From Concept to Collapse

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ABSTRACT

The development of new products is essential for the continued progress of the building industry. New products can improve the performance and efficiency of building systems; however, they must as a minimum maintain the same level of public safety provided by proven existing products.

This paper presents a case study of a new cold-formed steel joist roof framing system/product. The manufacturer designed and manufactured the product, taking it from the concept stage to implementation as a product sold for use in building structures.

One of the buildings with this new roof framing system experienced a roof collapse during a rainstorm. Investigation of the collapse led to the discovery of design errors of the joist product and defects in its fabrication, leading to questions regarding the safety of this product and its suitability for use in a roof system. This case study also highlights the role of the design professional with regards to the selection and verification of new building systems and products.

INTRODUCTION

In June 2004, a large section of a warehouse roof in the Dallas/Fort Worth, Texas area collapsed during a rainstorm. The collapse caused damage to multiple tenant spaces in this warehouse building. Fortunately, there was no injury or loss of life.

The roof framing for the warehouse building consisted of a cold-formed steel joist type system. The joists were similar in profile and geometry to open web steel joists; however, the chords and webs of the trusses were fabricated with cold-formed steel shapes. The subject structure was constructed approximately three (3) years after the manufacturer developed this new roof framing product. Therefore, this cold-formed steel joist system was considered a new structural framing product.

The collapse of the roof was extensive, as indicated in Figure 1. The collapse affected the framing bays along one side of the building for a majority of the length of the building.

Evaluation of the failed joist members uncovered weld failures at the connections between cold-formed steel members of the joists. Several weld failures were observed at the interface between the weld metal and base metal. Additionally, the joists typically failed at the connection between the diagonal webs and the bottom chord, particularly at the end diagonal web. The failure pattern of the joists and other details regarding the failed joists are discussed further below.

PRODUCT CONCEPT AND DESIGN

The subject cold-formed steel joist product was developed in the late 1990's for long span applications. This product was developed at least in part to compete with conventional steel joists in the warehouse building market.

The steel shapes utilized in the joist product design consisted of rectangular channel sections with openings along one side to allow fit-up and assembly. The top and bottom chords had vertical extensions along the openings to facilitate the connections with the web members. Refer to Figures 2 and 3 for a representative view of the joists and the constituent members. It should be noted that, due to their open shapes, the joist members were susceptible to torsional instability in compression.

The web members were designed and fabricated to be connected to the chord members by welds. Due to the geometry of the connections and the chamfered corners of the web members, two predominant types of welds were utilized: flare bevel welds and fillet welds.

This joist product design was analyzed by the manufacturer using commercially available structural engineering software. This joist design analysis consisted of a traditional two-dimensional truss analysis of the individual members. Connection design was performed separately and welds were specified for each of the joist member-to-member connection points. The connection design apparently consisted only of the weld design and specification and did not include modeling for localized stress conditions at the member connections, such as Finite Element Modeling (FEM). In lieu of sophisticated FEM for the local stresses, the manufacturer performed product testing to evaluate the performance of the joists. It should be noted that the authors do not find fault with this approach, if the testing is performed in a thorough manner and in conformance with generally accepted standards (in this case the AISI Specifications). The testing procedures for the subject joist product will be discussed further in the "Manufacturing and Testing" section below.

Effective Length Factor in Design. During a review of the joist design performed by the manufacturer, the authors noted that an effective length factor of k=0.65 was used. As stated in the design manual from the manufacturer,

> *The values of "K" are generally taken as 0.65 in that all interior webs are either continuous or fully restrained by welding.*

Using k=0.65 as opposed to k=1.0 significantly increases the design capacity of the compression elements, in this case the vertical webs. In our opinion, the joist manufacturer's use of k=0.65 was (and is) not the industry standard for joist design and may be unconservative for the design of joists of this type. The industry standard for steel joists is to use k=1.0 for compression members, as is published by the Steel Joist Institute (SJI 1994) in its *Standard Specifications for Open Web Steel Joists*, *K-Series.*

In addition, the American Institute of Steel Construction (AISC 1989) states the following in its *Manual of Steel Construction: Allowable Stress Design*, 9th Edition:

> *Although translation of the joints in the plane of a truss is inhibited and, due to end restraint, the effective length of compression members might therefore be assumed to be less than the distance between panel points, it is usual practice to take K as equal to 1.0, since, if all members of the truss reached their ultimate load capacity simultaneously, the restraints at the ends of the compression members would disappear or, at least, be greatly reduced.*

Considering the subject joists, it was observed that joist chords were severely distorted in relation to the web members at several locations; indicative of a flexible connection rather than full restraint. While the use of k=0.65 in lieu of k=1.0 for compression members did not significantly contribute to the subject roof collapse discussed herein, it is the authors' opinion that the use of this k value did not conform with the industry standards and may result in unconservative roof framing designs using the new cold-formed joist product.

SJI has requirements for both the design and manufacture of joists conforming to its specification, including the submittal of detailed design data for the joists to SJI or an SJI-approved independent agency (SJI 1994). The subject joist product was not a certified or accepted SJI joist product and there was no evidence that such an independent design review was performed. Therefore this joist product was not subjected to the same scrutiny as would be an SJI-approved joist product.

It is the authors' opinion that this case study illustrates the need for new products to undergo a thorough and independent design review; and the need for Structural

Engineers to insist upon such measures before specifying a new product for use in construction.

MANUFACTURING AND TESTING

The subject joists were generally manufactured in an assembly line fashion. This included multiple welders welding the connections for each joist. After the joists were assembled and the connections were welded, the joists were dipped in paint.

The joist manufacturer performed tests on joists during the product development stage. Furthermore, during the production stage, the manufacturer implemented quality control testing for the joists. These test regimes are discussed below.

Product Development Testing. Testing of full-scale joists under load was conducted during the product development stage. Based on information available from the joist manufacturer, 18 joists were tested prior to production, and some additional tests were conducted during joist production, for a total of 41 full-scale joist tests. Of these 41 tests, 38 were performed with downward (gravity) loading and three (3) were performed with uplift loading.

The results of the product development testing indicated that the most common failure mode of the tested joists was buckling of the top chord. Buckling of the top chord would not be an expected failure mode for these joists in actual construction, where they would be connected to a roof or floor deck, and this calls into question whether manufacturer's testing sufficiently replicated the expected as-built conditions for these joists in service.

Another common failure mode during the product testing was failure at the bottom chord connections. Multiple tests indicated "tube tear out of B.C [bottom chord]" as the failure mode and some also included the note "welds critical". In a summary of the tests performed prior to production, the manufacturer stated the following:

> *Many conclusions were drawn from these initial tests* [Tests 1-18]. *It was concluded that the welds connecting the web members to the top/bottom chords were critical.*

The failure modes for the test joists were not the desired failure mode for this type of joist product. Specifically, the tear out failure at the bottom chords was a connection failure, indicating that the design capacity of the joist members was not developed. The documented bottom chord failures that were encountered during the product testing appear similar to the observed joist failures at the subject building. The evidence suggests that the manufacturer did not learn from its own testing, and proceeded to manufacture joists with deficient connections that were prone to improper modes of failure. There was no evidence of testing of isolated welded connections to test the connections separately from the full-scale joists.

The authors also discovered significant deficiency in the failure load results for the full-scale joist tests performed by the manufacturer. Section F2 ("Tests for Confirming Structural Performance") of the American Iron and Steel Institute Standard (AISI 1989 and UBC 1994) states the following:

> *…A successful confirmatory test shall demonstrate a safety factor not less than that implied in the Specification for the type of behavior involved.*

The applicable safety factors specified by the 1989 AISI Standard and the 1994 UBC were:

- 1.67 for tension members,
- 1.92 for compression members,
- 2.50 for welded connections.

Considering the actual loads for the subject structure (which was a common loading regime for a structure of this type), and using the lowest applicable factor of safety (1.67 for tension failure), only 12 of the 38 gravity load tests performed by the manufacturer failed at or above the minimum prescribed loading. Several of the recorded tests indicated failure loads of less than 75% of the equivalent expected failure load at the subject structure. Furthermore, the joist configuration used for the subject structure was not even included in the full-scale failure testing.

Due to the combination of insufficient testing and poor test performance for this joist product, the ability of the subject joists to resist the design loads was not adequately established prior to their use as roof framing members. The importance of independent verification testing for structural products and systems is highlighted by the requirements of SJI and similar organizations. Independent verification is necessary to remove bias from the test/approval program and to provide a reliable testing program on which customers and the public can rely.

Quality Control Testing. The manufacturer's quality control testing was limited to 1 out of every 50 joists, and the joists were to be tested to 110% of the design load. If the specimen passed the test, then it was to be put back into production for shipping. Therefore, there was no full-scale failure testing of the actual production joists.

In the authors' opinion, testing the joists to only 110% of the design load was insufficient for proper quality control and did not conform with the building code (1994 UBC), which required the test to meet or exceed the safety factor for confirmation of structural performance. Testing the joists only up to 110% of the design load would not be sufficient to detect manufacturing or design defects in the joists. Furthermore, based on the information available, the subject joists were not load tested, even to the 110% criteria, because this quality control testing was not implemented until after the subject joists were fabricated.

PRODUCT SELECTION AND APPROVAL

The Structural Engineer of Record (EOR) for the project was responsible for determining the suitability of this joist product for use as roof framing in the subject building structure. One common method for a manufacturer of a new product to provide product verification to architects, engineers and building officials was to have the product certified by an ICBO (now ICC Evaluation Services) report. This certification by an independent, accredited laboratory would certify that the product meets the appropriate code requirements. This joist product did not have any such certification.

For new structural framing products, the EOR should require verification of the product by independent, accredited agencies. For the subject structure, there is no evidence that the EOR received any such information regarding this joist product. Due to the deficiencies in the design, manufacture, and testing of the subject joist product, it is the authors' opinion that the EOR should not have selected and approved this product for use as roof framing.

COLLAPSE

The observations and the pattern of the roof failure at the site, in addition to the available weather data, were indicative of a gravity load failure, and roof uplift failure was ruled out as a possible or contributing cause. While the collapse occurred during a rain event, a storm drainage analysis of the subject roof indicated that the equivalent loads and stresses imposed on the individual joist members from the storm were less than those imposed by the full design loads (dead load + live load). Additionally, while the analysis of the joists under the storm loading indicated some overstressed members in *compression* (due to design errors, as discussed above), the overstresses obtained from the analysis did not exceed the factor of safety for the design. Therefore, the subject joists should not have failed under the loads imposed by the rain event.

Failure Mode. The shape of the collapsed joists did not exhibit evidence of plastic deformation (refer to Figure 4), nor was there evidence of compression failures at the joists. The primary failure mode for the collapsed joists was failure at the welded connections between the tension webs and the joist chords. The pattern of the joist framing failures and the condition of the joists after the collapse were indicative of sudden failures in the elastic range, not indicative of "ductile" failure. Furthermore, the roof collapse was extensive and was consistent with a progressive collapse, whereby an initial failure caused subsequent failures in adjacent joists and the collapse spread along the length of the building.

Welds. Weld failures were observed at the joists. The failure of many of the welds occurred at the junction between the weld and the base metal. This type of weld failure was indicative of a lack of fusion and substandard welding, which was verified by metallurgical testing and evaluation.

At some welds, paint was observed at the weld surface, as indicated in Figure 5. As noted above, the joists were painted by dipping them after the welding was completed (during the manufacturing process). The presence of paint between the weld and the base metal was therefore indicative of a gap between the weld metal and the base metal from the time of fabrication. The gap indicates inadequate fusion.

Figure 6 below shows a failed joist at the subject building, where several web members detached from the bottom chord at the connections. The failure mode for each of these connections was separation of the base metal and the weld metal, indicative of a lack of fusion as discussed above. This type of weld failure at multiple connections of adjacent web members indicates that there were multiple poor welds for this individual joist, which was one of many that failed in this manner. Based on a review of the joists at the collapse area, poor welds were frequent. A metallurgical examination of welds from the subject joists indicated that the overall weld quality was unacceptable and that some welds were so poor that they had only 0-10% of the strength of a good weld. Refer to Figures 7 and 8 for typical poor welded connections which failed.

SUMMARY

The extensive and progressive nature of this collapse indicated that the new cold formed steel joist framing was deficient with regards to both load-carrying and load-sharing capabilities. The pattern of the joist failure was sudden and violent, and was consistent with failure of the welded connections. Inconsistent welding and poor weld quality were observed at joists throughout the collapse area. The poor weld quality had a significant impact on the strength of the welds and the overall load bearing capacity of the joists. The physical evidence from the failed joists indicated that they were not properly constructed to withstand the design loading and were susceptible to collapse.

Deficiencies in the design, testing, and manufacture of the joists were discovered during the evaluation of the collapse and by evaluating available information from the manufacturer. These deficiencies, especially the manufacturing deficiencies at the welded connections, contributed to the collapse event. Additionally the design deficiencies were indicative of improper design assumptions that could result in unsafe conditions at structures using this new product.

If the EOR had reviewed the product testing and standard practices of the manufacturer, he/she would have noted a lack of a proper testing program for the joists, many joist failures at equivalent loads less than the project design loads times the factor(s) of safety, and use of non-standard effective length factors. While this does not excuse the poor design and manufacture of the joist product, Structural

Engineers should not select and specify products without proven track records or proven independent testing and design verification.

REFERENCES

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FIGURES

Figure 1. Overall view of roof collapse.

Figure 2. Web to top chord connection. Also note the weld failures.

Figure 3. Typical joist geometry. Note the failure at the end web connection at the bottom chord.

Figure 4. Collapsed joists. Note the lack of plastic deformation.

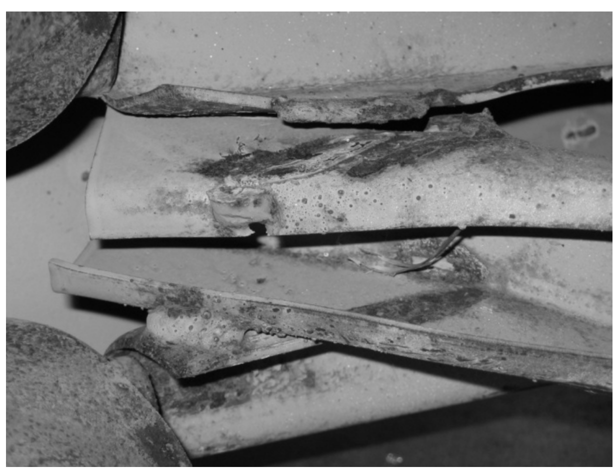

Figure 5. Close-up of weld failure. Failure was between base metal and weld metal. Note paint at surface of failed weld near middle of photo.

Figure 6. Failed joists. The webs failed at the bottom chord.

Figure 7. Failure at welded connection.

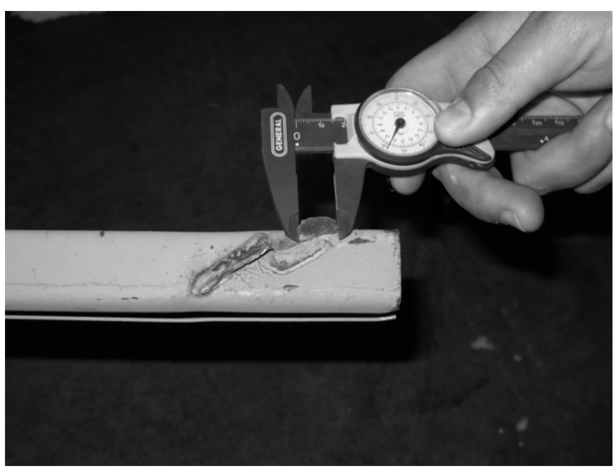

Figure 8. Failure at welded connection.