EXPERIMENTAL STUDY OF OPEN WEB STEEL JOISTS WITH CRIMPED CRITICAL WEB MEMBERS

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INTRODUCTION AND BACKGROUND

Open web steel joists are prefabricated truss like flexural members that are ideal for resisting low levels of load over long spans. These members are typically found in floor or roofing support systems. Joists are typically designed as simply supported and uniformly loaded flexural members that cover long spans to take advantage of their high strength-to-weight ratio. The top chords are almost always in compression and are continuously braced by some type of decking. The bottom chords are generally tension members and are stabilized by diagonal bridging placed at specific locations along the joist. The web members vary between tension and compression members and can be fabricated as bars, single angles, double angles or single angles with crimped ends.

Currently, the design methodology employed by the Steel Joist Institute (SJI) is based on both allowable stress design (ASD) and load and resistance factor design (LRFD). An LRFD design is performed through the use of resistance factors and by factoring design loads so that the required stress in any given member does not exceed the design stress. An ASD design guarantees that member stresses do not exceed pre-determined allowable stress levels at prescribed service level loads.

When single angle web members are used, a bending moment exists in this member because the load is not applied through the angle's

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centroid. The load is transferred to the web member with an inherent eccentricity because the centroid of the single angle does not intersect with the centroid of the top and bottom chords.

The designing a joist with single angle web members, this eccentricity and resulting bending moment need to be addressed. This reduces the overall load carrying capacity of the entire structural element. In order to eliminate the load eccentricity, the ends of single angle web members are crimped and rotated to align the member's centroid with the centroid of the chords. From a design standpoint, this method of fabrication is advantageous because it theoretically eliminates the bending stresses present that are caused by eccentric loads. It should be noted that crimping the member reduces the weak axis moment of inertia at the crimped locations.

Problem Definition

The motivation behind this study is to better understand the effects of using crimped ends on critical web members for open-web steel joists. The joists supplied for the study were provided by three different manufacturers which allows for comparisons to be made between each manufacturer and the different assembly processes used. These differences in construction and assembly provided a way to identify the joists' overall strengths and weaknesses.

EXPERIMENTAL METHODS

The research conducted for this consists of ninety different joists with crimped critical web members made by three separate manufacturers. The colors blue, white and red were given to each manufacturer to distinguish where each joist was assembled so proper comparisons can be made among like joists. Of the ninety joists, each manufacturer produced thirty specimens varying in length, depth, and critical web member size. For each design, two joists were made by each of the three different manufacturers for a total of fifteen different joist designs. Among the fifteen different designs there are three varying lengths. There are thirty joists of length 8 feet (J1), 22 feet (J2) and 28 feet (J3). The J2 and J3 joists all have a depth of three feet, while J1 has a depth of eighteen inches. There are five different critical web member sizes that are identical throughout the three joist lengths. The angle sizes of the critical web members are 1.25 in x 1.25 in, 1.50 in x 1.50 in, 1.75 in x 1.75 in, 2 in x 2 in and 2.5 in x 2.5 in. Table 1 shows the test matrix including design loads for each of the fifteen different joist designs. Joist length, depth and critical web member size are the only features of the joist that are required to be identical among all three manufacturers. Often times, joists with the same critical web member size did not have identical web member or chord sizes. Both the top and bottom chords were fabricated as double angles with one inch chord gaps. Single angles with crimped ends or double angles welded to the exterior of the chords were always used as the interior web members while double angle or solid round bar was used as exterior web members. The steel angle for all specimens used for the critical web members was cut from the same original length of angle. All specimens were statically loaded with a point load at midspan to failure. Buckley (2007) provides a detailed description of the testing system, loading rates, data acquisition, and pre-test measurements.

Table 1 Text Matrix for crimped web member tests

Joist Series	Span	Depth	Critical Web Size	Design Load (lbs)
J1	8' - 0"	3' - 0"	1.25" x 1.25" x 0.125"	14180
J1	8' - 0"	3' - 0"	1.50" x 1.50" x 0.170"	24232
J1	8' - 0"	3' - 0"	1.75" x 1.75" x 0.170"	29592
J1	8' - 0"	3' - 0"	2.00" x 2.00" x 0.232"	46764
J1	8' - 0"	3' - 0"	2.50" x 2.50" x 0.230"	60790
J2	22' - 0"	3' - 0"	1.25" x 1.25" x 0.125"	2627
J2	22' - 0"	3' - 0"	1.50" x 1.50" x 0.170"	6160
J2	22' - 0"	3' - 0"	1.75" x 1.75" x 0.170"	9910
J2	22' - 0"	3' - 0"	2.00" x 2.00" x 0.232"	19009
J2	22' - 0"	3' - 0"	2.50" x 2.50" x 0.230"	29913
J3	28' - 0"	1' - 6"	1.25" x 1.25" x 0.125"	2630
J3	28' - 0"	1' - 6"	1.50" x 1.50" x 0.170"	6160
J3	28' - 0"	1' - 6"	1.75" x 1.75" x 0.170"	9900
J3	28' - 0"	1' - 6"	2.00" x 2.00" x 0.232"	18940
J3	28' - 0"	1' - 6"	2.50" x 2.50" x 0.230"	30000

TEST RESULTS

Failure Types

All 90 joists were tested to failure and midspan deflection was recorded. For the crimped web member joists, 58 out of the 90 specimens failed at the critical web member. There were 29 critical web failures from the J1 series (out of 30 specimens), 18 critical web failures from the J2 series and 11 critical web failures of the J3 series. Figures 1 through 7 depict the different types of failure mechanism listed in the summary tables. Tables 2 through 4 summarize the critical web member failures for the J1, J2 and J3 joists.

Figure 1 Buckling of the crimp transition zone (J2250-R2)

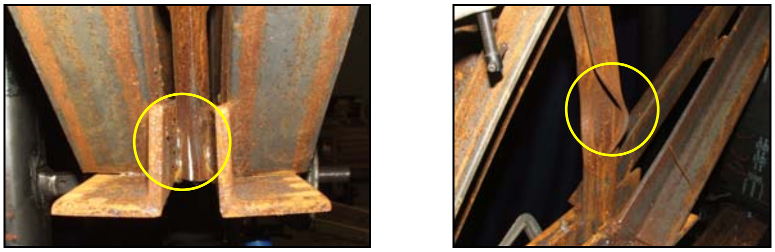

Figure 2 Buckling of crimp transition zone and member fracture (J2200-R1)

Figure 3 Out of plane buckling at the crimp (J3250-W1)

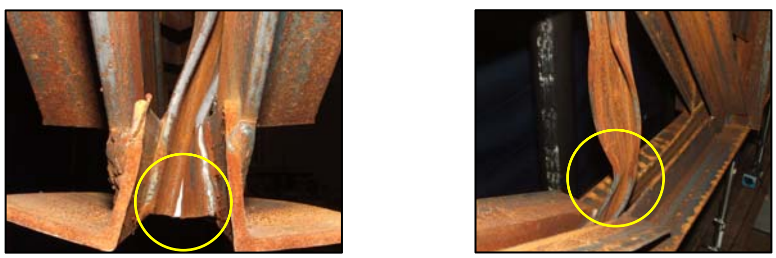

Figure 4 Out of plane buckling at crimp and member fracture (J1200-W1)

Figure 5 In-plane buckling of the uncrimped section (J2200-W2)

Figure 6 Out of plane buckling of the uncrimped section (J3175-W2)

Figure 7 Weld and member fracture at the chord connection (J1175-W1)

Table 2 J1 critical web member failure mechanisms

Test Specimen	Ratio (Exp/Design)	Notes	Failure Mode
J1125-B1	**1.09**	**R**	Buckling of the lower crimp transition zone
J1125-B2	**1.13**	**R**	Buckling of the lower crimp transition zone
J1125-R1	**1.40**	**L**	Buckling of the lower crimp transition zone
J1125-R2	**1.32**	**L**	Buckling of the lower crimp transition zone
J1125-W1	**1.49**	**L**	Buckling of the lower crimp transition zone
J1125-W2	**1.31**	**R**	Buckling of the lower crimp transition zone
J1150-R1	**1.75**	**R**	Buckling of the upper crimp transition zone
J1175-R1	**1.88**	**L**	Buckling of the lower crimp transition zone
J1175-R2	**1.75**	**R**	Buckling of the lower crimp transition zone
J1150-B1	**1.40**	**L**	Out of plane buckling at the lower crimp
J1150-B2	**1.53**	**L**	Out of plane buckling at the lower crimp
J1175-B2	**1.47**	**R**	Out of plane buckling at the lower crimp
J1150-W1	**1.43**	**L**	Out of plane buckling at the lower crimp in addition to weld failure at the bottom chord connection
J1175-W2	**1.56**	**L**	Out of plane buckling at the lower crimp in addition to weld & member fracture at the bottom chord connection
J1200-W1	**1.54**	**L**	Out of plane buckling at the lower crimp in addition to weld & member fracture at the bottom chord connection
J1250-B2	**1.62**	**R**	Out of plane buckling at the lower crimp in addition to weld & member fracture at the bottom chord connection
J1200-W2	**1.66**	**L**	Out of plane buckling at the lower crimp in addition to weld & member fracture at the bottom chord connection of the critical web member & member ***P1***
J1150-W2	**1.40**	**R**	Buckling of the crimp transition zone in addition to weld failure at the bottom chord connection
J1175-B1	**1.44**	**L**	Buckling of the crimp transition zone in addition to weld failure at the bottom chord connection
J1200-R1	**2.01**	**R**	Buckling of the crimp transition zone in addition to weld & member failure at the bottom chord connection
J1250-B1	**1.54**	**L**	Buckling of the crimp transition zone in addition to weld failure at the bottom chord connection
J1250-R1	**1.98**	**L**	Buckling of the crimp transition zone in addition to weld failure at the bottom chord connection
J1250-W1	**1.68**	**L**	Buckling of the crimp transition zone in addition to weld & member fracture at the bottom chord connection of the critical web member
J1175-W1	**1.60**	**L**	Weld and member fracture at the bottom chord connection
J1200-R2	**1.85**	**R**	Weld and member fracture at the bottom chord connection
J1250-W2	**1.98**	**R**	Weld and member fracture at the bottom chord connection
J1200-B2	**1.59**	**L/R**	Weld and member fracture at the bottom chord connection of both critical web members
J1200-B1	**1.51**	**R**	Weld and member fracture at the bottom chord connection in addition to weld failure at the bottom of member ***P6***
J1150-R2	**1.69**	**L**	Fracture along the back heel of the bottom of the angle followed by buckling of the upper crmip transition zone

Table 3 J2 critical web member failure mechanisms

Test Specimen	Ratio (Exp/Design)	Notes	Failure Mode
J2125-R1	**4.37**	**L**	In plane buckling of the uncrimped section
J2200-R2	**2.29**	**R**	In plane buckling of the uncrimped section
J2200-W2	**2.49**	**R**	In plane buckling of the uncrimped section
J2150-R2	**3.17**	**L**	In plane buckling of the uncrimped section
J2125-R2	**4.53**	**R**	Out of plane buckling at the uncrimped section
J2200-B1	**2.18**	**R**	Out of plane buckling at the uncrimped section
J2200-B2	**2.26**	**R**	Out of plane buckling at the uncrimped section
J2200-R1	**2.35**	**L**	Out of plane buckling at the uncrimped section
J2175-B1	**1.41**	**R**	Buckling of the lower crimp transition zone
J2250-R1	**1.39**	**R**	Buckling of the lower crimp transition zone
J2250-R2	**1.30**	**R**	Buckling of the lower crimp transition zone
J2175-B2	**1.97**	**R**	Out of plane buckling at the upper crimp
J2250-B1	**1.66**	**L**	Out of plane buckling at the lower crimp & fracture along the back heel of the critical web member
J2250-W1	**1.72**	**L**	Out of plane buckling of the lower crimp & weld failures at the bottom chord connection of members ***S1*** & ***P1***
J2175-W2	**2.56**	**X-TC / R**	In plane buckling of the top chord & out of plane buckling at the upper crimp
J2200-W1	**2.49**	**X-TC / R**	Local buckling of the top chord & out of plane buckling at the uncrimped secion
J2250-B2	**1.50**	**X-S1 / L**	Fracture along the back heel of ***S1*** & buckling of the lower crimp transition zone of the critical web member
J2250-W2	**1.71**	**X-S3 / L**	Fracture along the back heel of ***S3*** & weld failure at the bottom chord connection of ***S1*** & out of plane buckling at the lower crimp of the left critical web member

Table 4 J3 critical web member failure mechanisms

Test Specimen	Ratio (Exp/Design)	Notes	Failure Mode
J3150-B2	**2.17**	**L**	In plane buckling of the uncrimped section
J3175-B2	**1.83**	**R**	In plane buckling of the uncrimped section
J3200-W1	**2.25**	**L**	In plane buckling of the uncrimped section
J3175-W2	**2.44**	**R**	Out of plane buckling of the uncrimped section and local buckling of the top chord
J3200-R1	**1.47**	**R**	Buckling of the lower crimp transition zone
J3250-B1	**1.93**	**L**	Buckling of the lower crimp transition zone
J3250-B2	**2.01**	**R**	Buckling of the lower crimp transition zone
J3250-R1	**1.39**	**L**	Buckling of the lower crimp transition zone
J3250-R2	**1.36**	**R**	Buckling of the lower crimp transition zone
J3250-W1	**2.13**	**R**	Out of plane buckling at the lower crimp
J3250-W2	**2.10**	**R**	Out of plane buckling at the lower crimp

Load – Deflection Behavior

During each test, applied load data was collected and plotted versus in-plane deflection. Vertical deflection data was recorded using an LVDT at each bottom chord panel point. The *load-deflection* plots for all J2 and J3 joists share the same general behavior as the example plot given in Figure 8. The J1 plots, however, vary for the majority of the tests due to the fact that the joists did not immediately lose capacity after the critical web member initially failed. Figure 9 presents an example of the load-deflection behavior for a J1 specimen. At failure a typical J1 joist would slowly began to shed load due to local buckling, weld failure and member fracture at the bottom chord connection of the critical web member would then occur.

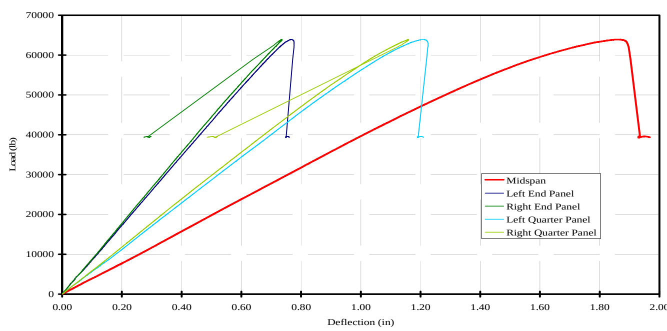

Figure 8 Load-deflection results for J3250-W1

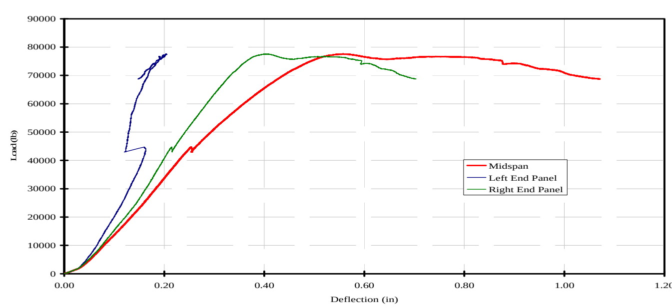

Figure 9 Load-deflection results for J1200-W2

This non-linear behavior during failure is exclusive to the J1 series joists and is most prominent in the joists with the larger web members. This phenomenon is also more pronounced in those joists that failed due to some degree of weld failure or member fracture. There were also several specimens that failed either due to local buckling or member fracture that regained stiffness after the initial local failure. After the local failure, the joists once again began taking load until the critical web member failed in a more global manner.

Non-linearity that occurs when the joist is first loaded is also a characteristic common to the J1 joists and is less obvious in the plots generated for the J2 and J3 series. This initial non-linearity can be attributed to the redistribution of load and leveling that takes place at each joist seat at very low levels of load.

DISCUSSION AND ANALYSIS

Overall Performance

The performance value that was common among all joists tested was the ratio of experimental capacity over the design capacity. In order to evaluate the data collected among different joist sizes and types, this was chosen as the baseline for all comparisons. As mentioned in the previous chapter, the design capacities that are being used are less accurate than desirable due to the basic analysis used to determine these numbers. The web members were assumed to be concentrically and axially loaded crimped compression members with prismatic section properties of symmetric angular shape. Design capacities will often be less conservative when using this type of fundamental analysis.

Overall performance values for each joist type and manufacturer that failed at the critical web member can be seen in Figure 10, while Figure 11 contains the average loads for all failure types.

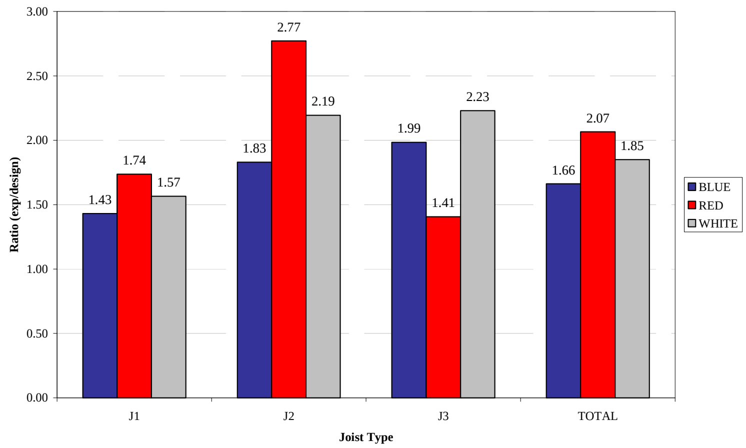

Figure 10 Critical web failures for all joist types

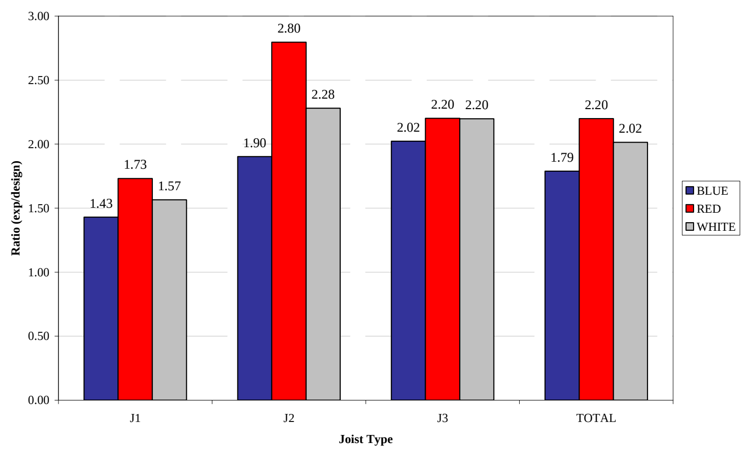

Figure 11 All failures for all joist types

Figures 10 and 11 demonstrate that the red joists failed at the highest average failure ratios for the critical web failures and for all failure types. The red joists that failed due to a critical web member failure averaged a failure ratio 2.07 while the white joists averaged 1.85 and the blue joists averaged 1.66. The red joists of all failure types failed at an average ratio of 2.20 while the white joists averaged 2.02 and the blue joists averaged 1.79. This data shows that in terms of overall performance, the red joists provided more strength than the white or blue joists.

Failure Mode Performance of Critical Web Members

In this section, the 58 critical web member failures will be categorized by seven different failure types. The failure types are buckling at the crimp transition zone, buckling at the crimp transition zone in addition to weld and member fracture, out of plane buckling at the crimp, out of plane buckling at the crimp in addition to weld and member fracture, in-plane buckling at the uncrimped section, out of plane buckling at the uncrimped section and weld and member failure at the bottom chord connection.

Buckling of the crimp transition zone is a local buckling failure that occurs when the transition zone bulges and the web member can no longer maintain its capacity. The transition zone can be defined as the location where the web member changes from its crimped shape to its natural angle shape. Table 5 shows a breakdown, in terms of joist type and manufacturer, of the eighteen joists that failed at the crimp transition zone.

Table 5 Buckling of lower crimp transition zone

	AVERAGE RATIO = *1.49*			
Buckling of the Lower Crimp Transition Zone	**J1**	*9*	**BLUE**	*6*
	J2	*4*	**RED**	*10*
	J3	*5*	**WHITE**	*2*

Table 5 shows that the J1 series joists are more likely to buckle at the crimp transition zones. These critical web members have short effective lengths that make a flexural buckling failure very difficult to achieve. Also evident from this table, is that red joists are more susceptible to this type of failure while the white joists rarely failed by buckling of the crimp transition zone. When a compression member fails locally it does not reach its ultimate global buckling capacity which explains the relatively low failure loads. The average ratio of experimental capacity versus design capacity for this failure type is the lowest when compared to six different failure modes.

The next failure type to be discussed includes a buckling of the crimp transition zone in addition to a failure of the weld or a fracture at the end of the critical web member. Table 6 shows a breakdown, in terms of joist type and manufacturer, of the seven joists that failed due to member fracture and buckling at the crimp transition zone.

Table 6 Buckling of lower crimp with weld/member failure

Buckling of the Lower Crimp Transition Zone in Addition to Weld & Member Failure	AVERAGE RATIO = *1.68*			
	J1	*7*	**BLUE**	*2*
	J2	*0*	**RED**	*3*
	J3	*0*	**WHITE**	*2*

This failure mode occurred only in the J1 series joists and happened exclusively at the bottom chord connections of the critical web member. There was an even distribution of this failure type among the three manufacturers. The failure load ratio for these joists is slightly higher than those of the joists that buckled at the crimp transition zone and experienced no weld failure or member fracture; however, the average ratio is relatively low when compared to the remaining types of critical web member failures. This can once again be attributed to the type of local buckling that caused these joists to fail.

The third failure type is out of plane buckling of the critical web member's crimped section. This type of failure occurs when the crimped section of the web member buckles at the chord connection in its weak direction, out of the plane of the joist. Table 7 shows a breakdown, in terms of joist type and manufacturer, of the eight joists that failed due to buckling of the crimp.

Table 7 Out of plane buckling at the crimp

Out of Plane Buckling at the Crimp	AVERAGE RATIO = *1.86*				
	J1	*3*	**BLUE**	*4*
	J2	*3*	**RED**	*0*
	J3	*2*	**WHITE**	*4*

This is another local buckling failure mode where the distribution among joist types is relatively even. This distribution is not even among manufacturers, as none of the red joists failed in this manner while there were four from both the blue and white groups. The average ratio for this type of failure is higher than the other local buckling modes. This means that this failure mechanism occurs when the joist is closer to reaching its global bucking capacity and therefore can handle more stress. The data indicates that the red joists are much more predisposed to buckling at the crimp transition zone than buckling out of plane at the crimp. This could be due to differences in the crimping, welding or fabrication process of the three joist manufacturers.

The fourth failure mode is out of plane buckling of the crimp in addition to a weld failure or fracture at the end of the critical web member. Table 8 shows a breakdown, in terms of joist type and manufacturer, of the seven joists that failed due to member fracture and buckling of the crimp.

Table 8 Out of plane buckling at crimp with weld/member failure

Out of Plane Buckling at the Crimp in Addition to Weld & Member Failure	AVERAGE RATIO = *1.60*			
	J1	*5*	**BLUE**	*2*
	J2	*2*	**RED**	*0*
	J3	*0*	**WHITE**	*5*

This failure type occurred mostly in the J1 series joists where the member fracture was more of a prevalent characteristic. The two J2 series failures experienced mostly a failure of the welds that occurred due to a violent “folding” of the lower crimped section. Just like the previous failure mode, there were no red joists that failed due to this mechanism.

The fifth critical web member failure mode is buckling of the uncrimped section in the plane of the joist. This is a flexural buckling failure of the entire critical web member. The uncrimped section can be defined as the portion of the web member, between the two transition zones, where the angle has returned to its natural shape. Table 9 shows a breakdown, in terms of joist type and manufacturer, of the seven joists that failed due to flexural buckling of the uncrimped section.

Table 9 In plane buckling in uncrimped section

In Plane Buckling at the Uncrimped Section	AVERAGE RATIO = *2.65*			
	J1	*0*	**BLUE**	*2*
	J2	*4*	**RED**	*3*
	J3	*3*	**WHITE**	*2*

This global failure did not occur in the J1 series joists because, as previously mentioned, local buckling occurred before the joist could reach its maximum flexural buckling capacity. There was an even distribution among the three manufacturers for this failure type. The longer, more slender members were more susceptible to this failure because of their low flexural buckling capacity compared to their tendency to locally buckle. As expected, the critical web members that failed due to global buckling reached higher capacities than those that buckled locally.

The next failure mechanism is out of plane buckling at the critical web member’s uncrimped section. This failure mode is identical to the previous one, with the only difference being the direction the buckling occurs in. Table 10 shows a breakdown, in terms of joist type and manufacturer, of the six joists that failed due to out of plane buckling of the uncrimped section.

Table 10 Out of plane buckling in uncrimped section

Out of Plane Buckling at the Uncrimped Section	AVERAGE RATIO = *2.71*				
	J1	*0*		**BLUE**	*2*
	J2	*5*		**RED**	*2*
	J3	*1*		**WHITE**	*2*

Once again, this global buckling failure did not occur in the J1 series joists but had an even distribution among the three manufacturers. The weak axis of the critical web members is in the plane of the joist, however, these members failed out of the plane of the joist. It is possible that this was caused by initial rotation of the critical web member when it was welded in between the top and bottom chords. Members that failed in this manner reached a much higher average load ratio than those members that failed locally. As expected, there is a minimal difference in failure ratio between out of plane global buckling and flexural buckling in the plane of the joist.

The seventh and final critical web member failure mode is weld failure or member fracture at the bottom chord connection. This type of failure is the only non buckling mechanism that the critical web members failed in. Table 11 shows a breakdown, in terms of joist type and manufacturer, of the five joists that failed due to weld and member fracture at the bottom chord connection.

Table 11 Weld/member fracture at bottom chord

Weld and Member Fracture at the Bottom Chord Connection	AVERAGE RATIO = *1.71*				
	J1	*5*		**BLUE**	*2*
	J2	*0*		**RED**	*1*
	J3	*0*		**WHITE**	*2*

This failure mode occurred only in the J1 series joists and was distributed relatively even among the three manufacturers. These joists failed exclusively due to member fracture and/or weld failure where local buckling did not cause the loss of load carrying capacity. The ratio of experimental capacity over design capacity for this failure mechanism was relatively low and very similar the other joists that failed due to some form of local buckling. The common behavior for this failure type was one in which the critical web member would fracture along the back heel of the angle and the crack would continue to grow and slowly split apart. These joists would not fail suddenly; rather they would slowly lose capacity over a long period of time and experience relatively large deflections.

Effects of Double Angle End Webs

During this testing program, there were twenty-three failures that occurred due some form of web member fracture at the bottom chord connection. Each of these failures occurred where a crimped member was sharing a joint with an exterior tension web. All twenty-three of these failures occurred when the exterior web member was constructed as double angles welded to the outside of the bottom chord angles. The other type of member used at this location is a solid round bar welded to the interior of both bottom chord angles. A photograph of this type of failure can be seen in Figure 12.

Figure 12 Fracture of Web Member at Bottom Chord Connection

SUMMARY AND CONCLUSIONS

This study consisted of the testing of 90 open web steel joists with crimped end critical web members. There were 30 eight foot joists, 30 twenty-two foot joists and 30 twenty-eight foot joists fabricated by three different manufacturers. Based on the results of the crimped angle web member joist study, several conclusions can be made. The failure mode data suggests that the non-critical joist members were not designed with a low enough stress ratio to ensure all of the failures would occur at the desired members. This is the result of critical web members reaching higher failure ratios than anticipated. This study also showed that, joists which failed locally, i.e. crimp transition zone failure, buckling at the crimp and member or weld fracture, did not reach failure loads as high as those reached by joists that failed globally due to flexural buckling. Failures were categorized into seven different categories.

REFERENCES

E. T. Buckley (2007) *Experimental Study of Open Web Steel Joists with Crimped Critical Web Members*, Villanova University Masters Thesis, Villanova, PA.