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Cyclic Behaviour of Existing and Retrofitted Riveted Stiffened Seat Angle Connections

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ABSTRACT

Specimens of riveted stiffened seat-angle beam-to-column connections were obtained from a building located in downtown Ottawa which was constructed in 1910 and demolished in 1992. The cyclic inelastic behavior of these steel beam-to-column connections has been experimentally investigated, along with that of two minimum-intervention seismic retrofit strategies. Special knee braces were designed as first retrofit strategy. As a second retrofit solution, a "selective retrofit" approach was proposed by a judicious application of welding and rivet replacement to greatly enhance the performance of the existing connections. The experimentally-obtained moment-rotation hysteretic curves convincingly demonstrate that the two proposed minimal-intervention seismic retrofit strategies can effectively increase moment capacity and considerably improve the cyclic ductile behavior of these connections.

INTRODUCTION

Rivetted stiffened seat angle connections were frequently used as beam-to-column joints of old steel frames through North America at times when seismic-resistant design requirements were nonexistent. Today, when conducting structural evaluations of the seismic-resistance of existing buildings, in absence of better knowledge, structural engineers would typically ignore the lateral resistance of steel frames having riveted stiffened seat angle connections. This translates into a greater perception of seismic vulnerability, and, eventually, demolition or the need to perform major seismic retrofit works for many steel buildings. Alternatively, these connections could be more realistically considered as semi-rigid if their potential seismic resistance could be quantified and their cyclic behavior was well understood. As riveted stiffened seat angle connections, when present, are usually found at every beam-to-column joint throughout an entire building, it is conceivable that an analysis using the actual semi-rigid hysteretic model of these connections could demonstrate that these connections and their steel frames, even in their as-is condition (or if partially retrofitted), have adequate resistance and ductility to survive small to moderate earthquakes, thus avoiding the high costs associated with a major retrofit or construction of a totally new structure. However, analytical studies on the performance of steel frames having such connections and subjected to earthquakes can only be conducted if the cyclic

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non-linear inelastic moment-rotation relationship of such connections is known. In this regard, a first task of this research was to experimentally obtain inelastic cyclic moment-rotation curves for riveted stiffened seat angle connections, observe the mechanism of their resistance and cyclic behavior, and formulate analytical models. Then, to enhance the observed hysteretic performance of these connections, two ductile seismic retrofitting techniques are proposed. Conventional retrofitting techniques, such as the addition of new braced or rigid steel frames, are effective but can be very costly for this type of building, requiring considerable reinforcement of beams, columns, foundations and floor diaphragm to accommodate the new load-paths, at great disturbance to the occupants, and may violate the current internationally accepted preservation goals for buildings of heritage value. Therefore, solutions which can be more harmoniously integrated into the existing fabric of a building were sought. In that perspective, two different retrofit schemes are proposed to improve the hysteretic behavior of riveted stiffened seat angle connections: (i) the addition of ductile knee-braces, and (ii) a selective welding approach. These make efficient use of the already existing steel structure, focus on the local reinforcing of individual beam-to-column connection (which can be performed sequentially throughout a building, causing minimum disturbance to occupants), and allow seismically-induced hysteretic energy dissipation to be uniformly distributed throughout all the frame joints.

In this paper, the design philosophy for each of the above proposed retrofit is outlined and the experimental results obtained from tests on non-retrofitted and retrofitted connections taken from an existing building are presented.

Prior Studies on Riveted Connections

Only a few tests of riveted semi-rigid connections were found in the existing literature (Moore and Wilson 1917, Young and Jackson 1934, and Rathbun 1935). These monotonic test were conducted mainly to determine degree of restraints for typical riveted connections. A study (Leon et al. 1994), still in progress at the time of this writing, investigates the inelastic cyclic behavior of some selected types of bolted and riveted semi-rigid connections. Preliminary findings indicate that moment-rotation curves obtained for riveted connections are pinched due to slippage of the connection upon load reversal. This last experimental study is noteworthy since it is, with the work reported herein, the only known seismic-related hysteretic testing program of riveted connections. However, Leon et al. have simulated old connections by developing an in-laboratory capability for riveting new steel sections, and consequently neglect any possible effect of aging of the rivets and base steel.

Test Specimens

Unlike most experimental studies where the test specimens are first designed and built to fulfil the purpose of a specific investigation, in this study the specimens were primarily part of a steel frame of the Daly Building, which was constructed in 1910 on the corner of Rideau and Sussex streets in downtown Ottawa and demolished in 1992. A limited number of specimens were obtained from the building, and most have been used to test seismic retrofit strategies.

Standard ASTM E8 tests indicated that the specimens are of a mild steel, with average yield point, F_y, of 225 MPa, and average tensile strength, F_u, of 400 MPa. More importantly, however, a normal plastic plateau was obtained, and elongation at failure was approximately 25%, putting to rest any suspicion that aging may have affected detrimentally the steel properties in this case. The weldability of this steel was also verified. Finally, experimentally obtained yield and tensile strength of rivets tested as part of existing connections were 258 MPa and 483 MPa respectively. This indicates that rivets are comparable to ASTM A502 grade 1 rivets.

Test Set-up and Instrumentations

In each test of this experimental program, two identical connections of the specimen were simultaneously tested, one on each side of column. The effect of column behavior on the results was minimized by applying an identical moment to the connection on both sides of the column, using the beams as double cantilevers in a symmetric manner for this purpose. The beams themselves were not susceptible to any undesirable failure modes in their as-is condition. Also, test results are not intended to include effect of the panel zone in the columns, or other case-specific failure modes of columns and beams which could detract from the main scope of this study.

A variety of instruments were installed to measure different parameters and facilitate monitoring and, control of the test. Measurements were taken on load, rotations, displacements and strains at points of interest. A total of 24 channels of data were recorded by a data acquisition system. A detailed outline of the instrumentation is presented elsewhere (Sarraf 1993).

Experimental Results - Non retrofitted connection

Details of the non retrofitted joint connection tested are shown in Fig. 1. The moment-rotation (M-θ) relationship of the two identical connections was chosen as a good descriptive and quantitative expression of the hysteretic behavior and resistance for this type of connection. For the following, an arbitrary sign convention is adopted for which positive moments produce tension in the top angles and compression in seat angles, and negative moments do the opposite.

The M-θ relationship of the connections, based on the average results of θ obtained from this experiment on a pair of connections, is shown in Fig. 2. Severe pinching of the hysteretic curves, even in the early stages of loading is clearly observed. This specimen experienced a maximum positive moment (M^{+}_{max}) of 81.1 kN·m and corresponding maximum rotation (θ^{+}_{max}) of 21.28×10^{-3} radian. During the seventh cycle, failure occurred due to shear failure of a rivet in the seat angle when maximum negative moment (M^{-}_{max}) reached -139 kN·m, at a maximum negative rotation (θ^{-}_{max}) of -27.9×10^{-3} radian.

Hysteretic Behavior of the Connections

The M-θ hysteretic curves of the tested connections show a distinct pinching. Since the area under the curves reflects the absorbed energy in each cycle, the presence of highly pinched curves means that the energy absorbed by the connection is lower than optimum and reduced by some factors. The main causes of this pinching can be categorized as follows.

Slippage at Rivet Holes

Slippage at rivet holes is apparently the result of two contributing factors. One is the lack of tight fit inherent to riveting practices in the past. The standard riveting practice required a minimum hole clearance of 1.6 mm, but specially in the case of field riveting, centre of the rivet holes were not always well matched. In addition, diametric shrinkage after the cooling of hot driven rivets can also cause small gaps to develop between each rivet's shank and the edge of its hole. The other factor is the insufficient frictional resistance between the connected parts; clamping force due to the pre-tensioning force of the rivets after cooling is not high enough to prevent slippage by frictional resistance between the connected plates. This is specially true for the rivets driven in the field for which the clamping force appears to be very low, since this operation is accomplished with different tools than those used in shop riveting (Kulak et al. 1987).

Rocking of Top Angles

Moment-strain hysteretic behavior recorded on top angles (Sarraf 1993) shows that the response of the top angles to the reversing force applied to their horizontal leg is also responsible for pinching of the M-θ hysteretic curves. When a positive moment is applied to the connection, the resulting and increasing tensile force which acts on the top angle horizontal leg eventually causes plastic hinging and tensile yielding of the rivets to occur. This is the major source of resistance of the top angle. When the load is reversed, instead of a tensile force, a compressive force is applied to the horizontal leg and causes the hinge deformations of the horizontal leg to reverse. However, the plastic hinge mechanism in the vertical leg is not as effective, since the already elongated rivet has lost its ability to provide, by clamping-force, a fixed support for the vertical leg of the angle. Moreover, the connection has no natural means of reversing deformation of the already yielded rivet; rivets can not be compressed by the plates they connect. As a result, without any considerable resistance, the vertical leg rocks over the column flange, i.e. the deformed vertical leg rotates about the hinge in the horizontal leg and the toe of the vertical leg gradually separates from the column face. This continues until the heel of the angle touches the column flange, at which point the compressive load is directly transferred to the column. Therefore, in every cycle, rocking of the angle occurs and causes some pinching in the M-θ curve. A schematic model which illustrate the different stages of response of the top angle, has been developed and is presented elsewhere (Sarraf 1993).

Lack of Integrity of Stiffened Seat Connection

Another contributor to pinching is the separation of the seat angle and stiffener angles. Negative moments produce inelastic deformations of both the seat and stiffener angles, i.e. flexural resistance is provided by two separate connection components. However, as the applied moment reverses the yielded stiffeners remain in their position and only the seat angles move back toward the column, gradually separating from the stiffeners. Therefore, stiffeners do not contribute in resisting the horizontal force applied to the seat connection subjected to positive moments since there are no mechanism present in this connection to force them back under this reversed moment, particularly if the rivets joining the stiffener angles to the columns have yielded in the prior negative moment cycle, as would often be the case. The capacity of the seat connection for loading in that direction is considerably reduced until the seat angles bear anew on the column.

Similarly in negative flexural excursions, the stiffener angles and the first row of rivets, when already yielded and inelastically deformed, do not provide any resistance until the seat angle deforms sufficiently to touch the stiffener angles, and this can only happen when rotations developed at the connection approximately reach the negative residual rotation obtained in the previous cycle. Therefore, before that value of rotation is reached, there is no contribution from the stiffener angles to the connection resistance.

Experimentally obtained results were comprehensively compared with various available analytical models, differences obtained were rationalized, and models were improved (Sarraf 1993).

Ductile Knee-brace Retrofit

The specimen retrofitted using the proposed ductile knee-brace technique is schematically shown in Fig.3. In the design of the braces, the objective is to maximize the energy dissipation of the knee bracing system. This desired performance must be achieved within the practical constraints normally encountered when operating on actual buildings. The following design guidelines are proposed:

i) Braces must be long enough to be connected properly to both beams and column (i.e., workability condition).

ii) Ideally, the plastic mechanism of the retrofitted system under the maximum applied moment should develop tension yielding in one brace member and compression yielding in the other, providing a most efficient energy dissipation mechanism. To maximize capacity and energy absorption, C_r / T_r ratio for the member must be as close as possible to 1.0.

iii) To have an efficient, reliable and easily repairable energy dissipating knee bracing system, it is desirable to have all plastic hinges form in the compression member itself rather than in the gusset plates or other parts. Thus, braces and gusset plates should be sized to ensure that buckling of the member occurs in the plane of the beam and column. This will also protect walls against out-of-plane induced damage when braces are embedded in walls. The welds to connect knee braces to gusset plate should be conservatively designed to provide resistance for the development of full tension capacity, as well as compression capacity combined with the plastic moment capacity of the member. Following these design guidelines, an effective length factor, k, of 0.5 can be used in the capacity calculations. Moreover, the braces must be designed to avoid local buckling or torsional buckling prior to formation of the plastic hinges in the compression member.

iv) The braces must act as a weak link, i.e., they must yield and dissipate energy. If overly strong braces are used, there would be risk of forming plastic hinges in the connected columns, which would defeat the intended purposes.

Selective Welding Retrofit

Although converting a semi-rigid connection into a fully rigid one by welding seems at first to be ideal, this approach may have some shortcomings. The weld preparation is difficult (back-up plates, cleanup, etc.), the amount of deposited material is considerable, particularly in the gap almost always present between the column face and end of the beam, the working area is congested and the weld-design can be very complex, in some cases nearly impossible, for example where columns are made of built-up sections. Moreover, since the columns in old steel buildings were never designed to resist earthquakes and are relatively more flexible than the beams, assuming that the conversion to full fixity was possible, it would create a very dangerous situation by inducing plastic hinges in the column (weak column/strong beam failure mode). Instead, based on an understanding of the cyclic performance of this type of connection as a result of the tests reported herein, a more judicious application of welding is possible to greatly enhance the performance of the existing connections, eliminating known weaknesses while keeping those inherently good energy dissipating mechanisms already present. It is noteworthy that, in the new proposed "selective welding" approach to the retrofit of riveted stiffened seat angle connections, weld preparation is limited to the cleaning of surfaces to be welded. The retrofit consists of three distinct tasks, as illustrated in Fig.5, and described as follows:

i) Replace selected rivets by high strength bolts. The extensive yielding and lack of clamping forces of the 4 rivets in the top angles have been shown to cause pinching and decrease the moment capacity. These are therefore replaced by A490 high strength bolts of 19 mm diameter. None of the other 48 rivets were replaced.

ii) Perform selective welding on stiffener angles. To reduce pinching caused by the gap that has been shown to progressively develop between the stiffener angles and seat angles, these two elements are welded together at the location where the gap would be otherwise expected.

iii) Perform selective welding on the beam. To increase the connection moment capacity by reducing the risk of rivet's bearing failure, and to eliminating pinching due to the lack of tight-fit and frictional resistance of the rivets connecting the beam flanges to the horizontal leg of the top and seat angles, welding is performed to provide a new load path to transfer shear at those locations. Here the weld was designed to be able to resist the full tensile capacity of the angle legs.

Experimental Observations

The resulting M-θ hysteretic curve for the knee braced specimen presented in Fig.4 is based on the averaged rotation developed in the two connections of the specimen. It is observed that the hysteretic loops are not pinched in the small range of rotation, but slightly pinched at larger rotations. Here, positive moments are assumed to cause tension in the top knee braces and compression in the bottom knee braces. The specimen in this test reached the maximum moment, M_{max}, of 197 kN·m and developed maximum rotation, θ_{max}, of 29.8×10^{-3} rad. The experiment ended after five cycles, when severe buckling deformations of the knee braces and large rotations were observed and continuation of the test would likely not have generated any new information.

The resulting M-θ hysteretic curve for the selective welding retrofitted specimen, based on the average rotation of connections on both sides of the column, is presented in Fig.6. The specimen was subjected to cyclic loads up to maximum positive moment, M^{+}_{max}, of 74 kN·m and maximum negative moment, M^{-}_{max}, of -136 kN·m. These loads respectively caused maximum positive rotation, θ^{+}_{max}, of 25.9×10^{-3} rad and negative rotation, θ^{-}_{max}, of -38.8×10^{-3} rad. The experiment ended after 10 cycles when the applied negative moments caused relatively large inelastic deformations in the seat angles as well as formation of plastic hinges and buckling of the stiffener angles. It is noticed that, throughout this experiment, the post-yield slopes of the M-θ curve during positive and negative loading are almost identical until the top angles, under negative moment, return to their original position, in contact with the column flange. Indeed as negative moments are applied to the specimen, top angles which have already been deformed, as described above, have a lower resistance and stiffness than those of the seat connections, and their stiffness when pushed back toward the column governs the overall stiffness of the connection until contact, at which point the seat angle connections start to deform and control the overall stiffness of the connection. This has been visually observed to be the mechanism responsible for the change in slope of the M-θ curve in negative flexure.

It is noteworthy that, to provide verification of the experimentally obtained results, a new analytical model was formulated. Based on a simplified physical plastic yield mechanism, this modified analytical model of the riveted stiffened seat angle connection is applicable to angles detailed for built-up columns, and can be reliably used to predict plastic moment capacity, as demonstrated elsewhere (Sarraf 1993).

CONCLUSIONS

From the experimental study of the hysteretic behavior of two proposed seismic retrofitted techniques for riveted stiffened seat angle connections, it is concluded that selective welding retrofit strategy, which consists of performing welds at specific locations on the connection and selectively replacing a few rivets by high strength bolts, is an effective retrofit solution which enhances moment capacity and significantly improves the hysteretic energy dissipation capability of riveted stiffened seat angle connections. The addition of ductile knee braces is another effective retrofit solution for these steel connections, capable to develop large moment capacities and dissipate considerable energy, in both positive and negative flexure. The design of these special ductile knee braces must however follow the guidelines developed in this study to provide efficient energy dissipation in the knee braces.

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References

Kulak, G. L., Fisher, J. W., Struik, and John H. A. (1987). "Guide to Design Criteria for Bolted and Riveted Joints", Second Edition, John Wiley and Sons, New York.

Leon, R., Forcier, G. P., Roeder, C. W., and Preece, F. R. (1994) " Cyclic performance of riveted connections." *Proceedings of 12th ASCE Structures Congress*, Atlanta, Georgia, USA, Vol. 2, 1490-1495.

Moore, H. F., and Wilson, W. M. (1917). "Tests to determine the rigidity of riveted joints of steel structures." *Engineering Experiment Station, Bulletin No. 104*, Univ. of Illinois, Urbana, Illinois.

Rathbun, J.C. (1935). "Elastic properties of riveted connections" *Trans*. ASCE, Paper No. 1933, Vol. 11, 524-563.

Sarraf, M. H. K. M. (1993). "Experimental study on cyclic behavior of riveted stiffened seat angle connections", Thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for the Master of Applied Sciences Degree in Civil Engineering, University of Ottawa, Ontario, Canada.

Young, C. R., and Jackson, K. B. (1934). "The relative rigidity of welded and riveted connections." *Canadian Journal of Research*, vol. 11, 62-100.

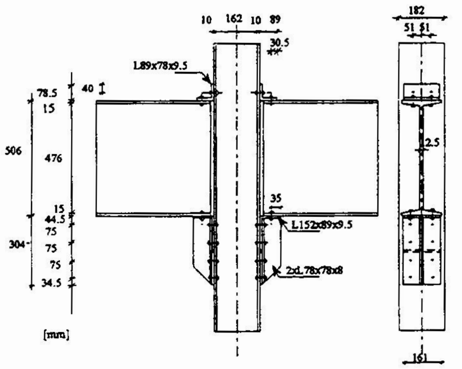

Figure 1: Detail of non-retrofitted riveted stiffened seat angle connection

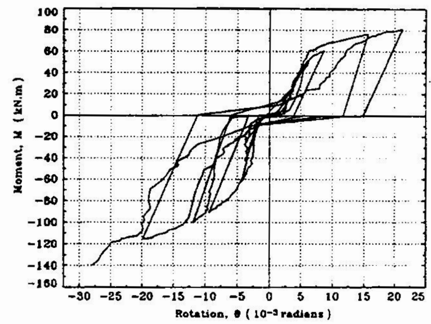

Figure 2: Hysteretic curve for non-retrofitted specimen

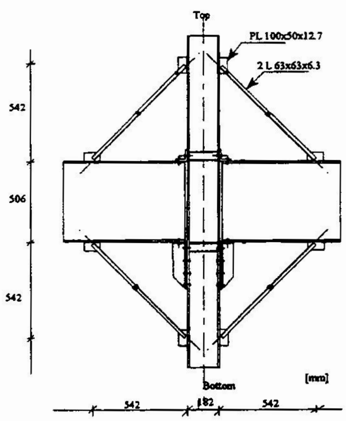

Figure 3: Specimen retrofitted using ductile knee braces

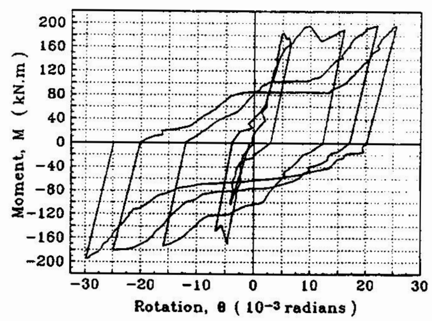

Figure 4: Hysteretic curve for tested knee braced specimen

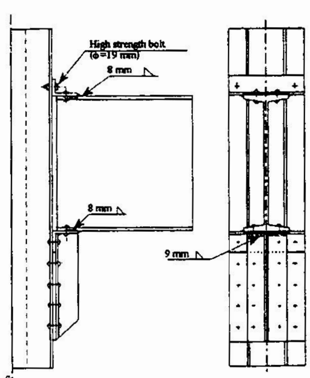

Figure 5: Specimen retrofitted using selective welding technique

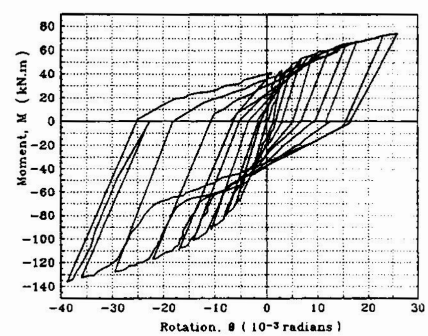

Figure 6: Hystretic curve for tested slectively welded specimen