The Results of Experiments on Seated Beam Connections

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Seated beam connections have been used for many years. They have historically been designed by tabular methods,[1] and this tradition was recently continued in the new LRFD Manual.[2] The derivation of these design tables are discussed elsewhere[3] and will not be repeated here.

It should be noted that the tables have historically considered local yielding of the beam web under edge loading, the strength of bolts or welds, the yielding capacity of the seat angle and the normal detailing dimensions.

The new AISC LFRD Specification includes the new equation (K1–5) which checks the beam web for crippling or buckling. In this paper, the term buckling is defined to mean a vertical crimping or crippling of the web due to the application of a concentrated load on the flange. This is a stability mode of failure rather than a web yielding failure as presently considered in ASD design (8th Edition Manual). Unlike a web yielding formula, it includes the depth and the flange thickness of the beam as variables. Table 1 summarizes LRFD beam web capacities according to Eq. (K1–5) and a 3-½ in. bearing length. It can be seen that there are cases where the tabulated unstiffened seat capacities exceed the beam web buckling capacity. Therefore, AISC funded a research program at the University of Washington to study these connections. This paper summarizes some of the results of this experimental program.

TABLE 1
LRFD Web Crippling Capacity—N=3½ in.

Web Thickness	$t_f/t_w = 1$			$t_f/t_w = 1.5$			$t_f/t_w = 2$		
	Beam Depth			Beam Depth			Beam Depth		
	10	12	16	10	12	16	10	12	16
3/16	22	20		18	17		16	15	
4/16	39	36	32	33	30	27	29	27	25
5/16	61	56	49	51	47	43	46	43	40
6/16	88	81	71	73	68	62	66	62	57
7/16	120	110	97	100	93	84	89	84	78

Resistance factor = .75—Load in kips for A36 steel

EXPERIMENTAL PROGRAM

Six wide flange beams of grade 50 steel were tested in both stiffened and unstiffened seat connections. They were the W8 × 10, W12 × 14, W12 × 22, W12 × 26, W14 × 22 and W14 × 26. These sections were chosen because they have thin webs and their predicted load capacity, with ½ in. bearing would be governed by web buckling, Eq. (K1–5). The tests are summarized in Table 2, and the test setup is illustrated in Fig. 1. Each of the six sections were tested with three different top angle arrangements and a stiffened seat. The stiffened seat prevented yielding of the seat angle and assured that failure occurred in the beam rather than in the connection. The top angle was L4 × 4 × ¼ and was attached to the top flange or optional web location as indicated in Table 2. These two locations are required by the AISC design procedure. The top or side angle is required to support the beam, but the design calculations[3] do not explicitly consider it. To evaluate this effect, a third support configuration (Fig. 2) was used for each of the six sections. This third configuration employed 2 angles which were bolted to the column but not to the beam. The angles guaranteed the stability of the beam web, but they did not contribute to the capacity of the connection seat. Therefore, this configuration was the most realistic in evaluating the capacity of the connection independent of any beam web attachments.

Four additional tests were performed with unstiffened seat angles. The beam was a W14 × 26 or a W14 × 22 for these tests, and the seat angle was ¾-in. thick. Three strain gages were attached to the seat angle and monitored during the test. These gages were placed on the inside of the leg of the angle, which was bolted to the column, near the toe of the fillet. They were spaced across the width of the angle so that the distribution of strain could be measured. Three of the four flexible beam tests were made with the standard ½-in. setback between the beam end and column face. The top angle was located either on the top flange (standard), or on the web (optional location) or an unbolted double angle detail was used as shown in Fig. 2. The fourth unstiffened seat test used a 1-in. setback between the beam and the column face. This fourth test illustrated the effect of fabrication error or inadvertent ec-

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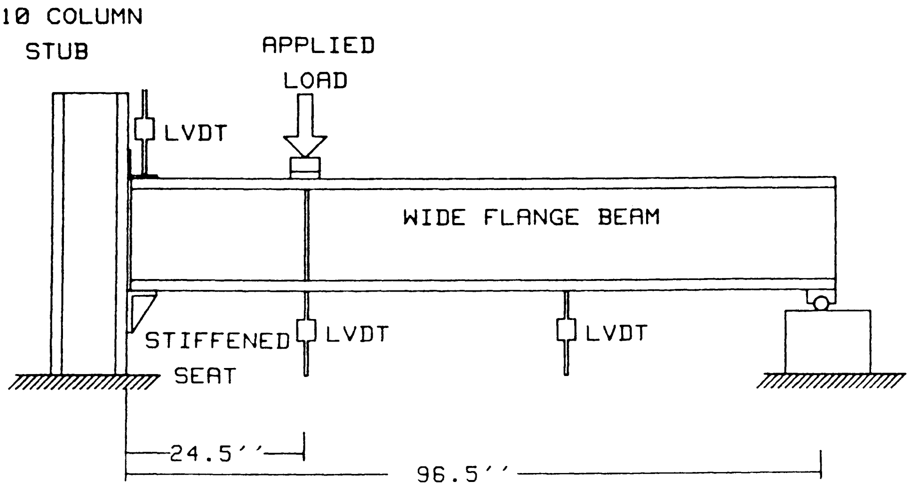

Figure 1

centricity on the connection detail. The bolts were all ¾ in. A325 with calibrated washers. Lateral support was provided to the beam in the region of maximum moment with a light frame as shown in Fig. 3. The loads were applied with a 2.3 million pound Baldwin hydraulic test machine, and a bearing stiffener was used to prevent damage to the beam at the load point. An elastomeric pad was used to distribute the load and prevent local damage. The concentrated load was applied near the quarter point of the eight foot span. This loading was needed to develop the required end reaction of the beam without yielding the beam in bending.

Deflections were measured at three locations in the beam span with linear voltage displacement transducers (LVDTs) as shown in Fig. 1. The data were recorded with a Hewlett-Packard computerized data acquisition system.

TABLE 2
Experimental Program

Beam Size	Seat Detail	Top Angle Detail	Ultimate Reaction	
W8x10	Stiffened	Top Angle	18.	A
W8x10	Stiffened	Optional Web	18.3	A
W8x10	Stiffened	Unbolted Web	18.	A
W12x14	Stiffened	Top Angle	36.8	A
W12x14	Stiffened	Optional Web	36.3	A
W12x14	Stiffened	Unbolted Web	27.6	A
W12x22	Stiffened	Top Angle	61.4	A
W12x22	Stiffened	Optional Web	60.3	A
W12x22	Stiffened	Unbolted Web	60.8	A
W12x26	Stiffened	Top Angle	64.5	B
W12x26	Stiffened	Optional Web	68.	C
W12x26	Stiffened	Unbolted Web	57.	C
W14x22	Stiffened	Top Angle	58.5	C
W14x22	Stiffened	Optional Web	57.	C
W14x22	Stiffened	Unbolted Web	54.	C
W14x26	Stiffened	Top Angle	60.9	C
W14x26	Stiffened	Optional Web	58.5	C
W14x26	Stiffened	Unbolted Web	45.	C
W14x26	¾ L	Top Angle	47.	D
W14x26	¾ L	Optional Web	47.	D
W14x22	¾ L	Unbolted Web	38.	D
W14x26	¾ L	Top Angle	33.	D

A—Beam yielded under load point
B—Local flange buckling of the beam
C—Beam web buckled at seat
D—Angle seat bent and could not accept more load.

The test specimens were all whitewashed and all yielding and buckling was carefully observed and photographed. The configurations were always tested in a given sequence. First, the beam was tested with the top angle, and the web and unbolted angles were tested sequentially. The first two tests were stopped before excessive damage was done to the steel. This permitted the use of the same steel section for three tests. Obviously, a slightly larger load capacity could have been attained if more damage had been permitted in the first two tests, but examination of the force-deflection behavior indicates that this effect is very small. More detailed data on the test procedures and test results are given elsewhere.

EXPERIMENTAL RESULTS

The experiments were performed and some of the more general results are noted in Table 2, but several observations require more elaborate description.

First, it should be noted that comparison of the reaction capacity obtained for the double angle support system shown in Fig. 2 with the reaction capacity obtained for identical seat connections with the top flange angle or the optional web location angle, illustrates the percentage of the load carried by the top angle. This effect is further illustrated in Figs. 4 and 5 for typical stiffened and unstiffened seat connections. The top angle carried between 8% and 35% of the end reaction for connections which failed through web crippling. Further, the top angle or optional web angle may stiffen the seat somewhat in the elastic range and, therefore, delay inelastic action. The reaction carried by the top angle is important to the connection behavior even though it is ignored in the design model used to develop the connection load tables. However, not enough data is available at the present time to warrant a less conservative model than that presently used.

The second observation is that web buckling is an important mode of failure for the case when beams with thin webs bear on stiffened seats. For this reason, the AISC LRFD Manual of Steel Construction design procedure includes a method for calculating the bearing length to prevent both beam web yielding and buckling. To facilitate this calculation, AISC has tabulated constants in the Load Tables for Uniform Load Constants for beams. Unless this tabulated bearing length is considered, web buckling may be the limit state as illustrated in Table 2 and the photograph of Fig. 6. The buckling was typically accompanied by yielding of the steel and resulted in large permanent deformations. The deformation probably contributed to the ability of the top angle to carry load. While web buckling is an important limit state, it requires a relatively unusual loading condition to achieve it. The experiments were performed with a concentrated load at approximately the quarter point of an 8 ft. span. This span is quite short for a 12 or 14 in. wide flange beam. Further, the quarter point loading is relatively uncommon and despite these unusual conditions the W8 × 10, W12 × 14 and W12 × 22 still failed by flexural yielding before web buckling could occur. Web buckling is unlikely to occur with rolled wide flange beams under uniformly distributed loading unless the span is very short compared to the beam depth. In any case, beam web buckling can be avoided by following AISC Specification Eq. (K1–5) and using the procedure outlined in the Manual.

A third major observation is that unstiffened seat angle connections can adequately yield without fracture. The connections are capable of rotating, without distress, far beyond that required to accomodate the end rotation of the beam it is connecting. The strain gages indicate that yielding initiates near the toe of the fillet in the center of the leg of the angle which is bolted to the column. Yielding propagated along the length of the angle as indicated in Fig. 7, and again the top angle reduces the load on the seat angle as illustrated in Fig. 5. The experiments suggest that yielding of the seat angle occurs near the toe of the fillet on the leg which is bolted to the column; this measurement is supported by the observed plastic rotation at the location in the photo of Fig. 8. It is interesting to note

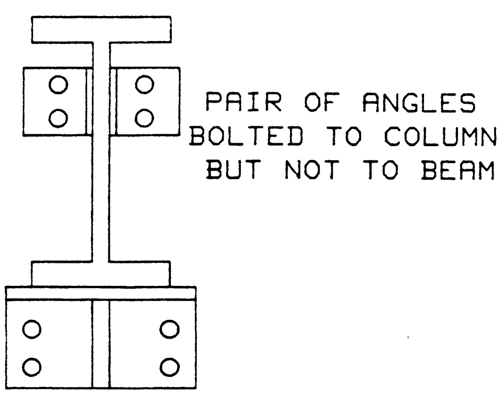

Figure 2

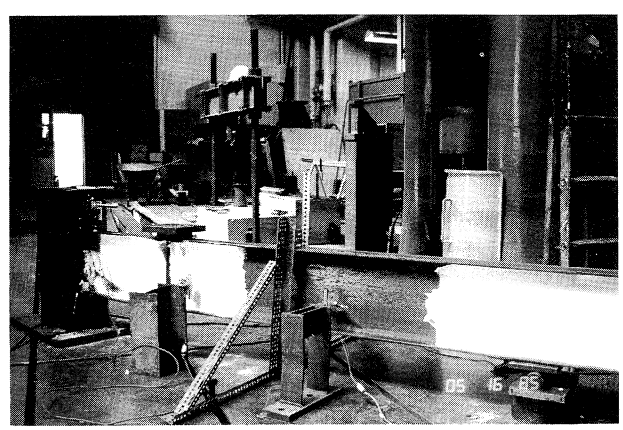

Figure 3

TABLE 3 Comparison Of Experiments With Design Values							
Beam	Seat	Top Angle	Ultimate	ASD DESIGN		LRFD Design	
Size	Detail	Detail	Reaction	Yield	Ratio	Yield	Eq. (K1–5)
W12x26	Stiffened	Top Angle	64.5	38	1.7	65	29
W12x26	Stiffened	Optional Web	68.	38	1.8	65	29
W12x26	Stiffened	Unbolted Web	57.	38	1.5	65	29
W14x22	Stiffened	Top Angle	58.5	38	1.5	65	31
W14x22	Stiffened	Optional Web	57.	38	1.5	65	31
W14x22	Stiffened	Unbolted Web	54.	38	1.4	65	31
W14x26	Stiffened	Top Angle	60.9	42	1.4	75	34
W14x26	Stiffened	Optional Web	58.5	42	1.4	75	34
W14x26	Stiffened	Unbolted Web	45.	42	1.1	75	34
W14x26	¾ L	Top Angle	47.	27	1.7	49	34
W14x26	¾ L	Optional Web	47.	27	1.7	49	34
W14x22	¾ L	Unbolted Web	38.	27	1.1	49	31

that the measured strains never exceeded 0.005 in./in. on the outer fibers, far less than the onset of strain hardening.

VALIDITY OF SPECIFICATION PROVISIONS

The experimental results are compared to the ASD provisions (1978 Specification) and the LRFD provisions in Table 3. The LRFD design limits include the appropriate resistance factors. Under the ASD design rules, only beam web yielding is considered. The LRFD rules consider both web yielding as well as buckling calculated by Eq. (K1–5), using only a 3-½ in. bearing. It is clear that, for both the stiffened and unstiffened case, web buckling should be considered. It is also interesting to note that, in the ASD case, the two cases where the ratio of Ultimate Reaction to the Web Yielding Load was only 1.1 were cases not permitted by the ASD Specification (no top or side angle). The test results for the W8 × 10, W12 × 14 and W12 × 22 are not included in Table 3 because these tests did not result in a beam web failure.

Stiffened Seats

Comparison of the stiffened seat test results with the LRFD factored resistance shows that the LRFD beam web buckling rule, Eq. (K1–5), is conservative but can not be ignored. The specimens with top flange angles or optional web angles had measured strengths more than 72% greater than predicted by the LRFD rules, including web buckling. If web buckling was not considered in the design calculations only one test in six achieved the computed strength. These observations suggest that a check for web buckling is essential but it is also apparent that LRFD Eq. (K1–5) is probably too conservative. This equation was analyzed in greater detail and compared to 69 other experiments in other papers.[4,6,7] There was great scatter in the experimental data and, when the statistical concepts of LRFD are employed, this scatter results in a small (0.75)

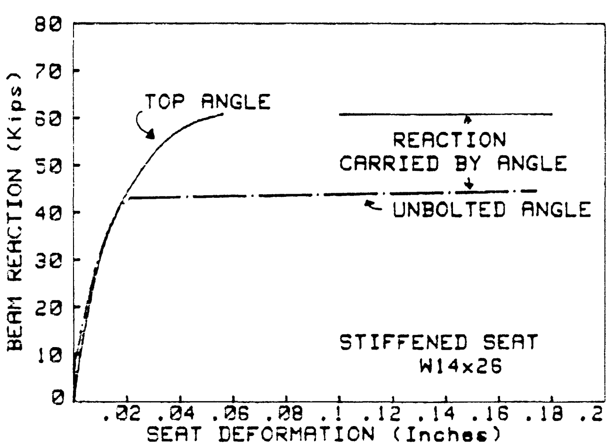

Figure 4

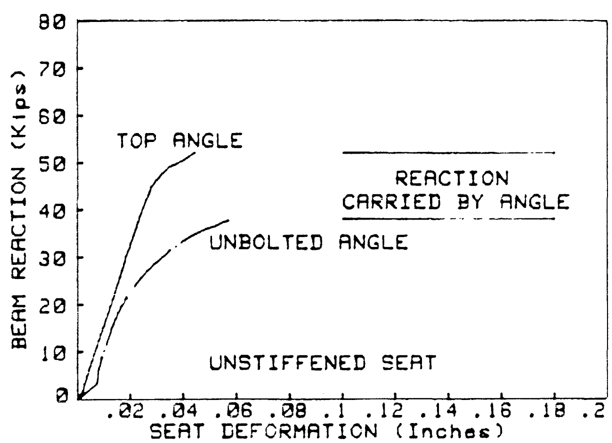

Figure 5

resistance factor. The LRFD resistance for web buckling and yielding; and the smaller of the two values divided into the measured strength for the 69 experiments.[5] The figure clearly shows that strengths much larger than the design values were often achieved. Most of the experiments were performed more than 40 years ago. It would appear reasonable to ask if a new series of tests could reduce the scatter through good experimental control and permit a considerable increase in the assumed resistance and, in turn, the resistance factor.

The third specimen in each group of three stiffened seat tests had unbolted double web angles as shown Fig. 2. This test configuration is more nearly consistent with the design model used to generate the tables for unstiffened seats. However, as has been pointed out, it is not permitted by either the AISC ASD or LRFD Specification. The double angles are not able to carry any part of the reaction, and as a result the reaction is reduced by 7% to 27% over the seat when provided with a bolted top or side angle. These tests illustrate the importance of a securely attached top angle which is of appropriate size for the connection. This third detail is still very conservative when compared to the web buckling equation. This observation supports the earlier observation that the resistance factor of 0.75 may be small for this application.

Similar observations may be made with respect to the allowable stress (ASD) design provisions.[1] ASD does not require a web buckling check and, without the top or side angle, an unconservative design may result for beams with slender webs. Even with these angles, two tests indicated a load factor of 1.4. This again suggests that, even though no failures have been reported, a web buckling provision should probably be included in the ASD Specification.

Unstiffened Seats

Only three tests are available for the unstiffened seat connection, since the 1 in. end spacing is not consistant with the design tables. Beams with a top or side angle developed measured reactions which were 5% less than the computed LRFD yield resistance, but they greatly exceeded the predicted web buckling resistance. The third test in this group had the unbolted double angle detail shown in Fig. 2. This detail is consistant with the design assumptions[3] used for unstiffened seats but it is not consistant with the requirement to provide a top or side angle. The measured strength for the specimens with the double angle was below acceptable levels for both the ASD and LRFD design. This again illustrates the importance of a securely fastened top or side angle. This angle carries a substantial portion of the end reaction, and the loss of this capacity appears to result in an unconservative estimate of the beam web buckling capacity. As noted earlier, the unstiffened seats were able to deform sufficiently while carrying the required load. It is concluded, therefore, that the present or LRFD design procedure for the seat, itself, is adequate. However, it is possible for the tabulated values to exceed the buckling capacity of some beams with slender webs so it is essential that LRFD Eq. (K1–5) be checked.

CONCLUSIONS AND PRACTICAL IMPLICATIONS

It can be concluded from the results of this research that:

1. The top flange angle (or optional web angle) carries a substantial portion of the end reaction for both stiffened and unstiffened seat connections. This makes it essential that this angle be securely fastened and be of an appropriate size and strength for the connection.
2. Web buckling is the controlling failure mechanism for many beams with slender webs and small end bearing lengths.
3. ASD design provisions do not explicitly include a

Figure 6

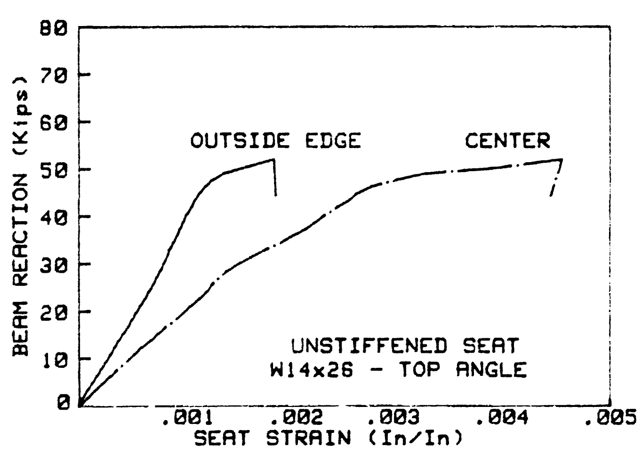

Figure 7

beam web buckling check and as a result, unconservative designs could result, particularly if the required top or side angle were omitted.

4. LRFD provisions have an equation for web buckling, Eq. (K1–5), but the experiments described in this paper suggest that this equation with a 0.75 resistance factor may be overly conservative. However, it must be emphasized that 69 tests performed 40 years ago and described in other papers[3,6] suggest that this formula and resistance factor are approximately correct.
5. The three tests of unstiffened seats indicated that the present design procedure results in seats that have ample rotation capacity and strength.

Practical Implications

The previous discussion suggests that the existing design rules for unstiffened seat connections are somewhat irrational. They employ a highly idealized and probably unrealistic distribution of forces and they sometimes ignore the critical mode of failure. This conclusion is unavoidable when the experimental evidence is considered. However, it important that one not lose sight of several important practical aspects. These connections have been used for many years and no problems have been noted and one must recognize why this is so. First, the buckling failure mode described in this paper requires a high shear force and a beam with a slender web. This would be unlikely to occur with rolled shapes loaded uniformly. The limit states would be more likely be a three hinge mechanism in these common applications. Secondly, and very important, the top or side web angle carries a significant portion of the end shear, and, if it is properly bolted and not too thin, it will help solve many potential problems. Finally, web buckling is most likely to occur with stiffened seats or unstiffened seats with thick angles and when the requirement for a top or side angle is violated. The unlikely combination of all these factors explains why these connections have had such a good performance record.

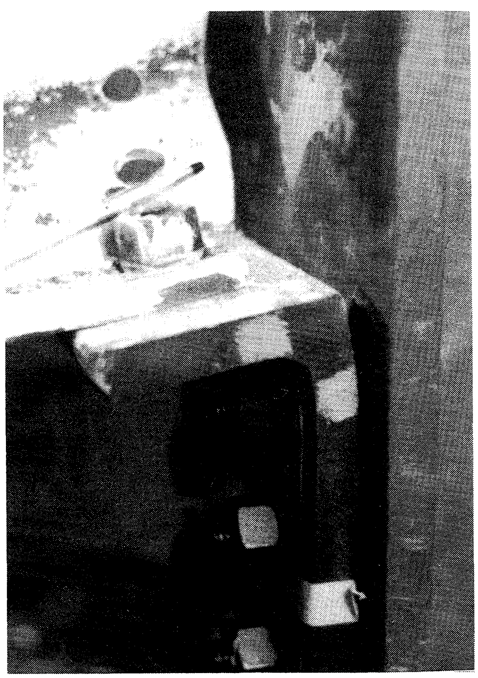

Figure 8

RECOMMENDATIONS

More research is needed to improve the design of seated connection through:

1. Developing models for predicting the effect of the top or side angle on the connection strength.
2. Better estimates of the web buckling capacity and the LRFD resistance factor. There is a great deal of scatter in the existing data[3] and this data was acquired more than 40 years ago. A well controlled experimental program may well reduce this scatter and provide more realistic strength estimates.
3. Development of better models for predicting the distribution of forces in the connection material.

ACKNOWLEDGMENTS

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