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EFFECTS OF VERTICAL SLOTTED HOLE ON COLD FORMED STEEL Z-SHAPE LAPPED PURLINS

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Lapped joints of cold-formed steel Z-shaped purlins are extensively used in metal building roof construction to create multi-span purlin systems. Conventionally, round holes are used in the lapped purlin connections. With the advantage of providing extra installation tolerance, vertical slotted holes are widely used in the lapped joints of cold-formed steel Z-shaped purlin systems to simplify and expedite the erection of multi-span purlin roof systems. However, the current design practice is based on the research for the lapped connections with round holes. Almost no research has been conducted to investigate effects of vertical holes on the flexural behaviour of cold-formed steel Z-shaped purlins. To investigate the effects of vertical slotted holes on the structural behaviour of lapped cold-formed steel Z-shaped purlins, tests were performed on the lapped purlins with different lap lengths, purlin depths, thicknesses and spans. The results show that the flexural strength and stiffness of the lapped purlins with vertical slotted holes are primarily influenced by three parameters, i.e., the ratio of lap length to purlin depth, the ratio of lap length to purlin thickness, and the ratio of purlin depth to purlin thickness. Based on the test results, design recommendations are proposed for designing lapped cold-formed steel Z-shaped purlins with vertical slotted holes.

Keywords: Cold-formed steel Z-section purlin, Bolted lapped connection, Combined bending and shear, Flexural strength and stiffness, Effective flexural rigidity.

1 INTRODUCTION

Cold-formed steel (CFS) Z-shaped purlins are extensively used in multi-span roof systems since the Z-shaped purlins can be lapped at the supports to provide a continuous structural member. For joining two lapped purlins at the supports, bolted connections are the most popular solutions, and round holes are conventionally used for such connections. In the past decade, a number of studies have been conducted on the structural behaviour of bolted connections between the lapped CFS Z-shaped purlins. Tests performed by Ho and Chung (2004) showed that the semi-continuity of lapped purlins was dependent on the stress level, the connection configuration, and the lap length-to-section depth ratio. Chung and Ho (2005) subsequently found that connection capacities of lapped purlins were governed by the combined bending and shear of the single section at the end of the lapped connections. Recently, Pham *et al.* (2014) confirmed that the flexural strength of lapped connection was governed by combined bending and shear of the critical section at the end of the lap. However, all the foregoing studies were primarily focused on lapped connections with round holes and Z-shaped purlins with unequal top and bottom flange widths. With the advantage of providing extra erection tolerance, vertical slotted holes are widely used in the lapped joints of cold-formed steel Z-shaped purlin systems. The extra tolerance at the connections allows two identical purlins with the same top and bottom flange width to nest together. It facilitates the fabrication, reduces the transportation and storage cost by providing more effective stacking, and also expedites the erection of multi-span Z-shaped roof purlins. However, almost no research has been conducted so far on effects of vertical slotted holes on the flexural behaviour of cold-formed steel Z-shaped purlins.

Presented in this paper are the results of an experimental study on the flexural behaviour of lapped CFS Z-shaped purlin with vertical slotted connections. 42 tests were performed on lapped Z-shaped purlins for three different purlin depths and thicknesses. Purlins with section depths of 203 mm (8 in) and 254 mm (10 in) were tested for 10 gauge (3.429 mm, or 0.135 in), 13 gauge (2.286 mm, or 0.090 in) and 16 gauge (1.524 mm, or 0.060 in) thicknesses with lap lengths of 0.864 m (34 in) and 1.524 m (60 in). The 305 mm (12 in) purlins were tested for 10 gauge (3.249 mm, or 0.135 in), 12 gauge (2.667 mm, or 0.105 in) and 14 gauge (1.905 mm, or 0.075 in) thicknesses with lap lengths of 0.864 m (34 in), 1.219 m (48 in) and 1.524 m (60 in). For each section depth, a specified span of specimen was used, i.e. 3.048 m (10 ft) for 203 mm (8 in) purlins, 4.572 m (15 ft) for 254 mm (10 in) purlins and 6.096 m (20 ft) for 305 mm (12 in) purlins. In addition, 6 confirmatory tests were performed on continuous 305 mm (12 in) purlins at same thicknesses as the lapped 305 mm (12 in) purlins to act as a baseline and to verify the calculated flexural strength and stiffness of the non-lapped purlins.

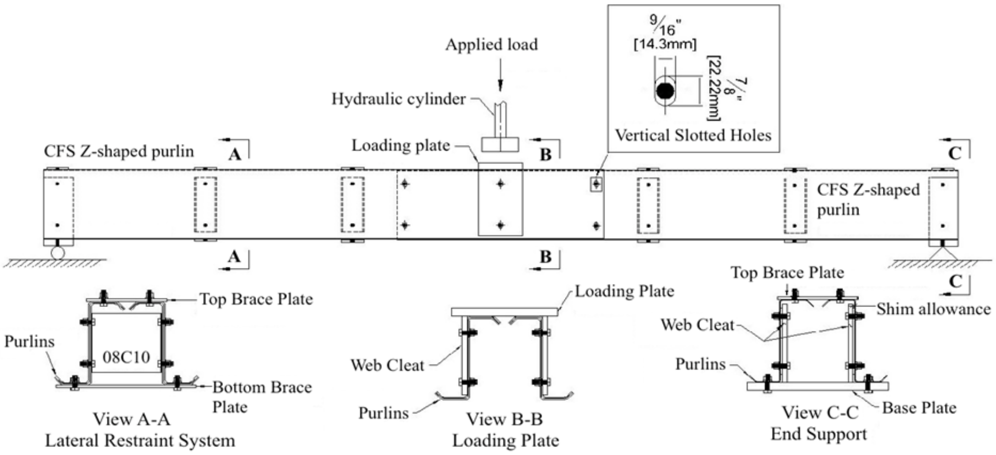


Figure 1. Test Specimen Assembles Details.

The arrangement of lapped Z-shaped purlin test was shown in Figure 1. The connection configurations are commonly used for lapped purlins in the North American metal building industry. The webs of the lapped Z-shaped purlins are connected using six 12.7 mm (1/2 in) diameter bolts, four outer bolts are used to resist the flexural bending and shear, and two inner bolts at the centerline of the lap are used to connect the web cleat of the loading plate to resist lateral loads. Vertical slotted holes with dimensions of 14.3 mm×22.2 mm (9/16 in×7/8 in) were used in the lapped section for connecting the webs of the Z-sections. Standard holes with a diameter of 14.3 mm (9/16 in) were used for bolts at end reaction supports and internal braces.

Specimens were supported at the ends and loaded with a single point load applied at mid-span with a constant rate of displacement of 6.1mm (0.24in) per minute until failure. Mid-span vertical deflections of the specimens were recorded using linear motion transducers. All steel materials conformed to requirements of North American Specification for the Design of Cold-Formed Steel Structural Members (2012) with 50ksi minimum yield strength. Standard tensile coupon tests were performed according to ASTM standard E8 (2011) to determine the mechanical properties of the test specimens. Section properties were calculated based on AISI S100 (2012).

2 TEST RESULTS AND DISCUSSION

The section failure location of the lapped purlins in all tests was just outside the end of the lap caused by combined shear and bending. The top flange was subjected to compression stress due to the bending, and was found to always initiate the failure. The applied load dropped rapidly once the top flange buckled, then the failure extended to the webs. The shear buckling of the web section was also observed just outside the end of lapped connections. Significant cross-section distortion of the Z-section occurred at the end of the lap with large deformation. After examining the dissembled tested specimens, no bearing deformation was found at the bolt holes.

2.1 Flexural Strength

For the six confirmatory tests of non-lapped purlins, the maximum flexural strength was evaluated at mid-span of each test specimen. The results were compared to the nominal section strength of the purlin, which was calculated based on the initiation of yielding of the effective section according to AISI S100 (2012). The mechanical properties obtained from standard coupon tests were used in the calculation of the maximum flexural strength of non-lapped purlins. The average difference between the tested and the calculated flexural strengths of non-lapped purlins was 8%. This difference was considered as low enough that the calculated flexural strength of non-lapped purlins could be used as the benchmark to compare with the tested flexural strengths of lapped purlins.

For the 42 lapped purlins tests with vertical slotted holes, the maximum flexural strength was also evaluated at mid-span of the test specimen and compared to the benchmark, which was the calculated nominal section strength of non-lapped purlins. The results indicated that flexural strength of Z-shaped purlins was enhanced by the lapped connection with vertical slotted holes. The moment resistance of the lapped purlins was dependent on the ratio of lap length to purlin depth and the ratio of purlin depth to purlin web thickness. In order to achieve the full strength of continuous purlins, the lap length of the connections should be at least 3.0 times of the purlin depth. The suggested minimum lap length to section depth ratio of 3.0 indicated in AISI S100 (2012) was verified for lap connections with vertical slotted holes. Also, the maximum purlin depth to purlin web thickness ratio should be limited to 155 when designing the lapped connection with slotted holes (Liu 2014).

2.2 Flexural Stiffness

For the six confirmatory tests of non-lapped purlins, the tested vertical deflection (Δ_t) at mid-span was taken at 60% of the ultimate load of the non-lapped purlins. For serviceability analysis, 60% of the ultimate load was used as a practical approximation of the service load level (P_s). The tested stiffness (K_t) of non-lapped purlins was calculated by using equation (1).

$$K_t = \frac{P_s}{\Delta_t} \tag{1}$$

where P_s is service load which taken at 60% of the ultimate load and Δ_t is the corresponding vertical deflection at the service load P_s.

For a simply supported beam with a concentrated load applied at mid-span, the flexural stiffness (K_d) for the serviceability design of non-lapped purlins was determined by using equation (2).

$$K_d = \frac{P_s}{\Delta_d} = \frac{48\,EI_e}{{l_t}^3} \tag{2}$$

where I_e is the effective moment of inertia computed at $f = 0.6\,F_y$, l_t is the total length of the specimen, and E is the modulus of elasticity of steel.

Table 1. Deformation and Flexural Stiffness of Non-lapped Purlins.

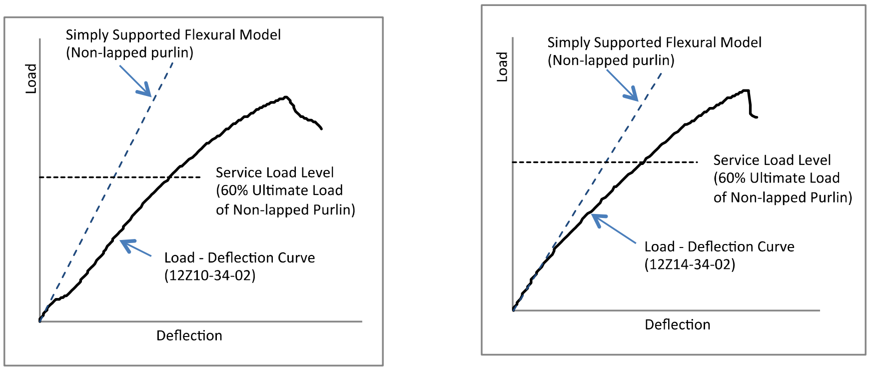
Non-lapped purlins^1	**Deflection Δ_t (in.)**				**K_t (kip/in)**	**K_d (kip/in)**	**$\frac{K_t}{K_d}$**
	Test 1	**Test 2**	**Avg.**	**Deviation**			
12Z10	0.900	0.896	0.898	±0.19%	5.19	5.66	92%
12Z12	0.862	0.845	0.853	±0.98%	4.24	4.79	89%
12Z14	0.721	0.731	0.726	±0.69%	3.04	3.26	93%
						Average	**9%**

Metric Conversion: 1 in. = 25.4mm, 1 kip/in = 175 kN/m

[1] Purlin designation: for example, 12Z10 represents the specimen for 12-inch Z-shaped purlins with 10-gauge (0.135 inch) thickness.

According to Table 1, the tested flexural stiffness (K_t) of a single section was calculated based on the average vertical deflection (Δ_t) of the purlins in two identical tests. The results showed that the tested flexural stiffness of the 12-inch non-lapped purlins was 9% lower than its calculated flexural stiffness. The difference was low enough that the calculated flexural strength of non-lapped purlins could be conservatively used as the benchmark to compare with the tested flexural strengths of lapped purlins.

For the 42 lapped purlins tests with vertical slotted holes, the flexural stiffness (K_t) of the lapped purlins was also calculated by using equation (1) at service load level. The results were compared to the calculated flexural stiffness of non-lapped purlins (K_d), which was the benchmark and was determined using equation (2). The results indicted that the stiffness improvement was very limited for lapped purlins with vertical slotted connections. The vertical slotted holes provided extra tolerance at bolt holes to facilitate the installation but considerably increased the connection flexibility. In order to study the reduced stiffness of lapped connections, the mid-span load-deflection curve for each specimen was plotted. Two typical shapes of load-deflection curve were found and are shown in Figure 2.



a) Thick Gauge Purlin

b) Light Gauge Purlin

Figure 2. Typical Load - Deflection Curves.

The flexural deformation curves of simply supported non-lapped purlins based on equation (2) were compared to the results of the tests. The stiffness of the lapped purlins is represented by the slope of the load-deflection curve. At the early stage of loading, the stiffness of the lapped purlin is the same as that of a non-lapped purlin. As the applied load increases, the stiffness of the lapped purlin decreases. This result is consistent with the observed connection rotation and cross-section distortion at the edge of the lap. In Figure 2(a), a sudden drop in the slope occurred for thick gauge lapped purlins. However, in Figure 2(b), the slope decreases slowly for light gauge purlins. The plateau of the load-deflection curve for the thick gauge purlins is caused by the initial slip at the lapped connections.

When two purlins lap together, they cannot be nested properly if the sections of the two purlins are identical as shown in Figure 3(a). Practically, there is always a gap between the two Z-sections. The vertical slotted holes at the same location on each purlin provide the extra tolerance at the connections. When the load is applied it is transferred through the bolts at the connections and the two top flanges. The load pulls the upper purlin down until the two vertical slotted holes align with each other and bear together as shown in Figure 3(b). The gap between two lapped purlins is related to the thickness and stiffness of the Z-sections. For thick gauge purlins, the thickness is large and the flanges are stiff. The two purlins are forced to fit to each other, so the gap is large and the initial slip is significant, which is shown as the plateau of the load-deflection curve. For light gauge purlins, the thickness is small and the flanges are relatively flexible. The two purlins fit properly, so the gap is minor and the initial slip is negligible.

a) Unloaded shape b) Loaded shape

Figure 3. Initial Gap of Lapped Section.

Therefore, the thickness of the section influences the stiffness of lapped connection. In order to achieve the full flexural stiffness of continuous purlins, the lap length to purlin thickness ratio should be equal to or greater than 935, and the lap length of the connection should be at least 7.7 times the purlin depth (Liu 2014).

3 CONCLUSION

The moment resistance of CFS Z-shaped purlins is enhanced by the lapped connection with vertical slotted holes. The presence of vertical slotted holes at lapped connections provides the extra installation tolerance, but substantially increases the connection flexibility and results in a major impact on the flexural stiffness of lapped purlins compared to non-lapped purlins. The ratios of lap length to purlin depth, lap length to purlin thickness, and purlin depth to purlin thickness have primary influences on the flexural strength and stiffness of the lapped purlins. To achieve the full flexural strength and stiffness of continuous purlins, the three parameters need to be carefully selected when designing lapped connection with vertical slotted holes.

References

Chung, K. F., and Ho, H. C., Analysis and Design of Lapped Connections between Cold-formed Steel Z sections, *Thin-Walled Structures*, Elsevier, 43(7), 1071-1090, March, 2005.

Ho, H. C., and Chung, K. F., Experimental Investigation into the Structural Behaviour of Lapped Connections between Cold-formed Steel Z Sections, *Thin-Walled Structures*, Elsevier, 42(7), 1013-1033, March, 2004.

Liu, J., *Structural Behaviour of Lapped Cold-Formed Steel Z-Shaped Purlin Connections with Vertical Slotted Holes*, MSc., Thesis, University of Waterloo, 2014.

Pham, C. H., Davis, A. F., and Emmett, B. R., Numerical Investigation of Cold-formed Lapped Z Purlins under Combined Bending and Shear, *Journal of Constructional Steel Research*, Elsevier, 95, 116-125, January 2014.

North American Specification for the Design of Cold-Formed Steel Structural Members AISI S100-2012, American Iron and Steel Institute, Washington, DC, 2012.

Standard Test Methods for Tension Testing of Metallic Materials, American Society for Testing and Materials, West Conshohocken, PA, 2011.