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Development of Reinforcement Schemes for Cold-Formed Steel Joists with Large Web Openings

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Abstract

The floor joists of cold-formed steel (CFS) structures may use large web openings and a cost-effective way to alleviate the detrimental effects of a large web opening is to affix appropriate reinforcements around the opening regions, to restore the original strength and stiffness of the member. The primary aim of this paper is to define the “Flexural Zone” and the “Shear Zone” and establish construction guidelines for the reinforcement schemes for cold-formed steeljoists with large web openings in these corresponding zones. To that end, a total of twenty-three laterally braced CFSjoists were simply supported and subjected to uniformly distributed loads until failure for flexural tests, which considered solid sections, circular and square web openings (65% of web depth) and sections with reinforced web openings. The reduction in the flexural strength of a cold formed steel joist section due to a large web opening is lessthan 15%. Twenty-seven joist sections were subjected to short span, mid-span point load, shear tests to establish the shear resistances of sections having a large web opening and a reinforced web opening. The reduction in the shear strength of a CFS section with a web opening may be as high as 60%. Thus, the residual shear strength of a joist witha large opening may be as low as 40%. A Virendeel type reinforcement system can restore the original shear strength of a cold-formed steel joist section. Based on these studies it is established in this paper that; The mid 40% region of a joist (0.30L and 0.70L) can be defined as “Flexural Zone” and will need flexural reinforcements. The regions outsidethe mid 40% region of a joist can be defined as “Shear Zone” and will need the shear reinforcements.

Keywords

Cold-formed Steel Joists, Construction Guidelines, Experimental, Large Web Openings, Openings Reinforcements.

1. Introduction

Cold-Formed Steel (CFS) structural members are currently widely used in small to medium size building construction, including housing projects, perhaps because the cold-formed steel design can be a cost-effective option, as compared to hot-rolled steel or other traditional construction materials such as reinforced concrete, masonry, wood, etc. Cold-formed steel floor joists are widely used in the floor construction of detached one- and two- family dwellings, townhouses, and other attached single-family dwellings. Typical cross section of such joists is a lipped channel shape. In order to keep the floor height of these structures to a minimum, the floor joists of such structures may use large web openings, which can provide the necessary pass-through space for ductwork, piping, drainage and other similar systems. Appropriate use of web openings can enhance the aesthetic appeal and can result in efficient construction of cold-formed steel floor systems. The depth of these large web openings, however, can be a substantial proportion of the beam depth. Thus, these large web openings can significantly decrease the joist strength and the failure characteristic of the entire member. Various studies exist on the flexural, shear, web crippling strengths of cold-formed steel sections having a large web opening. The current North American cold-formed steel design standard (CSA, 2016) also provides guidelines to account for the effects of such openings on the member design strength, which may be considerably low due to the presence of the large web opening. However, a cost-effective way to alleviate the detrimental effects of a large web opening is to affix appropriate reinforcements at strategic locations around the opening regions, so as to restore the original strength and stiffness of the member. Currently available Cold-formed Steel Design Standard (CSA, 2016) and Standard for Cold-Formed Steel Framing – Prescriptive Method for One and

Two Family Dwellings (AISI, 2019) provisions, however, either do not apply or do not provide adequate guidelines to facilitate the design and construction of reinforcements for floor joists with large web openings. Objectives of this investigation are to establish the effects of a large web opening on [a] flexural strength and [b] shear strength of cold-formed steel lipped channel shaped floor joists, and then to establish effective and economical reinforcement schemes for such large web openings that would restore the original flexural and the shear strengths of such floor joists, so that the original design of the joist need not be changed. Details of the first part of the investigation, establishment of reinforcement schemes for large web openings in flexural zones, has been published by Acharya, and Sivakumaran (2022), and is summarized below in Section 2. Details of the second part of the investigation, establishment of reinforcement schemes for large web openings located in primarily shear zones, has been published by Acharya, Sivakumaran and Young (2013), and is summarized below in Section 3. The primary aim of this paper is to define the "Flexural Zone" and the "Shear Zone" and establish construction guidelines for the reinforcement schemes for cold-formed steel joists with large web openings in these corresponding zones.

2. Flexural Strength of Joists with a Large Web Opening

This section discusses the flexural strength of cold-formed steel joists having a large web opening. A total of twenty three CFS joist sections [1.092 mm (43mils) thick, 203.2 mm (8") deep joist sections] were subjected to flexural tests. These tests considered solid sections, sections with unreinforced web openings and sections with reinforced web openings. Circular and square openings with 127mm (5") diameter and side, respectively, were considered for the study. The opening depth considered herein is 64.6% of the flat width of the web, and these openings were located at the center of the test specimen span. The objective of this part of the experimental investigation was to assess the effectiveness of a reinforcement schemes for flexural zone. The flexural tests were carried out on 2,743mm (9') long simply supported test specimens. Pinned and roller supports were used at the ends of the test specimen. Since, most of the CFS floor joists in practice are expected to carry uniformly distributed loads that are transferred from the floor deck, the test setup was designed to produce uniformly distributed loads on the test specimen. Such a uniformly distributed load was assumed have been created by using a series of six identical hydraulic jacks of maximum capacity of 10 ton each, connected to a single hydraulic pump. This arrangement results in equal loads on all jacks at all times.

First part of the investigation considered the flexural strength of [a] sections with no openings, [b] sections with a large circular opening, and [c] sections with a large square opening. Three identical tests were done for each case, thus, this part included nine tests. The second part of the investigation considered reinforced web openings. Three identical tests each considered the flexural strength of sections with reinforced circular and square openings, respectively. The reinforcement scheme considered herein involves screw fastening (No. 8 self-drilling screws) of bridging channels (depth 38mm, thickness 43mils) of length determined by the width of the opening plus one half of the depth of the opening on either side and plus a minimum edge distance for screws (10mm). As a result, the total length of the reinforcements was 274 mm. The reinforcement scheme consisted of two bridging channels, one along the top edge of the opening, and the other along the bottom edge of the opening. The bridging channels were screw fastened along the edges of the opening (12.7 mm(½") from the edge) at a spacing of 31.75 mm (d/4, where d is depth of the openings).

Table 1 summarizes the test results, which includes the moment resistances of the CFS sections with and without the reinforcments, sample photographs and descriptions of the the failure modes. The reduction in the flexural strength of a CFS joist section due to a large web opening (up to 65% of web height) is less than 15%. The test specimens with the proposed r/f scheme failed outside the opening and the reinforcement. The circular and square openings with reinforcement resisted 5% and 3% more moments, respectively, than the corresponding solid sections. Thus, the proposed reinforcement scheme is capable of restoring the original flexural strength of a CFS section.

It must be pointed out that the current steel framing standard (AISI, 2019) specifies two different patching schemes for a large web opening, where (a) the web openings maybe reinforced with a solid steel plate having the same size and the shape of opening, and (b) the web openings maybe patched with a CFS joist sections having same size and shape of openings. These patching schemes and other reinforcement schemes were also attempted during the course of this investigation. However, the associated results are not given herein and may be found in the paper by Acharya, and Sivakumaran (2022).

Key Observation: 1 -The reduction in the flexural strength of a cold formed steel joist section due to a large web opening (up to 65% of web height) is less than 15%.

Key Observation: 2 -The reinforcement scheme presented in this study can restore the flexural strength of cold formed steel joist sections having a large web opening (up to 65% of web height).

Table 1: Flexural strength of CFS joists with a large web opening

Test Designation	Moment at Opening Region (kN-m)	Reduction in Moment Capacity	Sample Pictures	Failure Mode
F-N	Test 1: 4.47 Test 2: 4.37 Test 3: 4.37 **Average: 4.40**	**0.00 % [Reference Test]**		Compression flange local buckling at mid-span
F-C	Test 1: 4.22 Test 2: 4.21 Test 3: 3.97 **Average: 4.13**	**-6.13 %**		Compression flange and web local buckling at opening location mid-span
F-S	Test 1: 3.68 Test 2: 3.92 Test 3: 3.75 **Average: 3.78**	**-14.09 %**		Compression flange and web local buckling at opening location mid-span
F-CRC Bridging Channel Reinforcement	Test 1: 4.60 Test 2: 4.59 Test 3: 4.66 **Average: 4.62**	**+5.00 %**		Compression flange and web local buckling out of reinforced region
F-SRC Bridging Channel Reinforcement	Test 1: 4.69 Test 2: 4.45 Test 3: 4.48 **Average: 4.54**	**+3.18 %**		Compression flange local buckling out of reinforced region

3. Shear Strength of Joists with a Large Web Opening

It is impossible to create a pure shear zone for "shear testing" because of the presence of a moment whenever there is a shear force. In practice though, a shear test is performed by creating a high shear and low moment region. Here, a 914mm (36") short span, with mid-span point load was considered as an appropriate test setup to achieve high uniform shear and low moment region. One end of the test specimen was pin-supported, whereas the other end was roller-supported in order to allow for any horizontal movements. The overall load was applied at the centre of the span using the 600kN capacity Tinius Olsen test machine and was divided into two equal loads at equal distance from the support, using a spreader beam. The test arrangement as described above results in uniform shear forces and increasing moments between the support and the load point. The concentrated loads at the load points and at the supports may cause web-crippling failure, prior to the anticipated shear failure. In this investigation the load and the support reactions were transmitted to the web of the specimen through steel brackets. Furthermore, the vertical planes of thesteel brackets were fastened to the webs of the test specimens using self-drilling screws, which was to help transfer the concentrated loads effectively into the web. The study considered mono-symmetric 203.2mm (8") deep 1.092 mm (43mils) thick galvanized lipped channel CFS sections. Mono-symmetric section is generally liable to torsional loadings, due to the fact that the shear center does not coincide with the centroid of the section. However, it is not convenient to apply a load through the shear center of a single channel section, as its shear center is outside of the section. Therefore, in this investigation two lipped channel sections with a length of about 1220 mm (48") were set face-to-face to form the test specimen. In this arrangement the torsional effects are counterbalanced by each other, since torsional restraints were provided at several locations utilizing different elements. The steel brackets that were used to prevent web crippling at the load and the support locations provide some torsional restraints at these locations. In addition, 6mm (1/4") thick steel plate strips were attached to the non-bearing flanges at load and at support locations which enhanced the torsional resistance at these locations. Short span specimen subjected to single mid-span load experiences high shear as well as high moment at the load location. Thus, this test setup simulates the high shear zones, as well as high shear-high moment conditions, which is the worst possible load-structural scenario, that exists at the over-the-support location in a continuous span joist.

Three identical tests were conducted for each case, and this paper presents the results for fifteen such tests. Solid section as well as circular and square openings with 127mm (5")-diameter and 127mm (5")-side, respectively, were considered for the study. The opening depth considered herein is 64.6% of the flat width of the web, and these openings were located in the shear span and at the mid-height of the test specimen. Table 2 summarizes the test results. The reduction in the shear strength of a cold-formed steel joist section due to the presence of a large web opening (up to 65% of web height), and in the presence of high moments, may be as high as 60%. In other words, the residual shear strength of a joist with a large opening may be as low as 40%.

Table 2: Shear strength of CFS joists with web opening in high moment regions

Test Designation	Peak Shear at Opening Region (kN)	Reduction in Shear Capacity	Sample Pictures	Failure Mode
S-N	Test 1: 12.23 Test 2: 12.56 Test 3: 12.49 **Average: 12.43**	**0.00 % [Reference Test]**		Primarily shear failure mixed in with flexural failure.
S-C	Test 1: 7.37 Test 2: 7.45 Test 3: 7.48 **Average: 7.43**	**-40.22 %**		Shear diagonal failure
S-S	Test 1: 5.10 Test 2: 5.27 Test 3: 5.06 **Average: 5.14**	**-58.65 %**		Shear diagonal failure
S-CRC Bridging Channel Reinforcement	Test 1: 12.77 Test 2: 12.86 Test 3: 13.22 **Average: 12.95**	**+4.18 %**		Shear + flexural failure out of the opening
S-SRC Bridging Channel Reinforcement	Test 1: 12.44 Test 2: 12.61 Test 3: 12.47 **Average: 12.50**	**+0.56 %**		Shear + flexural failure out of opening

The shear reinforcement scheme under consideration, which was used for both circular and square openings, is different from the flexural reinforcement scheme presented earlier, and it involves screw fastening (No. 8 self-drilling screws) of bridging channels [depth 38mm (1-1/2"), thickness 54 mils] along all four edges of the opening. Note that the bridging channels are 54mils thick whereas the main joist section is of 43mil (1.092 mm) thick. The shear reinforcements consisted of horizontal and vertical reinforcements. Horizontal reinforcements consisted of two bridging channels of length determined by width of the opening plus one half of the depth of the opening on both sides and a minimum edge distance for screws (10mm). Therefore, the total length of the horizontal reinforcements was 274 mm (10.7"). Vertical reinforcements included two bridging channels of length equal to the depth of the web of receiving channel 203mm (8 inch). One horizontal reinforcement was fastened along the top edge of the opening, and the other one was placed along the bottom edge of the opening. The channels were screw fastened at a spacing of 31.75 mm (1.25") (d/4, where d is depth of the openings) close to the opening edges within the opening region, starting from the central screw. Vertical reinforcements were placed closer to the vertical edges of the openings. Four screws were fastened at the corner of horizontal and vertical reinforcements to create a joint. This system produces a Vierendeel type reinforcement system. Associated test results are shown in Table 2. The circular and square openings with shear reinforcements resisted about 4% and 0.5% more shear, respectively, than the corresponding solid sections

(Reference Test). It is clear from the sample photographs that the specimens with the proposed shear reinforcement scheme failed at locations outside the reinforced opening location. Thus, it may be concluded that the proposed shear reinforcement scheme, a Vierendeel type reinforcement system, for web opening can restore the original shear strength of a cold-formed steel joist section.

Key Observation: 3 -The reduction in the shear strength of a cold-formed steel joist section, in the presence of high moments and due to the presence of a large web opening (up to 65% of web height), may be as high as 60%. In other words, the residual shear strength of a joist with a large opening may be as low as 40%.

Key Observation: 4 -A Vierendeel type reinforcement system proposed herein for web opening is capable of restoring the original shear strength of a cold-formed steel joist section.

4. Definition of the "Flexural Zone" and the "Shear Zone" and the Associated Reinforcement Schemes

In the analysis and design of cold-formed steel joists for house construction, it is reasonable to assume that; (1) the floor joist is subjected to uniformly distributed loads (2) the design of a floor joist is governed by the largest moment and that the moment resistance is equal to or more than the largest moment caused by the loads (3) the whole joist has a uniform cross-section, thus its moment resistance and the shear resistance are constant for the whole length of the joist, and (4) when a floor joist is selected based on moment resistance requirements, the shear resistance of that joist will be equal or more than the corresponding largest shear in the joist ($V_{resistance} \geq V_{loads}$)

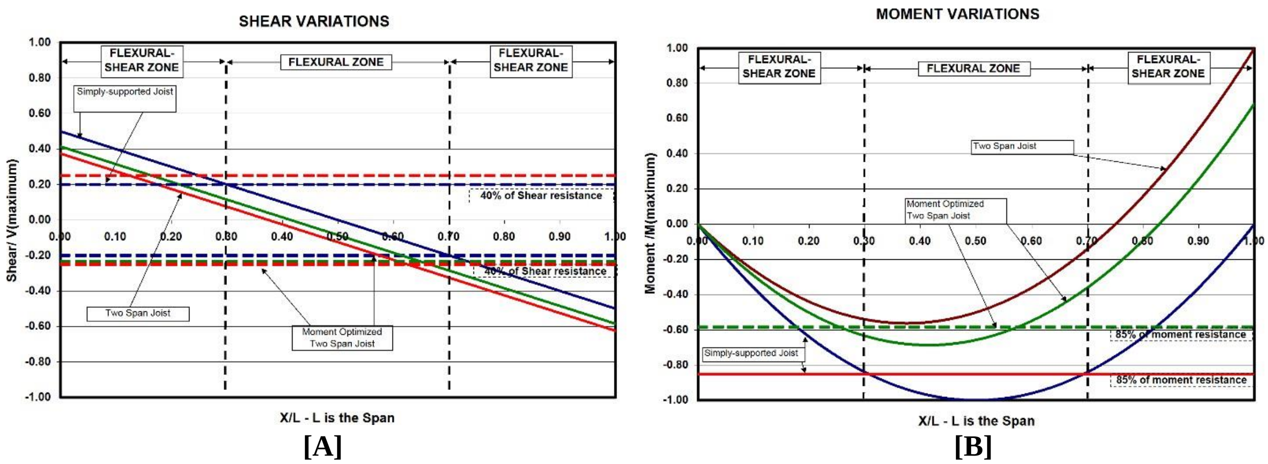

Fig. 1 [A] Shear Variations on Floor Joist, [B] Moment Variation on Floor Joist

Figure 1[A] shows the non-dimensional shear variation in a floor joist having different structural arrangements (simple support, continuous support, etc.). If the joist is simply supported, then the maximum shear (V_{max}= 0.50wL= V_{design}) occurs at the supports. Shears greater than 0.4V_{design} exist outside 0.30L and 0.70L, where L is the span length. The shears within the region 0.3L and 0.7L (mid-span region) for this structural arrangement will be less than 0.4V_{design}. If the joist is continuous over two or more spans (shown as two span joist), then the maximum shear (V_{max}= 0.625wL= V_{design}) occurs over the support. Shears greater than 0.4V_{design} exist outside 0.125L and 0.625L, where L is the span length. Choosing 0.30L and 0.70L region (mid-span region) the shear within this region for this structural arrangement will be less than 0.49V_{design}. If the joist has an over-hang and the joist had been designed such that the moment over the support is equal to moment at the mid-span (moment optimized two-span joist), then the maximum shear (V_{max}= 0.585wL= V_{design}) occurs over the support. Shears greater than 0.4V_{design} exist outside 0.18L and 0.65L, where L is the span length. Considering the region between 0.30L and 0.70L (mid-span region) the shear within this region for this structural arrangement will be less than 0.52V_{design}. Considering the three possible structural arrangements and choosing 0.25L and 0.75L region (mid 50% region) the shear within this region will be less than 0.60V_{design}. Considering the three possible structural arrangements and choosing 0.30L and 0.70L region (mid 40% region) the shear within this region will be less than 0.52V_{design}. Choosing 0.35L and 0.65L region (mid 30% region) and considering the three possible joist structural arrangements, the shear within this region will be less than 0.44V_{design}.

Figure 1[B] shows the non-dimensional moment variations in a floor joist subjected to uniformly distributed loads. If the joist is simply supported, then the maximum moment (M_{max}= $wL^2/8$= M_{design}) occurs in the mid-span. Focusing on the mid-span region, moments greater than 0.85M_{design} exist between 0.305L and 0.695L, where L is the span length. If the joist is continuous over two or more spans, then the maximum moment (M_{max}= $wL^2/8$= M_{design}) occurs over the support. Focusing on the mid-span region, no location experiences moments greater than 0.85 M_{design}. If the joist has an over-hang and the joist had been designed such that the moment over the support is equal to moment at the mid-span (moment optimized two-span joist), then the maximum moment (M_{max}= $0.686wL^2/8$= M_{design}) occurs over the support and in the mid-span region at 0.41 L. Focusing on the mid-span region, moments greater than 0.85M_{design} exist between 0.255L and 0.575L, where L is the span length. For all other structural span arrangement for the joist the maximum moment occurs either in the mid-span or at the support. Furthermore, it can be stated that regardless of the joist structural arrangement, focusing on the mid-span, moment more than 0.85M_{design} may exist between 0.255L and 0.695L, where L is the span length. Considering all possible structural arrangements and choosing 0.25L and 0.75L region (mid 50% region) the sagging moments within this region may be more than 0.84M_{design}. Considering all possible structural arrangements and choosing 0.30L and 0.70L region (mid 40% region) the sagging moments within this region may be more than 0.92M_{design}. For simply supported joists the moments within this region may be more than 0.84M_{design}. Choosing 0.35L and 0.65L region (mid 30% region) and considering all possible joist structural arrangements, the sagging moments within this region may be more than 0.98$M_{design.}$ For simply supported joists the moments within this region may be more than 0.91M_{design}.

Noting that, in general, the shear resistance ($V_{resistance}$) of a CFS joist designed based on governing moments is greater than the peak shear force due to corresponding uniformly distributed loads, and assuming that the reduction in the shear strength of a CFS joist section due to a large web opening (up to 65% of web height) would be less than 50%, it can be observed that the for all possible structural arrangements, the shear force within the mid 40% region of a joist (0.30L and 0.70L) will be less than 50% of the shear resistance of the joist. Thus, the openings in the mid 40% region of a joist will not need the shear reinforcements, however, such openings will need the flexural reinforcements. Since the shear forces outside the mid 40% region of a joist (0.30L and 0.70L) may be more than 50% of the shear resistance of the joist, and may be subjected to high moments, openings located in regions outside the mid 40% of the joist will need the shear reinforcements. Since the shear forces within the mid 40% region of a joist (0.30L and 0.70L) is less than 50% of the shear resistance of the joist no shear reinforcements are needed. However, since the moments within the mid 40% region of a joist (0.30L and 0.70L) is more than 85% of the moment resistance of the joist, openings located in regions within the mid 40% of the joist will need the flexural reinforcements. Therefore, the mid 40% region of a joist (0.30L and 0.70L) can be defined as “Flexural Zone” and will need flexural reinforcements for openings in this region. The regions outside the mid 40% region of a joist (0.30L and 0.70L) can be defined as “Shear Zone”, and openings located in regions outside the mid 40% of the joist will need the shear reinforcements.

5. Conclusions

The floor joists of Cold-Formed Steel (CFS) structures frequently require large web openings, which can enhance the aesthetic appeal and the constructional efficiency of floor systems. The test program considered flexural resistances and the shear resistances of CFS sections with large web openings. The tests considered circular and square openings. The reduction in the flexural strength of a cold formed steel joist section due to a large web opening (up to 65% of web height) is less than 15%. The reduction in the shear strength of a cold-formed steel joist section due to the presence of a large web opening (up to 65% of web height), and in the presence of high moments, may be as high as 60%. In other words, the residual shear strength of a joist with a large opening may be as low as 40%. Since the shear forces outside the mid 40% region of a joist (0.30L and 0.70L) may be more than 50% of the shear resistance of the joist, and may be subjected to high moments, openings located in regions outside the mid 40% of the joist will require shear reinforcements. Since the moments within the mid 40% region of a joist (0.30L and 0.70L) is more than 85% of the moment resistance of the joist, openings located in regions within the mid 40% of the joist will require the flexural reinforcements. Thus, the mid 40% region of a joist (0.30L and 0.70L) can be defined as “Flexural Zone”, and will need flexural reinforcements for openings in this region. The regions outside the mid 40% region of a joist (0.30L and 0.70L) can be defined as “Shear Zone”, and openings located in regions outside the mid 40% of the joist will need the shear reinforcements. The effectiveness of the reinforcements for floor joists of Cold-Formed Steel (CFS) having large web openings depends on the reinforcement type and its length, screw spacing and screw pattern.

Based on the results presented in the previous sections, the following key observation was made. The flexural reinforcement scheme, consisting of two parallel channels fastened along the compression and tension edges of the opening, considered in this study can restore the flexural strength of cold formed steel joist sections having a large web opening. Thus, the reinforcement details shown in Figure 2[a] are proposed for the flexural zone. The shear reinforcement scheme, a Vierendeel type reinforcement system, for web opening is capable of restoring the original shear strength of a cold-formed steel joist section. Thus, the reinforcement details shown in Figure 2[B] are proposedfor the shear zone.

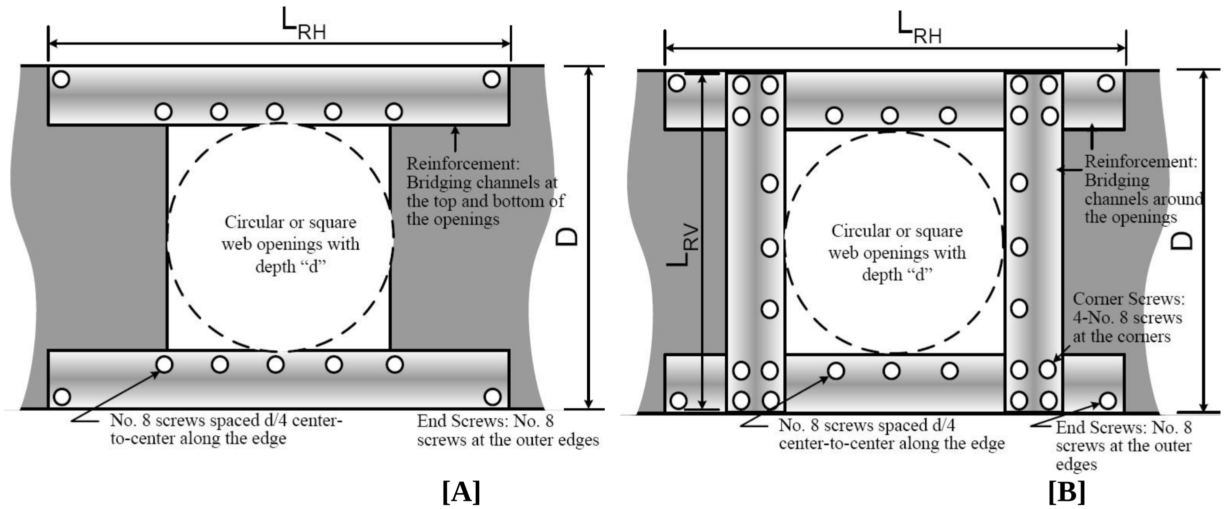

Fig. 2 Proposed Reinforcement Scheme for [A] Flexural Zone, [B] Shear Zone

References

Acharya, S.R. and Sivakumaran, K.S. (2022), "Reinforcement Schemes for Cold-Formed Steel Joists witha Large Web Opening in Flexural Zone - An Experimental Investigation", Canadian Journal of CivilEngineering, Volume 49, DOI: https://doi.org/10.1139/cjce-2021-0057

Acharya, S.R. and Sivakumaran, K.S., and Young, B. (2013), "Reinforcement schemes for cold-formed steel joists with a large web opening in shear zone—An experimental investigation", Thin-Walled Structures, Volume 72, November 2013, Pages 28–36.

AISI (2019), Standard for Cold-Formed Steel Framing – Prescriptive Method for One and Two Family Dwellings, (AISI-230-19), American Iron and Steel Institute, Washington, DC.

CSA (2016), North American Specification for the Design of Cold-Formed Steel Structural Members.
S136-16, Canadian Standards Association Group, Toronto, Ontario, Canada.