforced concrete shear walls are strong and stiff, but they are less ductile than most steel frames. Since seismic resistant design requires a combination of strength, stiffness and ductility, a combination of steel frames with reinforced concrete shear walls as shown in Fig. 1 is sometimes desirable.

This form of mixed construction can be very economical. The steel frame can be constructed of light members, since the lateral stiffness is provided by the shear wall. The shear walls can often be constructed around elevator shafts and stairwells and thus, they may utilize material which is normally required for fireproofing or ornamentation. Further economies can be realized during the construction process. The shear walls can be constructed quickly by modern slip forming methods. The steel frame can also be erected economically because of the smaller members and connections and the simpler connection details. While mixed construction can be very economical, they are seldom utilized in seismic resistant design. The shear wall and the steel frame exhibit very different behavior during an earthquake. Therefore, the connections between these diverse components may experience severe and unusual loadings.

DESIGN AND ANALYSIS OF PROTOTYPE STRUCTURES

The first step in the evaluation of these connections consisted of a series of designs and analyses of prototype structures. These mixed

[I]Assistant Professor, Department of Civil Engineering, University of Washington, Seattle, WA 98195, U.S.A.

structures were usually of intermediate height (10-15 stories) and they were designed to resist gravity, wind and seismic design loads for Seattle, Washington. The structures were analyzed under different loadings by a linear elastic finite element computer program. The connections between the structural components were varied as shown in Fig. 2. Alternate 1 employed rigid beam-column and beam-shear wall connections, and Alternate 2 utilized all pinned connections. Alternate 3 was intermediate with pinned beam-shear wall connections and rigid beam-column connections. The analyses provided some simple but useful results. Rigid moment resisting connections increased the lateral stiffness of the structures. Lateral deflections were always smallest with Alternate 1 and the largest with Alternate 2 when the loading and all member sizes were held fixed. This indicates that rigid connections may produce smaller walls and member sizes. However, rigid connections must resist large bending moments and shear forces. Pinned connections can theoretically be designed to resist smaller shear forces with zero moment, but the connection must be free to rotate.

Inelastic behavior of the structure is also important in seismic design. During extreme earthquakes, considerable inelastic activity is expected to occur, but the structure should not collapse. The application of this inelastic criteria to mixed structures requires that the steel beam-concrete shear wall connection must be capable of sustaining significant rotations without losing its shear or moment capacity. The magnitude of the required rotational capacity varies with the structural geometry. However, typical ductility requirements would necessitate rotational capacities in the order of 3 to 4 degrees. Rigid connections must maintain their shear and plastic moment capacity while sustaining these rotations. Pinned connections need only maintain their shear capacity during the plastic rotation.

TYPICAL CONNECTION DETAILS

The analysis clearly defines the required strength and ductility of the frame-shear wall connection. The connection must then be designed to develop this behavior. There are several types of connection which can be employed. Figure 3 shows one typical connection which combines a typical steel frame connection with headed metal studs. A steel plate is embedded into the concrete wall with metal studs and the beam is connected to the plate as if it were a steel column. This type of connection is commonly employed in structures where the shear wall is constructed first by slip-forming and the steel frame is erected later. This type has been used in several buildings which were recently constructed in the United States.

Figure 4 shows another type of connection, which is sometimes used in mixed structures. In this type of construction, the steel frame is erected first and the concrete shear wall is constructed later. The beams are connected to steel columns with the usual connection details. The shear wall is then formed around selected columns. Thus, the beam transmits its moments and forces to the encased steel column, which distributes them to the concrete wall. The steel column also serves as longitudinal reinforcement for the wall. Therefore, the column must develop sufficient bonding to the concrete to serve as longitudinal reinforcement and to accomplish the transfer of moments and forces.

HEADED STUD CONNECTION

The steel frame-shear wall connection shown in Fig. 3 combines a typical steel frame connection with a metal stud connection. There has been considerable research into the behavior of the individual components, but the combined connection for mixed construction has not been studied. The steel frame connection has been studied by a number of investigators [1,2]. These connections have been designed as pinned or moment-resisting, and both types of connection are very ductile, if they are properly designed. This indicates that required connection ductility can probably be attained within this component of the mixed connection, if the stud connection is capable of resisting the maximum moment and shear force delivered by the frame connection. Connections with bolted webs and unconnected flanges as shown in Fig. 3 are commonly assumed to be pin connections during the design process. However, research has shown that these bolted joints develop significant moment capacity, and the moment and shear capacity may be much larger than predicted by accepted working stress design methods. Previous research provides a method for predicting the plastic capacity of bolt group such as shown in Fig. 3. The plastic moment capacity of the bolt group, M_u, is the plastic shear capacity, V_u, multiplied by an eccentricity, e_2. Then

$$V_u = KA_s \tag{1}$$

where A_s is the shear area of a single bolt and K is a function of the moment of inertia of the bolt group, I, and the eccentricity, e_2. Fig. 5 provides a graphical solution to these functions for a single line of bolts.

While the behavior of steel frame connections is quite well understood, the behavior of stud connections, which are loaded with a combined moment and shear, is less well defined. One previous study [3] investigated the behavior of individual studs under combined loadings. More recent research [4] studied the behavior of stud groups under combined shear force and moment. This later study indicated that stud connections can resist large shear forces, but their moment resistance is severely limited. Further, the failure mechanisms may be very brittle. This study also developed a procedure for predicting the capacity of these stud connections. Applications of that procedure clearly indicated that practical stud connections cannot develop the moment capacity which is required for rigid shear wall steel frame connections. Thus, rigid wall-frame connections, which employ headed studs as shown in Fig. 3, are not possible. Flexible connections are possible, if the required ductility is attained within the bolts. This requires that the stud connection be designed conservatively to develop the full plastic capacity of the bolt group.

A design procedure [5] was developed to gain this objective. In this procedure, the bolted connection is designed to resist the required shear force for a pinned connection. The ultimate shear force of the connection, V_u, is then determined by applying the appropriate load factors to the service loads, and the graphical solution shown in Fig. 5

is applied to determine the eccentricity, e_2. It should be noted the eccentricity, e_2, has no physical meaning to the connection. It is simply the maximum eccentricity at which the shear force could be supported by the bolt group. This eccentricity, e_2, is then combined with the real connection eccentricity, e_1, as shown in Fig. 6, to determine the design plastic moment of the stud connection, M_{DP},

$$M_{DP} = V_u(e_1 + e_2). \tag{2}$$

The stud connection is then conservatively designed [4,5] to resist the required shear force, V_u, and moment M_{DP}.

A series of experiments [5] were then performed to evaluate the effectiveness of this design procedure. These tests indicate that the design procedure worked well. Specimens which were designed by this procedure, exhibited considerable ductility. The connection failure was a ductile tearing failure in the bolted connection. Specimens, which were not designed by this criteria exhibited brittle cone pull out failures. These brittle failures clearly indicated the importance of flexibility in the connection, and they further verified thatrigid stud connections are not possible. One specimen was tested under severe cyclic loading. This specimen exhibited large rotational capacity, but its maximum strength was decreased by approximately 23%. The hysteretic curves which were produced by the cyclic loading were pinched with deteriorating stiffness, and the failure was a relatively brittle cone pull out failure. This test shows the importance of conservative design for cyclic loading and it indicates that additional study is needed to fully understand the effect of cyclic loading.

EMBEDDED STEEL FRAME

Mixed steel frame-concrete shear wall structures are sometimes constructed with a portion of the steel frame embedded into the concrete shear wall. This produces a frame-shear wall connection as shown in Fig. 4. The beams of the steel frame are connected to the embedded steel column by the usual beam-column connection technique. These connections can be designed to be either rigid or flexible, and their behavior is relatively well understood [1,2]. They are very ductile and would be expected to possess sufficient inelastic rotational capacity to assure the satisfactory performance of the mixed structure during an extreme earthquake. However, there are two major problems with this type of construction as indicated in Fig. 7. Figure 7b indicates a typical beam-shear wall connection. The steel beam transfers shear forces and bending moment to the encased steel column, which distributes the forces and moments to the concrete. During a severe earthquake, the magnitude of these forces and moments will approach the full plastic capacity of the steel member. Thus, considerable bond between the encased column and the concrete is needed to assure the transfer. Figure 7c shows a second potential problem area. At locations such as the base of the shear wall, the embedded steel column serves as longitudinal reinforcement for the concrete wall. Thus, the column can be loaded to its full plastic axial capacity, and the bond between the steel and the concrete must be capable of developing this full plastic capacity within a reasonable development length.

There have been a number of studies [6] related to the behavior of steel structural shapes, which are encased in concrete. However, only a few [7,8] studies have considered the bond between steel shapes and concrete. These bond studies describe the results of push-out tests where a steel wide flange is embedded into a concrete block and loaded with an axial force. These tests indicate that the bond stress between the steel and concrete varies with the condition of the steel surface, the position during casting and the reinforcing ties which confine the steel and concrete. Sandblasted specimens developed higher bond shear stress than those with mill scale on the steel. Bond stresses decrease significantly after first slipping. Increased tie reinforcement increased the bond strength after slippage, but it had no consistent effect before slippage occurred. This slippage effect could be very relevant during the severe cyclic loading which is produced by a severe earthquake.

This previous research is relevant to the design of mixed frame shear wall connections. However, these studies do not provide all the information which is needed. Thus, two specimens were designed to simulate the behavior of a steel column embedded into a seismic resistant shear wall. The specimens were designed as shown in Fig. 8. The columns were sandblasted to remove all rust and mill scale. The two specimens were identical except that the encased column in Specimen 1 was a bare sandblasted wide flange while the column in Specimen 2 also had light angle strips connected to the flange at 6 inches on center. The angles were added to increase the bond between the steel and the concrete. Strain gages were mounted to the columns as shown in Fig. 9.

Each specimen was first loaded with an eccentrically applied load as shown in Fig. 9. This eccentricity produced a significant moment in the column, and it closely simulates the loading combination which would occur in a flexible shear wall-steel frame connection. Both specimens exhibited similar behavior under this loading. The force and moment were rapidly transferred to the concrete in both specimens, and there was no apparent slippage of the steel with respect to the concrete for either specimen even when the specimens were loaded to the full plastic capacity of the wide flange. This is shown in the strain versus depth plot for Specimen 1 in Fig. 10. This figure indicates that bond stresses far in excess of those reported in previous tests [6,7] were developed near the top of the specimen, and it suggests a very different bonding mechanism than that indicated by simple push-out tests when the encased wide flange is subjected to significant bending moment. Since there was no apparent slippage during the eccentric loading, both specimens were retested with a concentrically applied load. Specimen 2 again exhibited a very rapid transfer of stress between the steel and the concrete. The angle shear connectors provided a rapid transfer of load to the concrete, and there was no appreciable slippage even when the steel wide flange was loaded to its full yield capacity. However, significant slippage occurred throughout the depth of Specimen 1 at an average bond stress of 144 psi. A comparison of these results tentatively indicate that shear connectors will be required to develop the full plastic axial capacity of the steel column at locations such as shown in Fig. 7c. Beam-wall connections such as shown in Fig. 7b possibly can be attained with a sandblasted column with no shear connectors. However, further study is needed to understand the bonding mechanism and the effect of cyclic loading.

SUMMARY AND CONCLUSIONS

This study indicates that mixed steel frame—concrete shear wall construction can be very useful in seismic resistant design. However, the strength and ductility of the connections between the steel frame and the wall must be carefully evaluated. Rigid wall-frame connections are desirable, because they produce greater stiffness, smaller deflections, and small member sizes. However, these rigid connections are not practical with the stud connection shown in Fig. 3, because of the strength and limited ductility of the studs. These connections must be designed to develop rotational ductility within the bolted connection.

Embedded steel columns provide a second useful method for connecting steel frames and concrete walls as shown in Fig. 4. Both rigid and pinned connections can be developed with this method. The primary question with this type of connection concerns the bond between the embedded steel column and the concrete. A limited number of tests are performed to evaluate this bond. These tests tentatively indicate that the natural bond between an embedded, sandblasted steel column and the concrete is adequate for beam-wall connections such as shown in Fig. 7b when there is significant bending moment transferred to the column by eccentricity and/or rigidity of the connections. Other critical locations such at the base of the shear wall as shown in Fig. 10c require additional shear connectors to develop the full tensile capacity of the column.

This paper also indicates several areas which require further study before the seismic behavior of mixed structures can be fully understood. Additional tests are needed to understand the effect of cyclic loadings on the strength and ductility of both types of connection. Further studies are needed to determine the transfer mechanism for load and moments in embedded steel columns to the concrete. Finally, analytical models which describe this connection behavior would be useful in the analysis of the total structure, since connection behavior has a significant effect upon the strength, stiffness and ductility of mixed structures.

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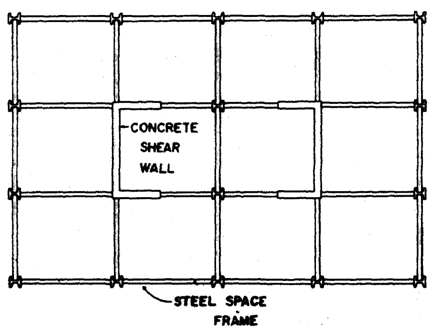

Fig. 1. Typical Mixed Structure

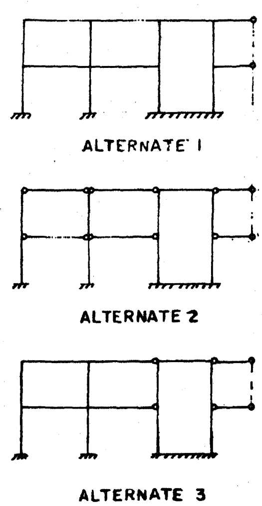

Fig. 2. Alternate Connections

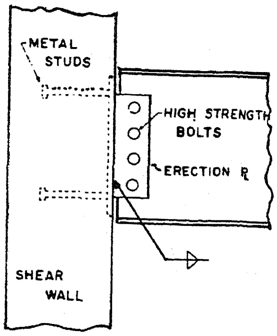

Fig. 3. Metal Steel Connection

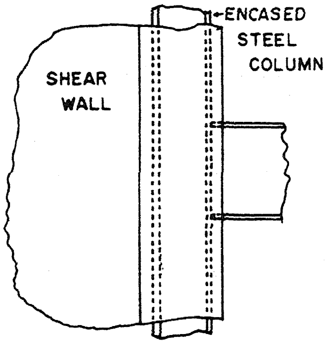

Fig. 4. Embedded Steel Column

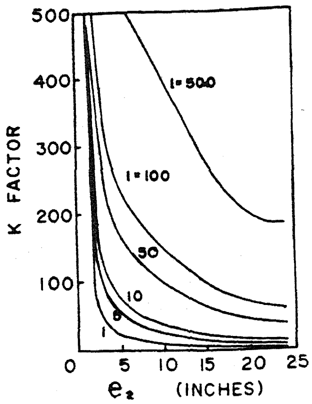

Fig. 5. Graphical Solution

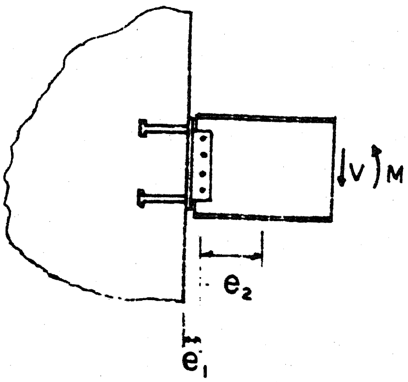

Fig. 6. Eccentricity of Connection

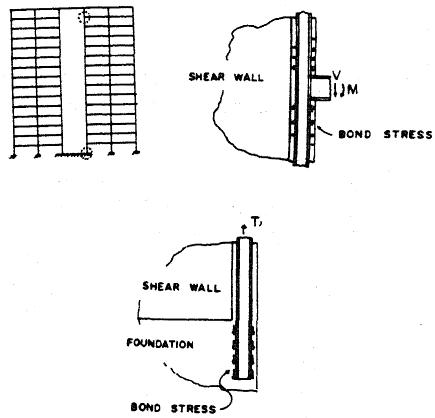

Fig. 7. Critical Locations
of Embedded Steel Column

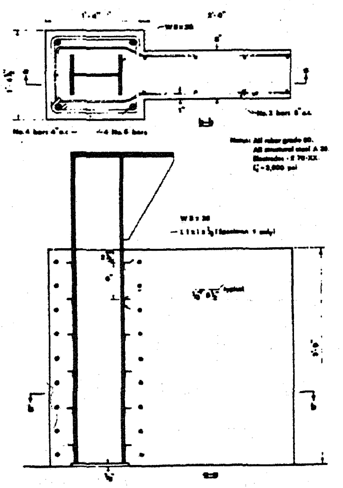

Fig. 8. Design of Test Specimen

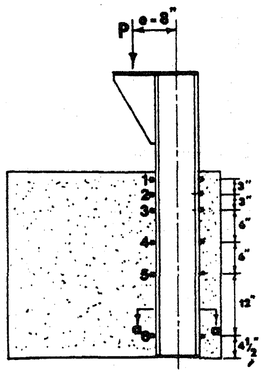

Fig. 9. Strain Gage
Locations

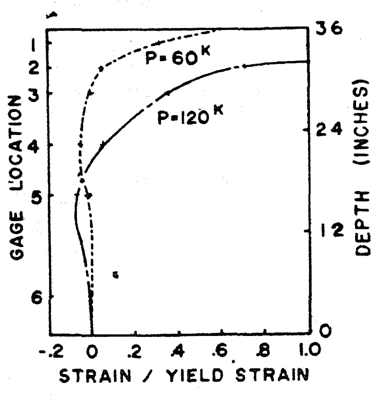

Fig. 10. Strain Distribution