Review Article

Flexural Behavior of lapped connections in multi-span cold-formed Z-purlins

ABSTRACT

Aims: Study the flexural behavior of the lapped connections in multi span cold-formed steel Z sections systems.
Study design: The effect of overlap length of the lapped connections was investigated in order to achieve the optimum overlap length/depth ratio. Different bolts arrangements were studied to connect lap splice. Also, a new method using epoxy was supposed and studied to connect lap splice. The effect of web stiffening and flange stiffening of the lapped connection were also investigated in this study.
Place and Duration of Study: The R.C. and Materials laboratory, Benha Faculty of Engineering, Benha University, Egypt, between February 2013 and May 2015.
Methodology: Seventeen full scale specimens with lapped connections were prepared and experimentally tested taking into account the variables of this study.
Results: The experimental results included ultimate load, vertical deflection at mid-span and mode of failure.
Conclusion: As expected, the length of lapped connection clearly improved the flexural behavior of the tested specimens. The bolts arrangement at lap splice was very important in increasing the strength and stiffness of lapped connection. The experimental results showed that using epoxy was a practical and good method to connect lap splice. Both web stiffening and flange stiffening delayed the local buckling of lapped connection. However, the flange stiffening produced a more improvement of local buckling resistance.

Keywords: [Purlins, Overlaps, Cold-formed, Connection}

1. INTRODUCTION

Cold-formed sections have been used in car bodies, high way barriers and in secondary structural elements including roof and wall systems. Cold-formed sections are fabricated from steel sheets, strips or plates, where their thickness is typically between 0.5 and 6 mm. In the last 20 years cold formed sections have also become popular for primary structures, particularly in domestic, agricultural, light commercial and light industrial applications. In last decades, many researchers studies structural behavior of cold-formed steel beams. Instability phenomena, such as local, distorsional, lateral-torsional buckling and their interactions, all this studies based on simply supported beams.

In single storey industrial buildings and low to medium rise offices and warehouses, cold-formed steel sections are widely used as secondary structural members such as purlins to support roof cladding. Four different types of purlin systems may be found in modern roofs with different degrees of continuity: single span, double span, multi-span with sleeves, and multi-span with overlaps.

As its effective stacking and easy connection, multi-span cold-formed steel Z purlin systems with lapped connections over the internal supports are the most popular purlin systems used in practice. Lapping configuration is the most important parameter affects on the load capacity of Z purlin systems. Weak technical data for designer engineers to assess the structural behavior of this type of connections, force the researchers to develop and study a full-scale samples study its structural behavior.

Recent developments of using lapped connections in multi-span cold formed steel Z purlins have been increasing lately.

An experimental study of the behavior of lapped connections between cold-formed steel Z sections was presented by Chung K.F. et al (2004). A total of 26 one point load tests on lapped connections between Z sections with various lap lengths, test spans and a practical configuration for generic lapped connections were carried out. The strength and the deformation characteristics of these connections were monitored. Among all tests, section failure at the end of lap under combined bending and shear was observed to be critical in the connected Z sections. This study concluded that the moment resistance and the flexural rigidity of lapped connections did not depend only on the lap length to section depth ratio, but also on the lap length to test span ratio. The assumption that lapped sections always doubles the moment resistance and flexural rigidity of those of connected sections was not always correct. Also, it was observed that ‘full strength laps’ and ‘full stiffness laps’ may be obtained in lapped connections provided that the lap length to section depth ratios are equal to or larger than 2.0 and 4.0, respectively.

Zhang L. et al [2007] presented an experimental investigation on the structural behavior of lapped connections over the internal supports in multi-span cold-formed steel Z purlin systems. The tests of moment resistance and effective flexural rigidity were prepared on two typical connection configurations, i.e. web bolts plus self-drilling screws at both flanges or at the top flange only. This study concluded that the edge section of lapped connection is the most critical section of the lapped connection. The load-carrying resistance of tested lapped connections is dominated by the bending moment. The moment resistance of internal support section is almost twice that of edge sections of lapped connections, which imply only the edge sections, are necessary for strength checking in practical applications. The self-drilling screws at the bottom flange have a slight effect on the moment resistance of lapped connections but do not have a notable influence on the flexural rigidity of lapped connections. The length of lapped connection has a significant effect on its effective flexural rigidity.

Dubina D. et al [2010], assumed that purlins were semi-continuous at the junction between the single and lapped sections, and proposed to take into account the web crippling action at the edge of the lapped zone in interaction with the bending moment. In author’s opinion, this type of interaction is a new approach compared with the traditional interaction bending moment and shear force. Based on this assumption, relevant design formulae were proposed for both strength and stability checking, accounting for different types of overall and local stress interactions. For validation, numerical and experimental tests results obtained from the review were used for the comparison with results obtained based on these assumptions. This study concluded that the lap edge single section was found to be the most critical point for design in the case of multi-span lapped bolted connection Z-purlins, and the interaction of bending moment with web crippling is the relevant criterion. Also, the study confirmed that the lateral torsional buckling should be checked for cold-formed steel purlins which are laterally unrestrained.

This article aims to study the behavior of lapped cold-formed steel Z sections. Mode of failure, ultimate load, and the vertical deflection at mid-span are observed and recorded to examine the flexural behavior of lapped connections in multi span cold-formed steel Z purlin systems.

2. EXPERIMENTAL PROGRAM

As mentioned from previous works, and our main target to increase the ultimate load carried by a lapped splice, we supposed the following four parameters. The length of the lap splice, the arrangement of bolts at lap splice, using epoxy resin to connect the lap splice and the stiffness of lap splice are the main parameters which were proposed to investigate experimentally their effects on the behavior of the tested specimens. Seventeen full-scale steel specimens with lapped connections were prepared and experimentally tested. It should be noted that in general, instead of carrying out prolonged and expensive full-scale testing in order to examine the behavior of lapped connection, regardless the length of span test, it is sufficient to test the lapped connections of reduced section lengths. This length affect ultimate moment, and it's a structure concept for continuous beams, as shown in figure 1, the main effective tested part which represents the lap connections was taken as the distance between points of zero moment. Points of zero moment were nearly at a distance of quarter span length from each supports. Assuming the practical full span of the purlin equal to 4800 mm so, the effective length of the tested specimen was taken equal to 2400 mm which equal to half span length. Z shape cold-formed steel section with plate thickness equal to 1.5 mm was used. Figure 2 shows the details of Z section used for all tested specimens of this study. Bolts of 12 mm diameter (M12) and grade 8.8 are used for all specimens.

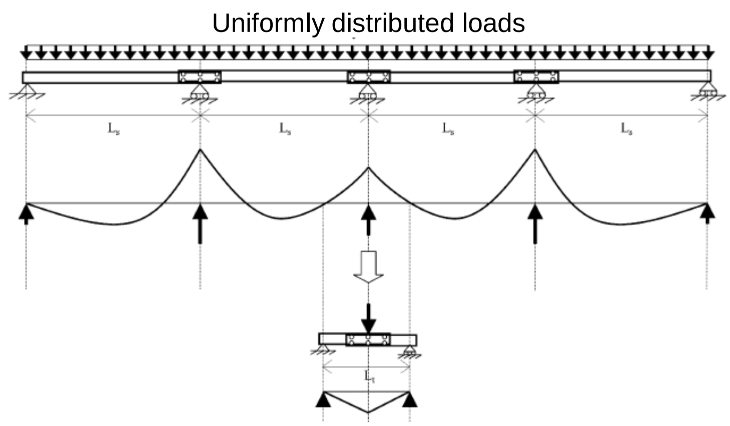


Fig. 1. Multi-span purlin systems with overlaps

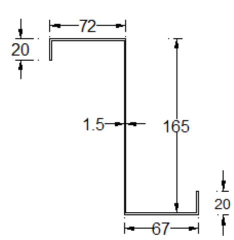
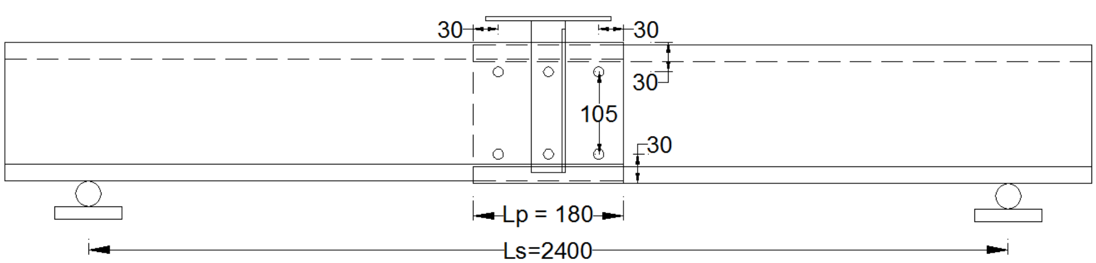


Fig. 2. Details of cold formed Z section (all dimensions in mm)

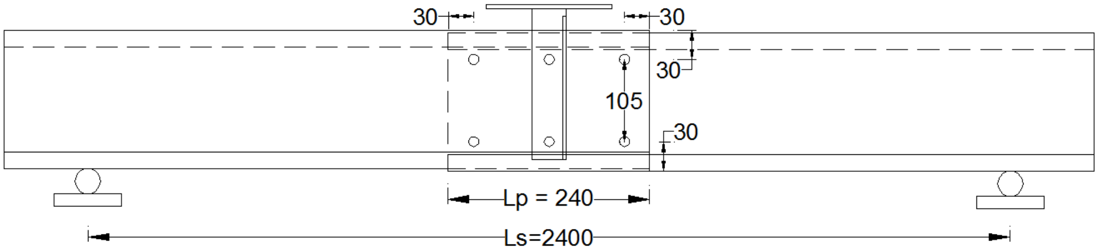
The four mentioned parameters correspond to the test series A, B, C, and D, respectively, as presented in table 1 which summarized the experimental program of this study. To study the effect of lap splice length, five specimens (A180, A240, A300, A600 & A900) were prepared with 180, 240, 300, 600 and 900 mm lap lengths, figure 3 (a-e) show the details of these specimens. To study the effect of bolts arrangement, three specimens (B300-1, B300-2 & B300-3) were prepared with 300 mm lap length and three different bolts arrangements (all comparisons between these arrangements were taken for the same lap length, i.e. all results taken in this length can be applied for any length), as shown in figure 3 (f-h). To study the new technique which proposed to connect the lap splice by using epoxy resin, four specimens (C180, C240, C300 & C600) were prepared with 180, 240, 300 and 600 mm lap lengths, as shown in figure 3 (i-l). To study the effect of lap splice web stiffening, four specimens with 240 mm lap splice length were prepared by various web stiffening schemes. The web stiffness of the lap splice was improved by extending the web of spliced Z section members on both sides of the lap splice by 120, 240, 360 & 480 mm, which correspond to the specimens D240-1, D240-2, D240-3 & D240-4, respectively, as shown in figure 3 (m-p). To study the effect of lap splice flange stiffening one specimen with 300 mm lap splice length was prepared. The flange stiffness was improved by using four equal angles of 40x4 mm size (specimens D300-5), as shown in figure 3 (q).

Table 1. Experimental Program

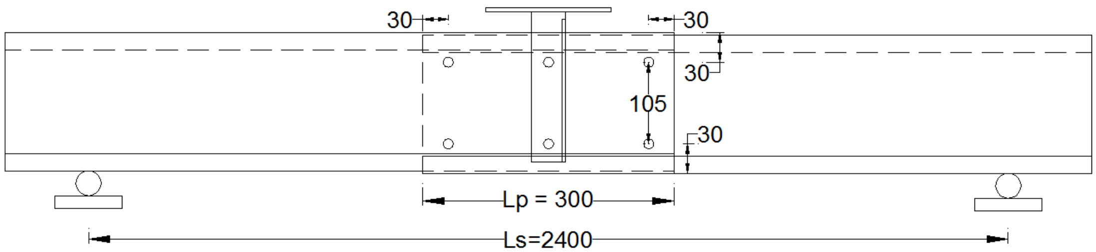
Test series	Specimen	Lap length Lp [mm]	Parameter study
A	A180	180	Length of lap splice
	A240	240	
	A300	300	
	A600	600	
	A900	900	
B	B300-1	300	Arrangement of bolts
	B300-2		
	B300-3		
C	C180	180	Using epoxy to connect the lap splice
	C240	240	
	C300	300	
	C600	600	
D	D240-1	240	Stiffness of lap splice, by gradually changing section stiffness, as shown in Fig.3 (m-p).
	D240-2		
	D240-3		
	D240-4		
	D300-5	300	Stiffness of lap splice, by applying four angles at flanges, as shown in Fig.3 (q).



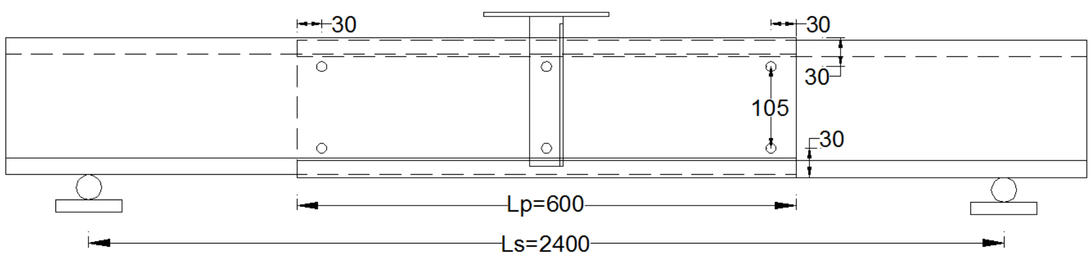
(a) A180



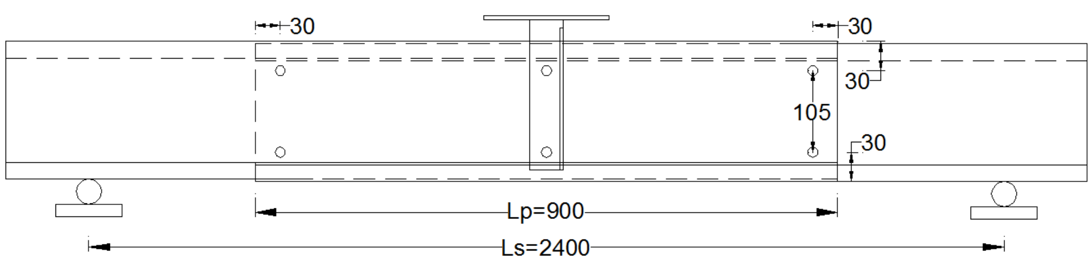
(b) A240



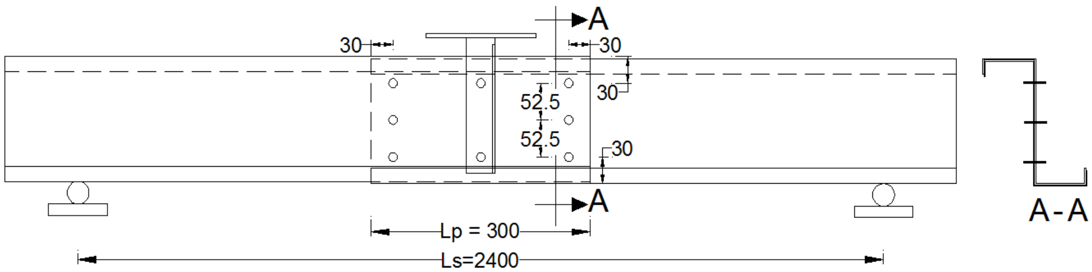
(c) A300



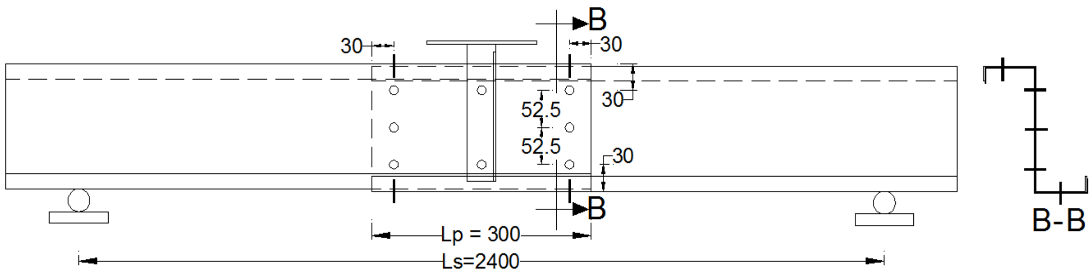
(d) A600



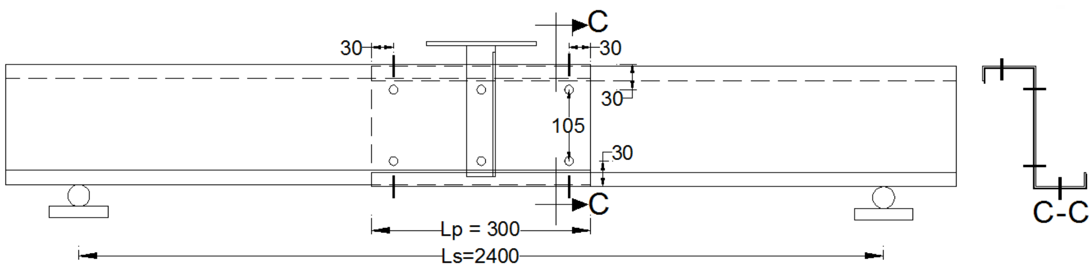
(e) A900



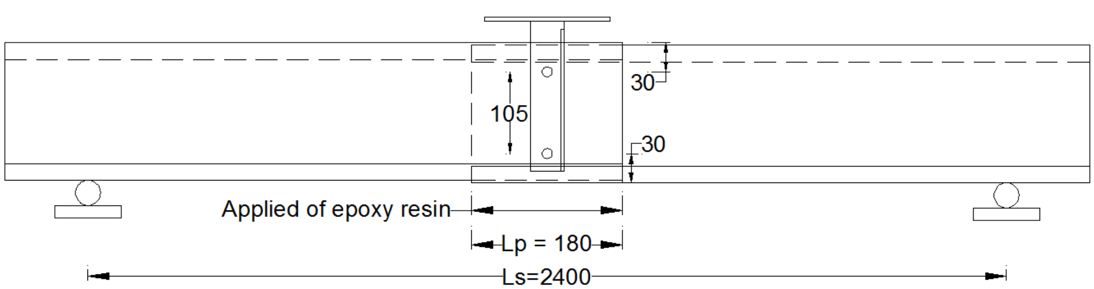
(f) B300-1



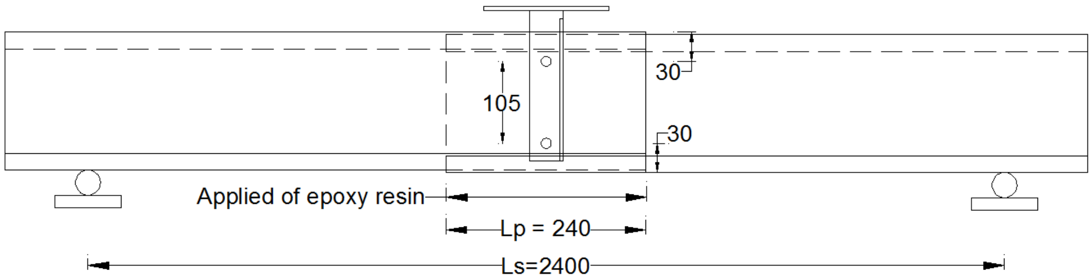
(g) B300-2



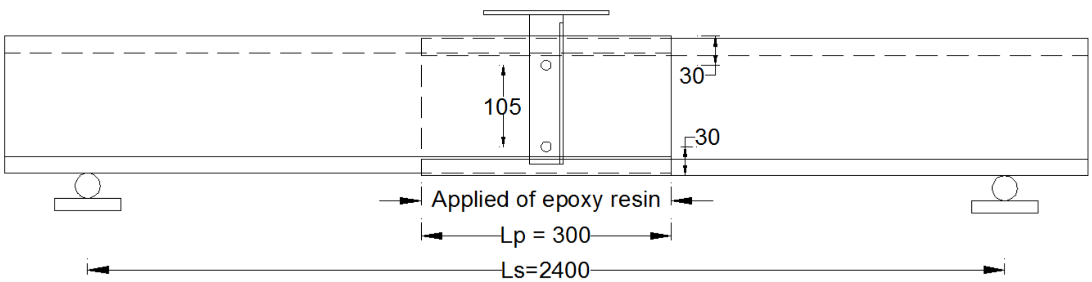
(h) B300-3



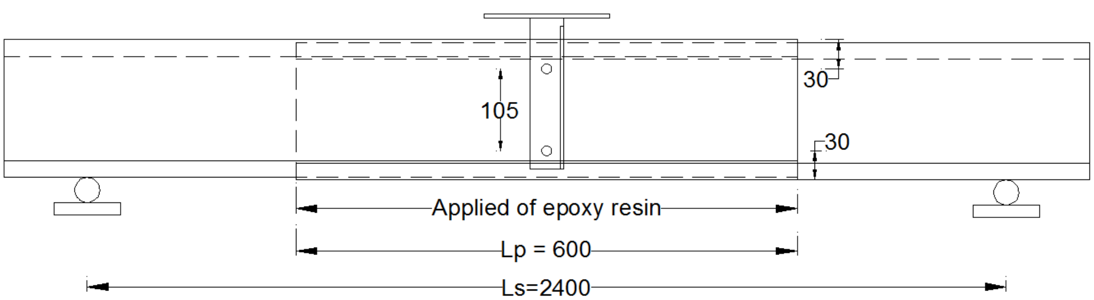
(i) C180



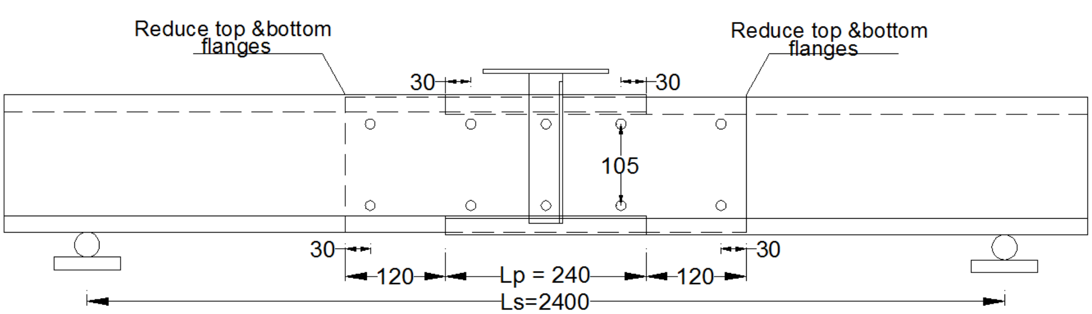
(j) C240



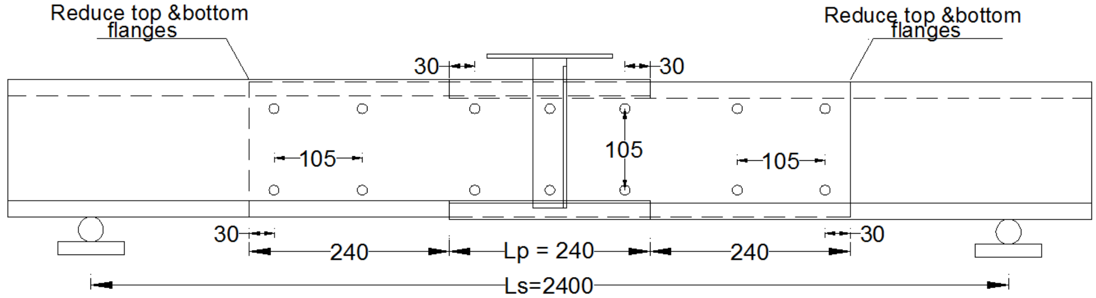
(k) C300



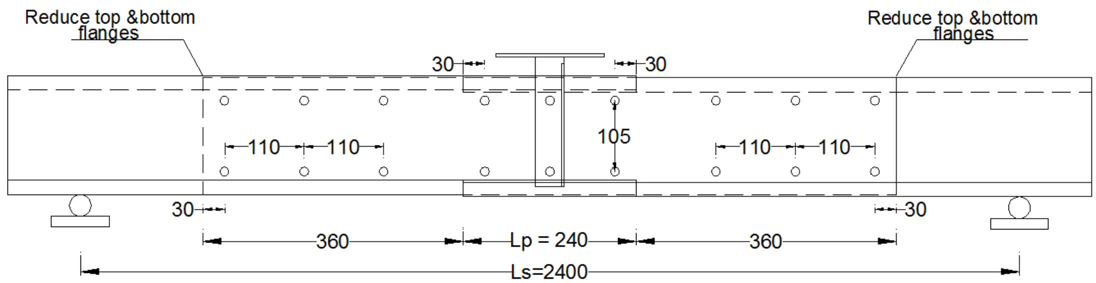
(l) C600



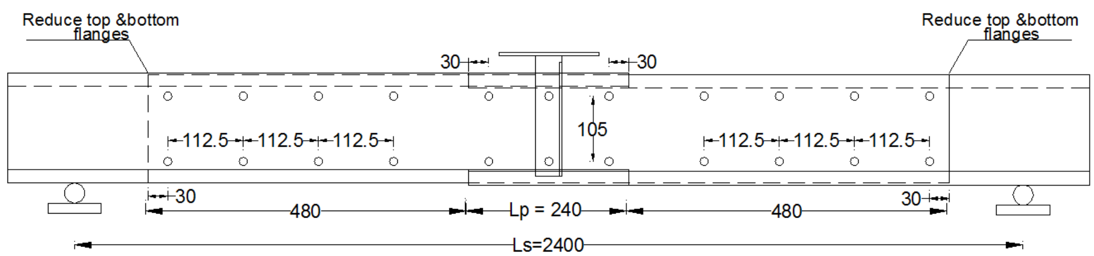
(m) D240-1



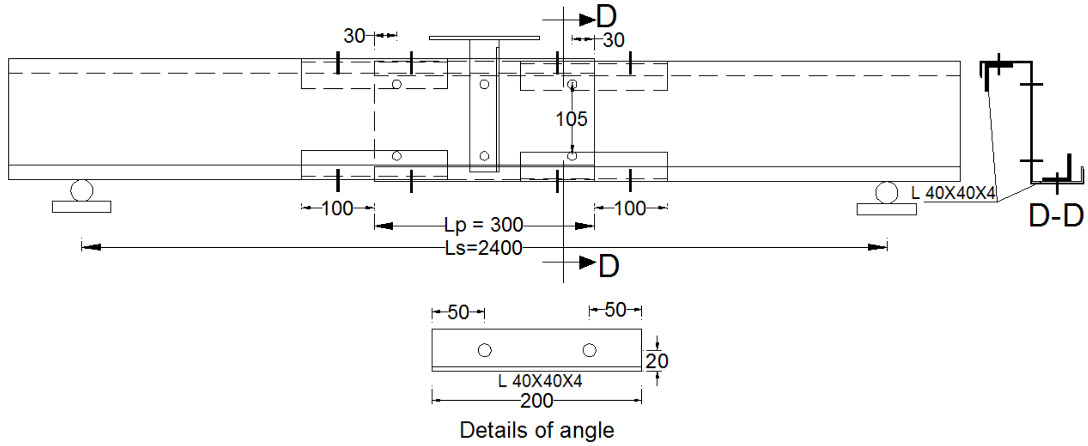
(n) D240-2



(o) D240-3



(p) D240-4



(q) D300-5

Fig. 3. (a)-(q) Test specimens (all dimensions in mm)

Lp, length of lap connection; Ls, span of test.

The actual geometric and mechanical properties of the used cold-formed Z-section are listed in table 2. The mechanical properties of the steel section were determined according to tension test on three coupons (we tested three pieces to get the average value only). Table 3 and table 4 show the material properties of the used bolts and epoxy, respectively, according to their manufactures.

Table 2. Properties of Steel cold-formed Z-section

Steel Z-cold formed properties				
E-modulus [N/mm²]	Yield stress (Fy) [N/mm²]	Ultimate stress (Fu) [N/mm²]	Yield strain (εy) %	Ultimate strain (εu)%
210,000	240	360	0.5	3.5

Table 3. Properties of M12 Bolts

Bolts properties				
Bolt grade	Yield stress (Fyb) [N/mm2]	Ultimate stress (Fub) [N/mm2]	Permissible friction load for M12 (Ps) [N]	Pretension force for M12 (T) [N]
8.8	640	800	11830	37030

Table 4. Properties of Adhesive epoxy

Sikadur® -30			
Compressive strength [N/mm²]		Tensile strength [N/mm²]	
E-modulus	Strength at 7 days	E-modulus	Strength at 7 days
9,600	70-95	11,200	24-31
Shear strength [N/mm²]		Bond strength on steel [N/mm²]	
Strength at 7 days		Mean value	Min. value
14-21		>30	>21

To prevent the lateral torsional buckling, lateral supports were applied to the specimens at equal distance of 400 mm. The lateral supports consisted of two vertical angles of 40x40x4 mm size, two bolts M10 and two steel plates of 5 mm thickness, as shown in figure 4.

To ensure a complete bonding between steel specimens connected by epoxy, surface at lap zone was treated by an abrasive disk then cleaned with acetone. Surface preparation was completed until the oxidation layer accumulated on the steel surface was removed. The adhesive was applied to the steel adherent surfaces with a spatula and the surfaces were then squeezed together with a small pressure to force out the air bubbles.

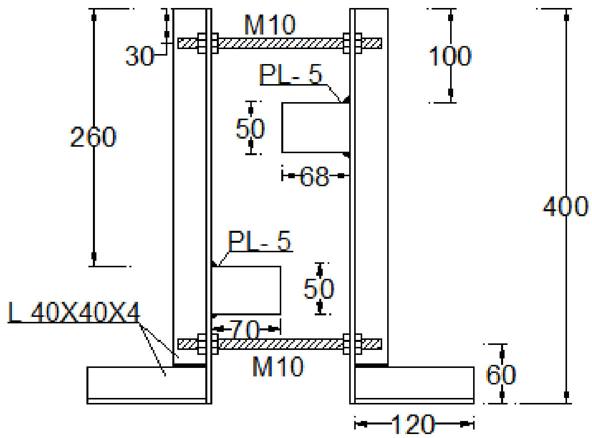


Fig. 4. Typical Detail of Lateral Restraint (all dimensions in mm)

3. TEST SETUP

Linear Variable Deformation Transducers (LVDTs) of 0.01 mm accuracy and 100 mm total length were used to measure the deflection of tested specimens. Three (LVDTs) were used to measure the vertical deflections as shown in figures 5 and 6. The LVDTs were removed just prior to failure to avoid the probability of any damage occurrence. A loading cell was mounted as shown in figure 6 to monitor and control the applied loads during the test.

The prepared specimens were carefully lifted and fixed into the frame test as shown in figure 6. The tested specimens were loaded in one point by using one hydraulic jack. The initial readings of all instruments were reset to make it zero. The load was applied incrementally in small load intervals to get accurate readings (also the measurements are taken by reading load steps intervals with the rate of (1) reading / second). All data of instruments devices were recorded automatically and saved in the format of well-known office software “excel”. Also, the behavior of the tested specimen was recorded and photographed during the test.

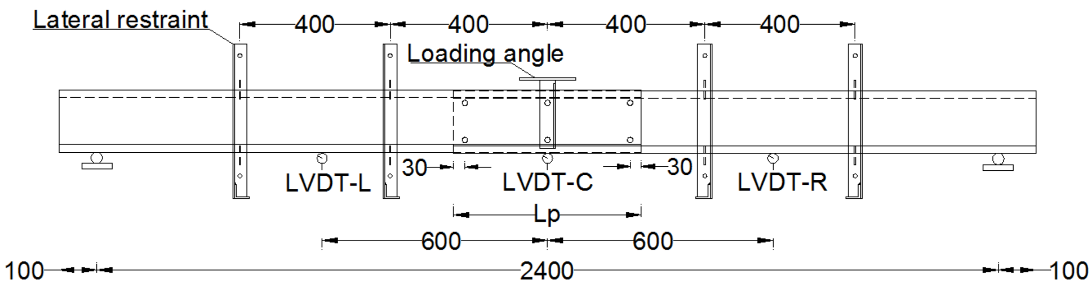


Fig. 5. Schematic view of the test setup and positions of Lateral Restraint and LVDTs (all dimensions in mm)

Fig. 6. Setup of the Experimental Test

4. RESULTS AND DISCUSSION

4.1 Modes of failure

It was observed that all bolted specimens trend the same mode of failure which occurred at the end of lap splice where a combination of bending moment and shearing force were acting. Local buckling in compression flange and the web, section distortion and separation of the lapped tension flanges are the main features of the observed mode of failure, as shown in figure 7. The localization of failure at the ends of lapping is due to the sudden change of the beam cross section. For specimens of series (A), clear separation between tension flanges, local buckling in compression flange and slight section distortion were observed at ultimate load. However, the separation between tension flanges was the main responsible of the large deformation occurred to the tested specimens. It seems that the lap splice length has no effect on the mode of failure of the tested specimens.

For tested specimens of series (B) where different arrangements of bolts were applied, also, the common features of the failure were localized at the ends of lap splice. For specimens B300-2 and B300-3 where the upper and lower flanges of lap splice were bolted, a noticeable distortion of Z-section was occurred suddenly at the ends of lapping when the load reached its ultimate value. It seems that a transverse bending moment was occurred suddenly at ultimate load and led to the cross-section distortion and the collapse of tested specimen as shown in figure 8.

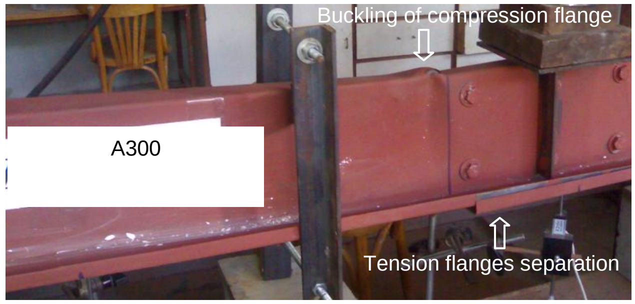


Fig. 7. Typical modes of failure of tested specimens with bolted connections

Fig. 8. Mode failure of test series (B)

For series (D), where the stiffness effect of lap splice was studied, local buckling in compression flanges and the web, and tension flanges separation were observed at failure. However, the position of local buckling was dependent on the stiffness of lap splice. For specimens D240-1 and D240-2, the web stiffness of lap splice was improved by extending the web of lapped sections on the both sides of lap splice by 50% (120 mm) and 100% (240 mm), respectively, of lap splice length. The local buckling of the former specimens appeared just outside the ends of extended webs, as shown in figure 9.

For specimens D300-5, the stiffness of the upper and lower flanges was improved in comparison with specimen A300 by adding steel angles at the four ends of lap splice. For this specimen, a local buckling of compression flange was observed of the ends of added angles, as shown in figure 10.

However, extending the web stiffness by 150% (360 mm) and 200% (480 mm) for specimens D240-3 and D240-4 did not affect the position of local buckling which appeared always at the ends of the lap splice. The separation between the tension flanges was observed at ultimate load for specimens D240-3, D240-4, as shown in figure 11.

Fig. 9. Mode failure for specimens (D240-1, and D240-2)

Fig. 10. Mode failure for specimen (D300-5)

Fig. 11. Mode failure for specimens (D240-3 and D240-4)

For all the specimens of series (C), where the bolts were replaced by the epoxy resin to connect the lap splice, only local buckling in compression flange and the web was observed at a distance from the ends of lap splice, as shown in figure 12, the maximum recorded distance at which local buckling appeared was 80 mm from the end of lap splice, i.e. half the beam depth.

Fig. 12. Mode failure of test series (C)

4.2 Ultimate load

Table 5 presents the values of ultimate load and mid-span deflection for all tested specimens.

Table 5. Experimental Results specimens

Test Series	Specimen	Lap Length (mm)	Measured ultimate load (KN)	Maximum Recorded Deflection (mm)
A	A180	180	5.90	19.39
	A240	240	6.56	16.54
	A300	300	6.96	15.07
	A600	600	8.94	14.01
	A900	900	11.12	13.10
B	B300-1	300	6.75	12.76
	B300-2		10.23	11.55
	B300-3		10.37	9.97
C	C180	180	7.63	15.50
	C240	240	9.41	12.63
	C300	300	10.28	12.32
	C600	600	10.46	11.40
D	D240-1	240	8.21	9.40
	D240-2		8.55	13.13
	D240-3		8.53	12.77
	D240-4		8.49	11.68
	D300-5	300	10.51	9.11

The effect of each parameter of this study on the ultimate load is discussed and analyzed in the following subsections.

Figure 13 presents the relationship between the lap length to beam depth ratio and the ultimate load for tested specimens with bolted lap splice and with lap splice connected by epoxy resin. For both lapping techniques, increasing the lap length to beam depth ratio from 1.09 to 3.64 led to increase the ultimate load by 51.5% and 37.1% for bolted lapping and epoxy lapping, respectively.

As shown in Figure 13, epoxy led to increase the ultimate load by 29.32%, 43.45%, 47.7% and 17.00% compared with that bolted specimens A180, A240, A300 and A600 (that with web bolts only) respectively, so, this technique was better than the conventional technique by using bolts. Also, it is noted that epoxy lapping increase the ultimate load with (lap length / beam depth) ratio equal 1.81 and have a constant value with the increase of lap length.

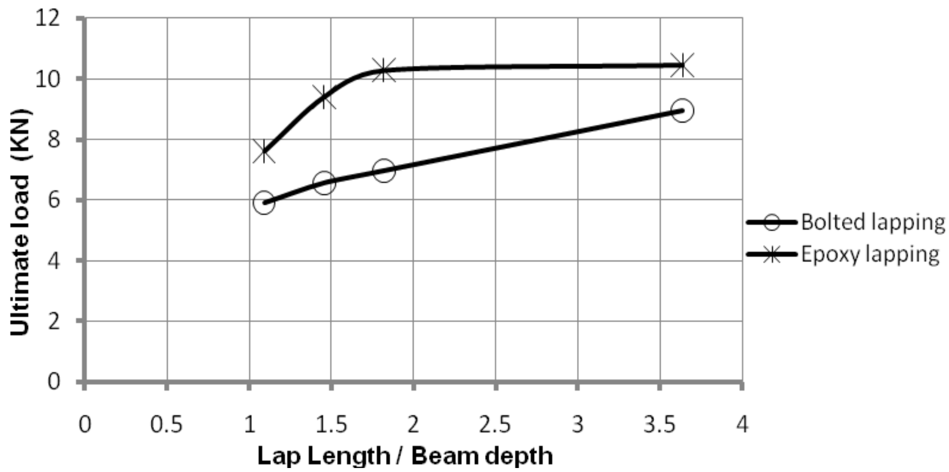


Fig. 13. Relationship between ultimate load and lapping length as percentage of beam depth

Increasing the web bolts of the lap splice did not reveal a clear effect on the ultimate load of tested specimens, as can be seen for specimens B300-1 and B300-2 where their web bolts were increased in comparison with specimens A300 and B300-3, respectively. However, adding bolts to connect the upper and lower flanges of lap splice led to a significant increase in the ultimate load as can be seen for specimens B300-2 and B300-3 where their ultimate loads increased by 51.6% and 49%, respectively, in comparison with specimens B300-1 and A300 in which web bolts are used only to connect the lap splice.

Increasing the web stiffness of the lap splice by extending the web on both sides of the splice by 50% (120 mm) of the splice length, in specimen D240-1 led to increase the ultimate load by 25.2% in comparison with specimen A240. However, increasing the web extension by 100% (240 mm), 150% (360 mm) and 200% (480 mm) in specimens D240-2, D240-3 and D240-4, respectively did not lead to a significant extra increase in the ultimate load. On the other hand, increasing the flanges stiffness by adding additional steel angles at the ends of the lap splice, in specimen D300-5, produced a significant increase in the ultimate load by 51% in comparison with specimen A300.

4.3 Vertical deflection

The effect of the investigated parameters on the load-deflection curve of the tested specimens was discussed and analyzed in the following subsections.

As shown in figure 14, increasing the lap splice length produced stronger and more rigid specimens but led to reduce its ductility, i.e. long lap length give strong and rigid connection with less ductility compared to short lap length.

Series B includes specimens with different bolt arrangements to connect the lap splice. The web bolts were increased in specimens B300-1 and B300-2 compared to specimens A300 and B300-3, respectively. Also, flange bolts were added in specimens B300-2 and B300-3 compared to B300-1 and A300, respectively. Adding flange bolts led to increase the rigidity and resistance of the tested lapped specimens B300-2 and B300-3, as shown in figure 15. However, increasing the web bolts did not produce a clear effect on the load-deflection curves of the tested specimens B300-1 and B300-2 in comparison with specimens A300 and B300-3.

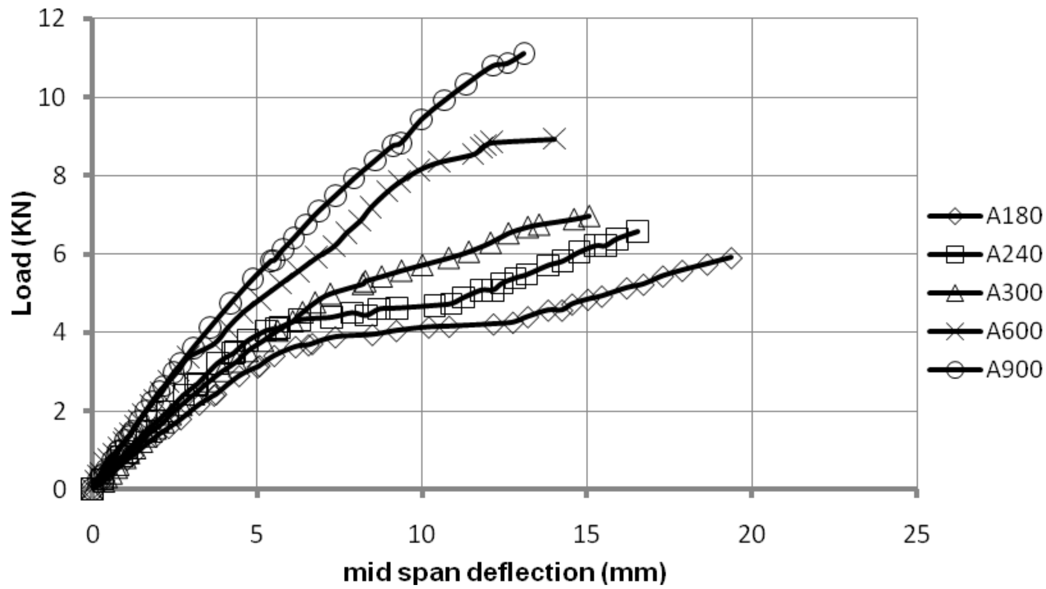


Fig. 14. Load-vertical deflection relationships for specimens of series A

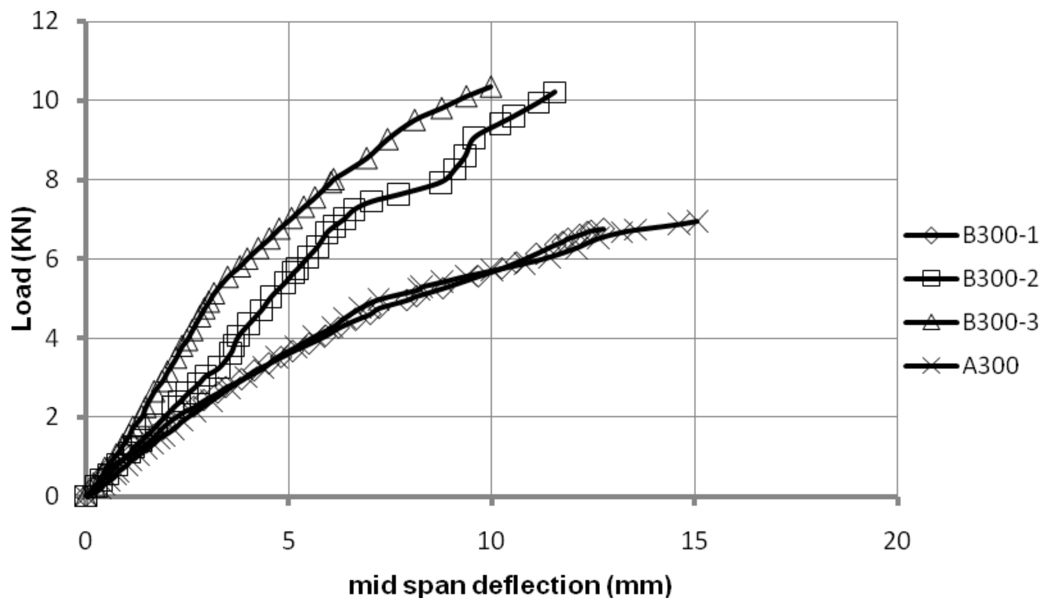


Fig. 15. Load-vertical deflection relationship for specimens of series B and specimen A300

As previously mentioned in above, using epoxy to connect the lap splice in place of bolts led to increase the ultimate load. However, the deflection at ultimate load is significantly decreased, as shown in figure 16. So, the lap splice connected by epoxy is stronger and more rigid but less ductile than that connected by bolts. Figure 17 shows the load-deflection curves of all tested specimens which their lap splices were connected by epoxy.

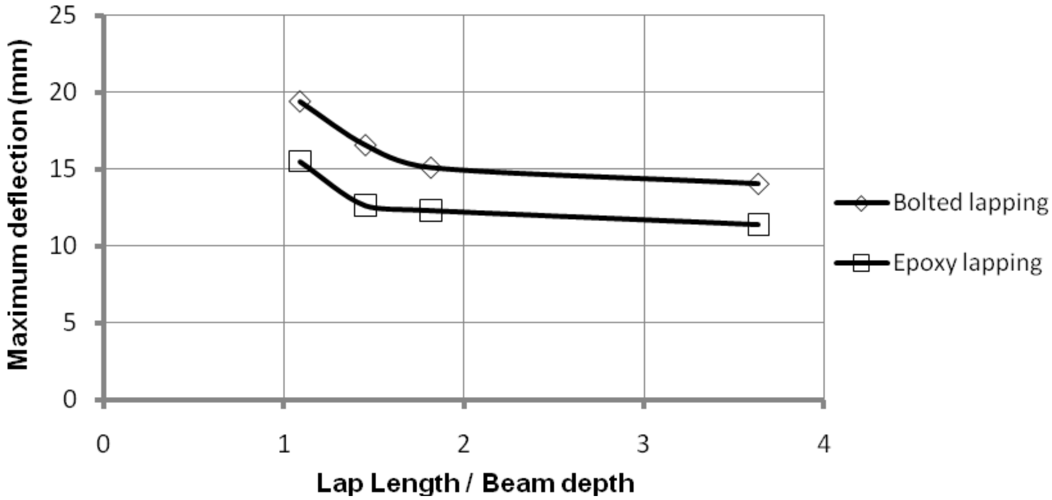


Fig. 16. Relationship between the maximum deflection at mid span and lapping length as percentage of beam depth

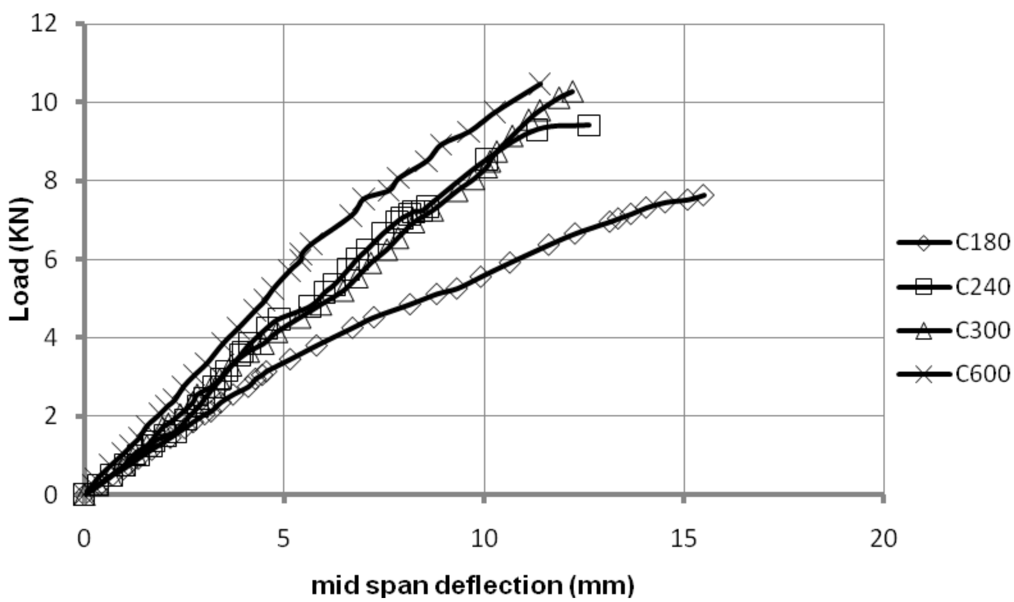


Fig. 17. Load-vertical deflection relationships for specimens of series C

The effect of improving the lap splice on the load-deflection curves was studied through the specimens of series D. Extending the web length of lapped sections to 50% (120 mm) of lap splice, as in specimen D240-1, in order to improve the web stiffness of the lap splice, produce a stronger and more rigid lapped specimen in comparison with specimen A240, as shown in figure 18, but the ductility of the enhanced specimen (D240-1) was reduced. However, extending the web length to 100% (240 mm), 150% (360 mm) and 200% (480 mm) for specimens D240-2, D240-3 and D240-4 did not reveal an extra effect on the load-deflection curve.

On the other hand, improving the flange stiffness of the lap splice by adding four steel angles at their ends, as in specimen D300-5, produced a significant effect on the load-deflection curve, in comparison with specimen A300. Improving the flange stiffness produced stronger and more rigid specimen but with less ductility.

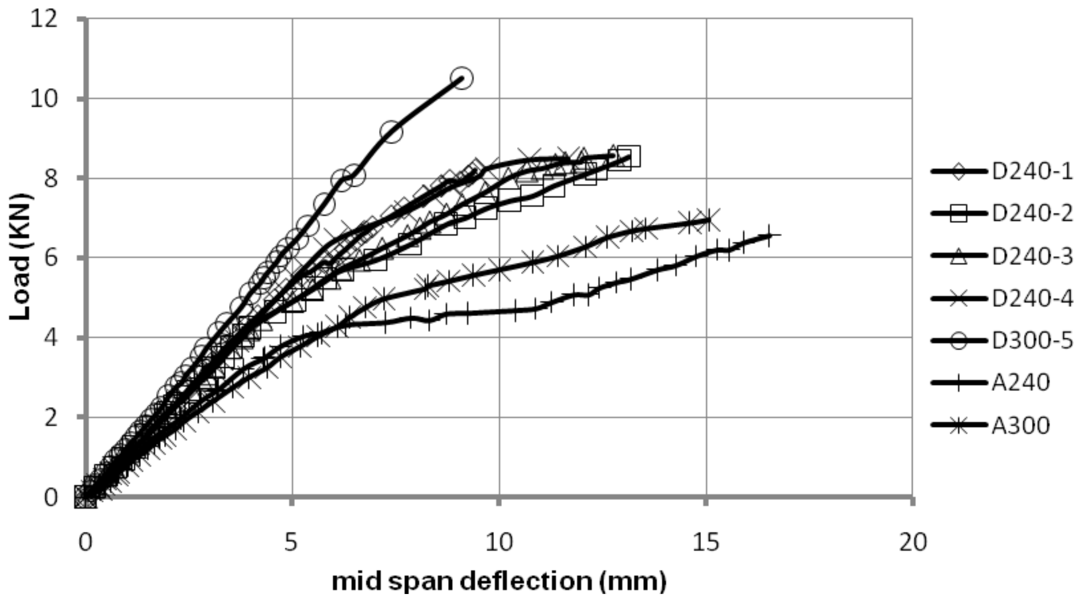


Fig. 18. Load-vertical deflection relationships for specimens of series D and specimens A240 and A300

5. CONCLUSION

According to the obtained results, the following points can be concluded:

1. In all tests, section failure at the end of a lap of connected sections was found to be critical under combined bending and shear. Compression flange buckling, web buckling, and tension flange separation were the failure modes observed in the bolted connection specimens. For epoxy connections, compression flange buckling and web buckling were apparent at distance equal half the beam depth from the end of a lap of the lapped connections.

2. Increasing the length of lapped connection to beam depth ratio from 1.09 to 3.64 has significant effect on the load capacity of Z-purlins and led to increase the ultimate load by 51.5% and 37.1% for bolted lapping and epoxy lapping, respectively, also, give stiff and strong connections than connections with short lap length.

3. Presence of bolts in the upper and lower flanges of lap splice, increasing the ultimate load between 49% and 51.6%, also, increasing the rigidity of the lapped connections compared with specimens that with web bolts only.

4. Increasing the web bolts in the lapped connections did not reveal a clear effect on of the ultimate load of lapped Z sections.

5. Using epoxy resin to connect the lapped sections was the better technique where the ultimate load increased by 17 to 47.7% compared with the corresponding bolted specimens.

6. For epoxy connections, using lap length twice beam depth led to increase the ultimate load, after which the ultimate load was almost constant.
7. The length of web stiffening or flange stiffening to 100% of lap splice length was a noticeable effect on the mode failure of lapped connection, after which this percent it's no affect, also, increasing the ultimate load by 25.2% and 51% compared with specimens without web and flange stiffening respectively.

REFERENCES

1. Ho HC, Chung KF. Experimental investigation into the structural behavior of lapped connections between cold—formed steel Z sections. Thin-Walled Structures 2004; 42(7):1013–33.

2. Chung KF, Ho Hc. Analysis and design of lapped connections between cold—formed steel Z sections. Thin-Walled Structures 2005; 43:1071–90.

3. Ho HC, Chung KF. Analytical prediction on deformation characteristics of lapped connections between cold—formed steel Z sections. Thin-Walled Structures 2006; 44(1):115–30.

4. Ho HC, Chung KF. Structural behavior of lapped cold—formed steel Z sections with generic bolted configurations. Thin-Walled Structures 2006; 44(4): 466–80.

5. Zhang L, Tong G. Moment resistance and flexural rigidity of lapped connections in multi-span cold-formed Z purlin systems. Thin-Walled Structures 2008; 46(5):551–60.

6. Dubina D, Ungureanu V. Behavior of multi-span cold-formed Z-purlins with bolted lapped connections. Thin-Walled Structures 2010; 48:866-871.

7. Dubina D, Ungureanu V. Behavior of multi-span purlins of bolted lapped cold-formed Z-sections. In: Proceedings of the fifth conference on coupled instabilities in metal structures-CIMS 2008, Sydney, Australia, 23–25June 2008, vol.1, P. 507–514.ISBN:978-0-646-49439-5.

8. Lawson RM, Chung KF, Popo-Ola SO. Building design using cold--formed steel sections. Structural design to BS5950-5:1998-section properties and load tables, The Steel Construction Institute, SCIP276; 2002. P. 1–234.

9. Chung KF, Ho HC, Wang AJ. An investigation into deformation characteristics of lapped connections between cold—formed steel Z sections. Special issue on cold—formed steel structures. Int J Steel Structures 2005; 5: 23–32.

10. Chung KF, St Quinton D. Structural performance of modern roofs with thick over-purlin insulation-experimental investigation. Journal of Constructional Steel Research 1996; 40(1):17–38.

ABBREVIATIONS

Lp, length of lap connection; ***Ls***, span of test; ***M10***, bolt with 10mm diameter; ***L***, steel angle; ***PL-5***, steel plate with 5mm thickness; ***LVDT-R***, linear variable deformation transducer in the right side of specimen; ***LVDT-C***, linear variable deformation transducer in the center of specimen; ***LVDT-L***, linear variable deformation transducer in the left side of specimen.