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Seismic Performance of Older Steel Frames

Comportement parasismique de vieux cadres métalliques

Seismisches Verhalten von älteren Stahlfachwerken

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SUMMARY

To study the performance of older steel frames, over twenty bolted and riveted connection specimens were tested and companion analytical studies conducted. The experimental results indicate that the cyclic performance of riveted connections governed by rivet shear capacity is poor, and that their hysteretic behavior degrades rapidly. The effect of encasement is to considerably strengthen and stiffen the frame and delay the degradation.

RÉSUMÉ

Dans le but d'étudier la performance de cadres métalliques anciens, plus de vingt spécimens furent testés. Cette étude fut complétée par des calculs numériques. Les résultats expérimentaux indiquent que les réponses cycliques des connexions dont les déformations majeures proviennent du cisaillement des rivets, et ont des boucles d'hystérèse se dégradant rapidement. Les effets des revêtements en béton permettent d'augmenter considérablement la rigidité et la résistance des cadres ainsi que de retarder leur dégradation.

ZUSAMMENFASSUNG

Zu der Untersuchung der Leistung von älteren Stahlfachwerken wurden über zwanzig Versuche an geschraubten und genieteten Verbindungen im vollen und im Dreiviertel-Massstab gemacht, mit gleichzeitigen rechnerischen Studien. Die Versuche zeigten, dass die zyklische Leistung der genieteten Verbindungen, wenn die Stärke von der Schraubkraft der Nieten bestimmt ist, mangelhaft ist und dass ihr hysteritisches Verhalten schnell degradiert. Die Wirkung der Umhüllung ist eine erhebliche Verstärkung und Verstiftung des Fachwerkes und eine Verschiebung der Degradation.

1. Introduction

The recent 1994 Northridge and 1995 Kobe earthquakes have once again emphasized the need to develop accurate techniques to evaluate the seismic safety of older structures. Among the classes of structures that have traditionally performed very well in moderate and large earthquakes is the older steel moment resisting frames. These structures, dating from the first half of this century, are substantially different from steel moment frames erected more recently. The main differences are in the detailing of the connections, the encasement of the beams and columns, and the presence of heavy infill walls typical in this type of older construction. While designed as moment frames, these building probably would not respond as such under large seismic loading. Because of the infills these buildings will probably behave as stiff masonry structures initially, with their behavior shifting to that of steel frames as the infills failed. The effect of the encasement will probably remain for much larger deflections than that of the infills, but the degree of composite action is uncertain. These structures are potentially brittle because the larger forces resulting from the added mass of the encasement and infill walls cannot generally be accommodated by the frame alone unless substantial connection ductility and energy dissipation can be provided. In this regard the main concern is the cyclic performance of steel connections fabricated with rivets, since little experimental data was available to generate models or provide guidance in an evaluation process. This paper reports on the results of an analytical and experimental study aimed at determining the performance of the connections in older steel frames, with emphasis on the effects of the rivets and the encasement. The main aim of the research was to assess the strength, stiffness and ductility of these steel frames.

2. Background

Older steel frames (prior to about 1950) were erected utilizing complex riveted connections and members. The main members were routinely encased in concrete or masonry for fire-proofing. The encasement was often cast integrally with the floor slabs which contained appreciable amounts of mild, undeformed steel reinforcement. The dimensions and quality of the encasement varied widely, but it is well known that some degree of composite action will be activated in such members even if shear connectors are not present. The net result is that these frames cannot be evaluated as pure steel moment frames since this would overestimate the natural period and reduce the design forces in the structure. The evaluation of these buildings is complicated by the fact that these buildings were designed for relatively low equivalent lateral loads and do not comply with current seismic design provisions. Strengthening and retrofitting of these frames would probably be prohibitively expensive and technically unjustifiable given that a large number of these buildings have performed very well in past earthquakes (1906 San Francisco and 1923 Great Kanto events, for example).

To study the performance of these older steel frames, a joint experimental and analytical study was undertaken by the U. of Washington, the U. of Minnesota, and Preece, Goudie and Assoc. The study was divided into experimental and analytical tasks. The experimental part was aimed at determining the cyclic behavior of a wide class of riveted connections. This knowledge was then utilized in the analytical studies to develop and study both local models for the connection response and global models for use in frame analysis.

3. Experimental Study

Data on the behavior of full-sized riveted connections subjected to large load reversals is scant. With the exception of several tensile tests carried out in the wake of the Quebec Bridge disaster [1] and a single bending test in the 1930's [2], little or no cyclic studies on riveted connections are documented in the literature. To obviate the need for more experimental data, seven full-scale and sixteen 3/4-scale specimens were tested in this program. The connections tested included T-stub, top-and-seat angle, and stiffened seat connections, with and without encasement, and utilizing a variety of connector (rivets, modern high strength bolts, and high strength friction bolts.) The specimen configuration was taken directly from the connections in a 26-story frame erected in San Francisco in 1926. This building was deemed to be typical of the construction of that period and had already been evaluated by Preece, Goudie, and Assoc.

Due to space limitations only the results of selected full-scale specimens tested at the U. of Minnesota will be discussed here. Details of the complete test series are available elsewhere [3]. Cruciform specimens, about 4 m high by 6 m long, utilizing both stiffened seat and T-stub connections were used. They were loaded by displacing the bottom of the column under a slowly increasing pattern of alternating loads to simulate the seismic forces. The only important departure in these specimens from the prototype building was in the column size. This was reduced since no meaningful axial loads could be applied to such large specimens and the effect of axial load on connection behavior was assumed to be small. The specimen discussed here all utilized the T-stub connection shown in Figure 1.

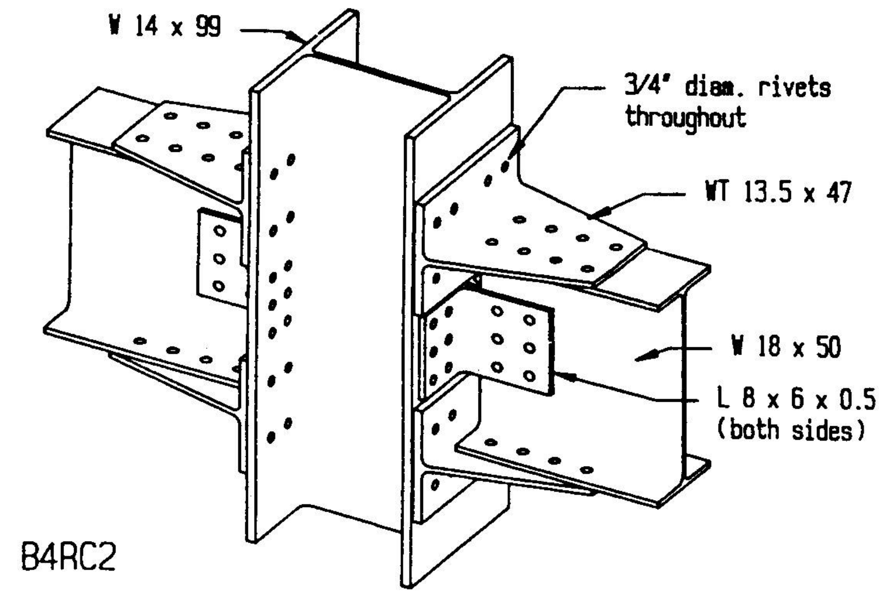

Figure 1 - Typical riveted connections used in the tests.

One of the more important features of these tests is the use of 19 mm A502 Grade 1 rivets (Fy = 310 MPa, Fu = 413 MPa), very similar to those used in the real structure. For these tests standard size holes, about 1.6 mm larger than the rivet diameter, were used for the connection. The rivets were heated to at least 1000 C and then shaped with pneumatic hammers. The riveted connections were fabricated following typical practice as verified by several experienced riveters. Post-test sections cut across the connections showed that the holes were properly filled by the rivets.

The first three tests were run on all-steel specimens, with the only variable being the connector type: rivets (A502 Grade 1), black bolts (A307), and friction bolts (A325). Figure 2 illustrates the moment-rotation behavior of these specimens. The pronounced pinching behavior in the riveted specimen was surprising and contrary to what many researchers had assumed in the past. The pinching was due primarily to slip at the shear interface where very large local deformations had taken place. This in turn led to an elongation of the rivet and a rapid loss of any clamping action. The energy dissipation capacity decreased rapidly with increasing deformations, but the connection regained stiffness and strength once the rivets went into bearing. Typically these hysteresis loops would be considered unsatisfactory. However, the load history imposed was severe and in the real structure the connection would have benefited from additional restraints and force redistribution. Thus the performance of a structure incorporating these connections would probably be better than gleaned from this isolated example.

In the remaining tests, which included the effect of encasement and floor slabs, the behavior improved markedly. The encasement increased both the strength and stiffness of the specimens even though there were no shear studs in the beam or column. In fact, the measured response indicated that the sections behaved as fully composite under cyclic loads until the cover concrete began to crush around drifts of 2.5%. The beneficial effect of the concrete cover was also surprising since the confinement steel was minimal. The concrete also acted to restrain the slip. Although a crack formed at the beam-column interface early in the load history, it did not grow appreciably resulting in smaller rotations for the encased specimens than for the all-steel specimens. Two mechanisms can be postulated to explain this behavior. First, in the compression side of the connection the concrete transferred most of the force directly by bearing directly into the end of the T-stub and the column directly. Thus no appreciable shears were induced in the rivets and the resulting slip was very small. Second, in the tension side of the connection the rivet heads provided an additional load transfer mechanism by bearing, which in addition to the friction between the two materials, resulted in only the first few rivets being loaded to their yield in shear. As the loading progressed the web of the T-stub began to yield resulting in a stable hysteretic response. Connections governed by yielding in the beams or connecting plates, which were tested as part of this program, performed better but at large deformations loss of cover resulted in large strength losses [3].

4. Analytical Studies

Two general approaches, a local and a global one, were used to model the connections. The intent of the former was to develop comprehensive local models

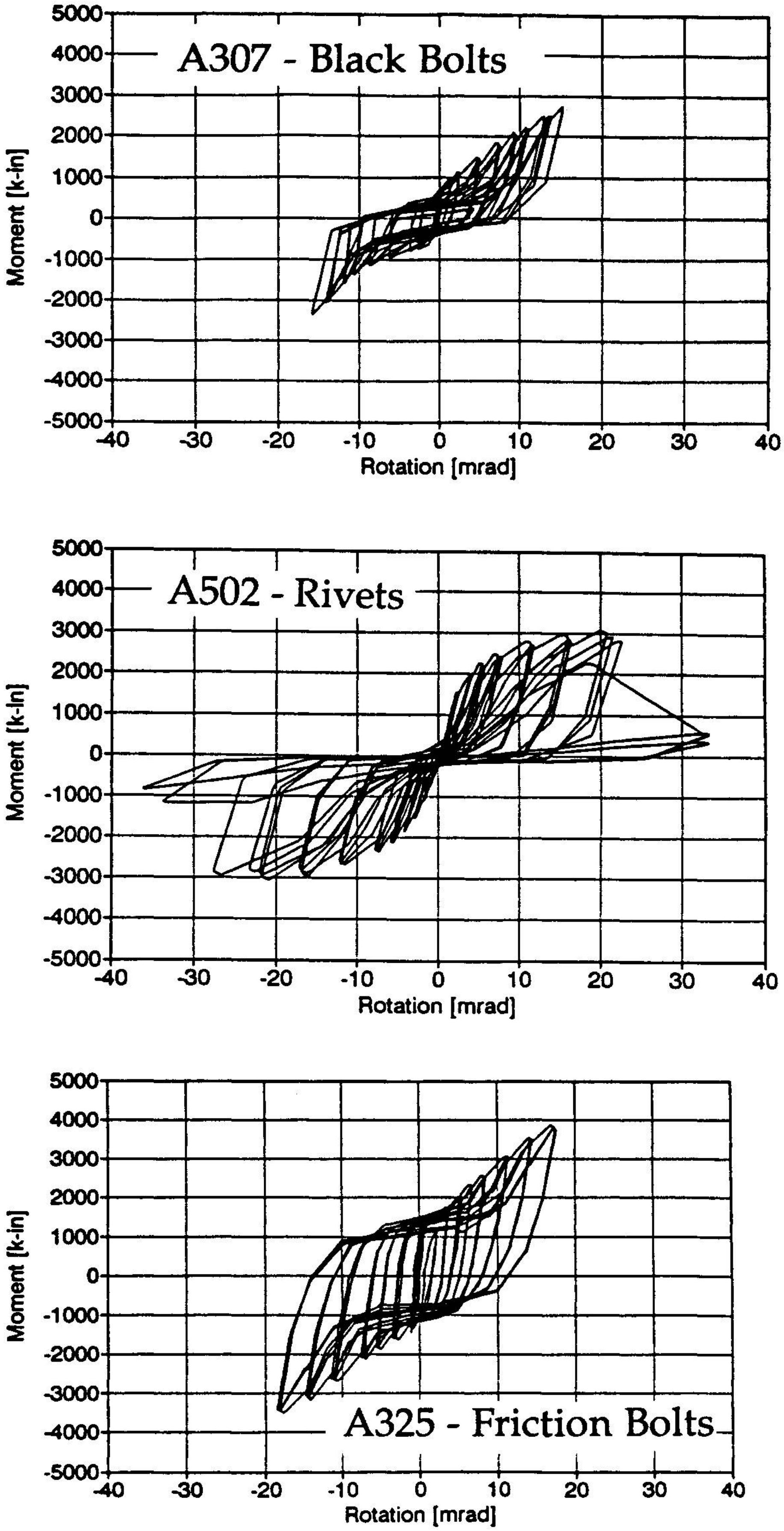

Figure 2 - Comparison of moment-rotation behavior.

utilizing finite elements. For the case of the all-steel connections a new element to describe the local shear behavior was developed utilizing ABAQUS. This element was successful at modeling the degrading behavior shown in Fig. 2. Theoretically this approach is very accurate, but the numerical difficulties encountered while trying to model the conditions at the interfaces of the assemblages render it very difficult for cases with several large load reversals[3]. This is particularly true when the composite action and slip need to be included simultaneously.

The second approach is of a more macroscopic nature. This second method consists of modeling the subassemblages with large structural elements, where different minute connection effects (slip, yielding and friction) are lumped together into dimensionless rotational springs at the beam ends. The panel zone area is modeled with a planar element allowing for shear deformation only. Non-linearities are handled by relationships between the forces applied on the elements and their associated deformations. These relationships can be derived from experiments, or from any other suitable method. Use of this later method leads to a problem of much smaller size. Studies of small frames (up to 10 stories) utilizing these models indicated that the frames possessed the necessary strength and ductility to survive ground motions of up to 0.4g.

5. Summary

The experimental results indicate that the cyclic performance of riveted connections governed by rivet shear capacity is poor, and that their hysteretic behavior degrades rapidly. The effect of the encasement is to considerably strengthen and stiffen the frame and delay the degradation. The companion analytical studies centered on non-linear dynamic analysis of 8 to 10 story frames indicate, however, that the performance of the frames will be acceptable if an accurate modeling of the connection behavior, including slip and panel zone yielding, is made.

6. Acknowledgements

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