CHAPTER 2

REVIEW OF LITERATURE

2.1 GENERAL

Literature pertaining to studies on the behaviour of hot-rolled steel girders with corrugated web and composite hot-rolled steel girders with corrugated web subjected to static loadings are presented. A detailed review of literature has been carried out to study the behaviour of hot-rolled steel I-girders with corrugated webs. Very scant literature is available on the behaviour of corrugated web beam using cold-formed steel section.

2.2 OVERVIEW OF LITERATURE

2.2.1 Studies on Hot-Rolled Steel Beams with Trapezoidally Corrugated Web

Luo and Edlund (1995) performed the non-linear finite element analysis and compared the numerical results with existing empirical and analytical formulae. They found that the ultimate shear capacity increases proportionally with the girder depth and not dependent on the ratio of girder length over girder depth, while the post-buckling shear capacity not only increases with the girder depth, but also dependent on the ratio of girder length over girder depth. They also found that the corrugation depth did not have much effect on the ultimate shear capacity but affected the degree of the localization of the buckling mode.

Luo and Edlund (1995) analyzed the strength of the hot-rolled steel plate girders with trapezoidally corrugated webs in shear or under patch loading. For the numerical simulation, a non-linear finite element program ABAQUS was used and an eight node quadrilateral thin shell element was chosen to model both the webs and flanges. In the failure pattern two modes of local buckling type occurs and then the buckles successively develop over the whole girder depth leading to failure of this girder. It was concluded that the load carrying capacity of plate girders with trapezoidally corrugated webs in shear or under patch loading is more when compared with the plate girder with plain web.

Luo and Edlund (1996) studied the shear capacity of hot-rolled steel plate girders with trapezoidally corrugated webs numerically using a non-linear finite element method. Effects of large deflections were taken into account and a perfectly elastic-plastic material model obeying a Von Mises Yield criterion was assumed. The influence of the geometric parameters such as the overall dimension of the web panel, the web thickness, the corrugation depth of the web, the corrugation angle and the width of the plain sub-panel of the web on the shear capacity of such girders were investigated. More specifically, the influence of these parameters both on the ultimate shear capacity and on the remaining shear capacity in the post-buckling range, as well as on the buckling modes were studied. It was concluded that the shear capacity increases slightly as the corrugation angle θ increases from 30^0 to 60^0. The buckling mode changes from a global buckling mode for $\theta = 30^0$, to a zonal buckling mode for $\theta = 45^0$ and to a more localized buckling mode for $\theta = 60^0$.

Elgaaly et al (1998) studied the behaviour of girders with corrugated webs up to failure using non-linear element analysis**.** The use of corrugated webs to increase the out-of-plane stiffness and buckling strength

without the use of vertical stiffeners had been considered. Finite element models of test specimens were developed using thin shell elements. The specimens were tested under shear, uniform bending and local discrete compressive loads on the top flange. Non-linear finite element analysis, which considered both geometric and material non-linearity was performed. The analysis was able to depict the test results to a very good degree of accuracy under the three loading conditions.

Chan et al (2002) studied the effect of web corrugation on the bending capacity of the beam using finite element method. Beams with plain web, horizontally corrugated web and vertically corrugated web were studied. The corrugation profiles studied was half circle corrugation. It was concluded that the vertically corrugated web provides a stronger support against the flange buckling than those with horizontally corrugated and plain webs. It was also concluded that corrugated web beams with larger corrugation radius, could sustain higher bending moment and there is 10.6% reduction in weight when compared with the beam with flat web.

Khalid et al (2004) studied the behaviour of mild steel structural beams with corrugated web subjected to three-point bending. Semi circular web corrugation in the cross-sectional plane (horizontal) and across the span of the beam (vertical) was investigated both experimentally and computationally using finite element technique. In the finite element analysis, test specimen was modeled using commercially available finite element software LUSAS and a non-linear analysis was performed. The comparisons between the experimental and the finite element analysis results were satisfactory. It was concluded that the vertical-corrugated web beam could carry between 13.3% and 32.8% higher moment compared to the plain and horizontal-corrugated web beams. It was also concluded that the web corrugation in the vertical direction (along the length) contributed higher

bending capacity than in the horizontal direction (in the cross-section plane) and also the beam weight could be reduced by 13.6% by using vertically corrugated web with the maximum size of corrugation radius.

Sayed-Ahmed (2005) had investigated the lateral torsional buckling behaviour of hot-rolled steel I-girders with plain and corrugated webs. A numerical analysis based on the finite element technique was performed on these girders. The critical moment causing lateral instability was numerically determined. The finite-element model results were used to investigate the applicability of the critical moment design equations, used for a girder with a plain web, to corrugated web girders. The validity of the equivalent moment factor concept to corrugated web girders was also examined. The numerical model was then used to scrutinize the local buckling behaviour of the compression flange for girders with corrugated webs. It was concluded that resistance to lateral torsional buckling of such girders is 12% to 37% higher than the resistance of plate girders with traditional plain webs.

Sayed-Ahmed (2005) investigated the local flange buckling and lateral torsion-flexure buckling of steel girders with corrugated steel webs. A numerical analysis based on the finite-element technique was adopted to determine the critical moment initiating lateral torsion-flexure buckling of corrugated web girders. The numerical model was also used to investigate the local buckling behaviour of the compression flange for girders with corrugated steel webs. The applicability of the limits defining the section class for girders with plain webs to corrugated web girders was examined using the results of the numerical analysis. It was concluded that the resistance to lateral torsion buckling of girders with corrugated web is higher than that of plate girders with plain webs.

Abbas et al (2006) investigated the behaviour of hot-rolled steel I-girders with corrugated web under in-plane loads with emphasis on the

flange transverse bending behaviour. Under a set of simplifying assumptions, the equilibrium of an infinitesimal length of a corrugated web I-girder was studied, and the cross sectional stresses and stress resultants were deduced. The in-plane bending behaviour was analyzed using conventional beam problem whereas the out-of-plane behaviour was analyzed as a flange transverse bending problem. The analysis showed that a corrugated web I-girder would twist out-of-plane simultaneously as it deflects in-plane under the action of in-plane loads.

Ibrahim et al (2006) investigated the behaviour of hot-rolled steel plate girders with trapezoidally corrugated webs under fatigue loading. Six girders were tested under both monotonic and cyclic four-point loading arrangements. It was concluded that the fatigue life of plate girder with corrugated web is more than the conventional stiffener by 49% - 78% when subjected to the same stress range.

Abbas et al (2007) investigated the behaviour of corrugated web steel I-girders under in-plane loads. A theoretical method was proposed as an analytical tool for quantifying flange transverse bending in corrugated web I-girders. To validate this method, experiments were conducted on a large-scale corrugated web I-girder. The measured flange transverse displacements and flange stresses were in good agreement with the theoretical results especially in regions of constant shear.

Robert et al (2007) investigated the shear behaviour of corrugated web bridge girders. Two nominally identical full-scale corrugated web girders made of steel were designed, fabricated and tested to shear failure. The girders were designed to reach the shear yield strength. The girders failed suddenly due to web buckling at shear stresses of 91% and 85% of yield. One girder failed near the load point where the bending moment is largest and the

other girder failed near the support, indicating that bending has little effect on the shear strength.

Sayed-Ahmed (2007) conducted a numerical analysis on hot-rolled steel corrugated web girders to investigate the buckling modes of the corrugated web, verify the validity of the proposed equation and explore the post-buckling strength of corrugated web girders. The numerical model was extended to determine the critical moment causing lateral instability for corrugated web girders. It was concluded that the resistance to lateral-torsional buckling of such girders is 12% to 37% higher than that of plate girders with plain web.

Yi et al (2008) developed a finite element model to study the behaviour of trapezoidally corrugated steel plates which was used as the web of pre-stressed concrete box girder bridges to reduce dead load and increase structural efficiency. A series of finite element analysis were carried out to study the geometric parameters affecting interactive shear buckling modes and strength. Based on the analysis results, the interactive shear buckling strength formula was proposed which agreed well with the experimental data. It was concluded that the interactive shear buckling mode and strength is not influenced by material inelasticity or yielding, but rather by the geometry of the corrugated plate.

Moon et al (2009) studied the lateral-torsional buckling behaviour of hot-rolled steel I-girders with corrugated webs under uniform bending. Approximate methods for locating its shear center and calculating the warping constant were proposed. It was concluded that the shear center of the I-girder with corrugated webs is located at a distance of two times the depth from the center of the upper and lower flange and the warping constant of the I-girder with corrugated webs is larger than that of the I-girder with flat webs, while

the shear modulus of the corrugated plates is smaller than that of the flat plates.

Balazs Kovesdi and Laszlo Dunai (2010) studied the geometric parameters which had influence on the patch loading resistance of the structural behaviour. The analyzed parameters were the web depth and thickness, the corrugation angle and loading lengths. The effect of the parameters on the interaction behaviour was analyzed and tendencies were determined. A new design interaction equation was proposed which is applicable for corrugated web girders. The analyzed parameters showed that the interaction criteria depend significantly on the ratio of the flange and web patch loading resistance.

Fatimah De'nan et al (2010) carried out an experimental and numerical study on the lateral-torsional buckling behaviour of steel section with trapezoid web. Comparison was made with conventional beams with flat web. In the experimental work, sections with nominal dimension 200 x 80 mm and 5 m length were loaded vertically while the lateral deflection were unrestrained to allow for the lateral-torsional buckling. In the analytical study, eigen-value buckling analysis in the finite element method was used to determine the critical buckling load. It was concluded that the steel beams with trapezoidally corrugated web section have higher resistance to lateral-torsional buckling compared to that of section with flat web. The result showed that corrugation thickness influenced the resistance to lateral-torsional buckling.

Hartmut Pasternak et al (2010) investigated the buckling behaviour of cold-formed steel beam with sinusoidal corrugated web experimentally. Due to the thin web of 1.5 mm to 3 mm, corrugated web beams afford a significant weight reduction compared with hot-rolled profiles or welded I-sections. Buckling failure of the web was prevented by the corrugation.

The buckling resistance of sinusoidal corrugated web was comparable with plain webs of 12 mm thickness or more. It was concluded that local buckling does not occur before the web reaches its yielding shear capacity in the beams with sinusoidally corrugated web.

Kazemi Nia Korrani and Molanaei (2010) constructed the three-dimensional finite-element model using ANSYS for the inelastic nonlinear flexural-torsional analysis of I-girder and used it to investigate the effects of the corrugation profiles of the web on the lateral-torsional buckling strength. I-girders were simply supported with constant flange dimensions but with different web dimensions. It was concluded that the critical moment increases by 40 percent with corrugation profiles of the web.

Kiymaz et al (2010) studied the behaviour and design of corrugated web steel beams with and without web openings using the finite element program ABAQUS. Simply supported corrugated web beams of 2 m length and with circular web openings at quarter span points were considered. Various cases were analyzed including the size of the openings and the corrugation density which was a function of the magnitude and length of the sine wave. Models without web holes were also analyzed and compared with other cases which were all together examined in terms of load-deformation characteristics and ultimate web shear resistance. It was concluded that introducing a web opening causes strength reductions between 15% to 50%. As the opening size increases, the percentage reduction values also increases.

Korrani (2010) studied the stiffness requirements of lateral restraints that were intended to restrain simply supported I-girders with corrugated webs so as to increase their lateral buckling moment to those of rigidly restrained beams under pure bending. For this purpose, a finite element model based on the commercial software package ANSYS was developed for the non-linear inelastic flexural-torsional analysis of I-girders

with corrugated webs with a wide variety of slenderness and brace stiffness. Then, it was used to investigate the effect of elastic lateral bracing stiffness on the inelastic flexural-torsional buckling load of simply supported I-girders with corrugated webs with an elastic lateral restraint under pure bending. It was concluded that a central elastic lateral restraint generally increases the inelastic strength of the I-girder, but the effect of the restraint depends not only on the stiffness of the restraint but also on the modified slenderness of the I-girder.

Ngoc Duong Nguyen et al (2011) investigated the moment modification factors of the I-girder with trapezoidal web corrugations subjected to concentrated load, applied at different heights on the cross section and with various end restraint conditions. The theoretical results of moment modification factors were compared with commercial finite element software ABAQUS using shell elements. A series of finite element analysis with different corrugation profiles and lengths was performed. Through comparative numerical studies, the theoretical results were verified. Finally, it was concluded the moment modification factors improve the accuracy of lateral–torsional buckling strength.

Fatimah De'nan et al (2012) developed a three-dimensional finite element model using LUSAS to investigate the effects of web corrugation angle on bending behaviour of Triangular Web Profile steel sections. Thin shell element was chosen to represent the element type of the model. Each beam section was modeled using several spans and different corrugation angle (15^0, 30^0, 45^0, $60^0$and 75^0). It was noted that deflection of 45^0 and 75^0 web corrugations angle was the lowest deflection value either in minor or major axis of Triangular Web Profile steel section. It was concluded that the Triangular Web Profile steel section is stiffer when the web corrugation angle is 45^0 or 75^0 and higher resistance to bending in minor and major axis.

Amir Shahmohammadi et al (2013) assessed the feasibility of the application of corrugated plates as the web of steel coupling beams as a proposition for improving seismic behaviour of such beams. Linear elastic buckling analysis and non-linear analysis of steel coupling beams with flat and corrugated webs were carried out using finite element technique. 160 models have been studied, considering parameters such as shape of web plate (flat, trapezoidal, curved, and zigzag), web thickness, number of corrugations, and corrugation angle. The finite element results were validated through comparison with the experimental results of a common steel coupling beam. In addition to the advantages of eliminating web stiffeners, results of this study showed that the application of corrugated web with the proposed geometric criteria makes it possible to achieve further rotation capacity in comparison with common steel coupling beams. Finally, it was concluded that the average ultimate rotation of trapezoidal and curved models increases more when compared with flat web.

Fatimah De'nan et al (2013) developed a three-dimensional finite element model using LUSAS to study the effect of the triangular steel beam web profile on the shear buckling behaviour compared to that of the normal flat beam. All specimens were cantilever beam with variable web thickness and were fixed at one end. Eigen value buckling analysis was used in analyzing the buckling load of the flat plate model and triangular web profile. Results showed that the web thickness gave a significant impact on the shear buckling. In addition, the corrugation thickness of web was also effective in increasing the shear buckling capacity of the profile. It was concluded that the triangular web profile section has higher shear capacity compared to that of normal flat web profile section.

Fatimah De'nan et al (2013) conducted an experimental investigation on the bending behavior in major and minor axis of Triangular

Web Profile compared to flat web steel sections. Each beam section was modeled using various spans such as 3 m, 4 m and 4.8 m. It was observed that the section has a higher stiffness about minor axis compared to that of flat web steel section but has lower stiffness about major axis.

Jiho Moon et al (2013) investigated the flexural–torsional buckling strength of an I-girder with corrugated steel webs under linear moment gradient by using finite element analysis. From the results, it was concluded that the buckling behaviour of the I-girder with corrugated steel webs differed depending on the number of periods of the corrugation. Also, a simple equation for the moment gradient correction factor for the I-girder with corrugated steel webs was suggested.

Limaye and Alandkar (2013) studied the behaviour of welded plate girder for variation in geometry of corrugation and thickness of web plate. The finite element analysis of a plate girder was carried out using ANSYS to determinate the buckling strength of a plate girder considering rectangular corrugated web plate. The results obtained from analysis were then compared with the plate girder with plain web of uniform depth. It was concluded that the corrugated web plate has high buckling strength and sufficient reduction in weight with light gauge elements, than plate girder with plain web.

Mattias Larsson and John Persson (2013) constructed the finite element model on trapezoidally corrugated web to study the lateral-torsional buckling of steel girders with trapezoidally corrugated webs. A method was established for finding the torsion and warping constants of I-shaped girders with arbitrary web profiles using finite element simulations of cantilevers subjected to torsion. This method was verified by comparing the results from linear buckling finite element analysis and analytically calculated values of the torsion and warping constants of girders. Finally, it was concluded that the torsion constant could be increased due to the corrugated web.

Sedky Abdullah et al (2013) compared the ultimate strength of plate girders with trapezoidally corrugated and flat webs. Finite element analysis using the computer package ANSYS was employed to investigate the behaviour and ultimate strength capacity of the girders. Influence of the parameters that affect the behaviour of these girders, such as overall dimensions of the web panel, web thickness, corrugation depth, corrugation angle and sub-panel width of the web on shear capacity of plate girders with corrugated webs on the collapse behaviour was examined. Results were obtained in terms of ultimate strength, failure mechanism and load–deflection curves from the finite element analysis. It was concluded that plate girder with trapezoidally corrugated web has a higher load-carrying capacity as well as less deflection when compared with plate girders with stiffened flat web.

2.2.2 Studies on Composite Hot-Rolled Steel Beams with Trapezoidally Corrugated Web

Hanim et al (2007) conducted an experimental work on a composite beam with trapezoidally corrugated web steel section to study its structural performance. A full scale composite beam test specimen with trapezoidal steel section was tested under pure bending. For comparison, a specimen of composite beam with flat web section was also tested in the same way. Deflections, position of neutral axis, distribution of strain across the depth of the composite section were measured and analyzed. The results showed that the composite beam with trapezoid web has no significant difference in its structural performance compared to the composite beam with normal flat web.

Tahir et al (2008) investigated the strength, the rotational stiffness, and the ductility of the composite connections and non-composite connection used in trapezoidal web profiled steel sections. Eight full scale testing of beam-to-column connections comprised of four specimens for composite and

four non-composite connections with different geometrical configurations had been carried out. It was concluded that composite connections have higher moment resistance, higher stiffness, and less ductility compared with the non-composite connections when used in trapezoidal web profiled steel sections.

Jun He et al (2012) investigated the shear behaviour of partially encased composite I-girders with corrugated web analytically and numerically. A 3-D finite element model with geometric and material non-linearity was established and verified by the experiments. A parametric study was also carried out to examine the effects of geometric and material properties on the shear behaviour which included corrugation, height, thickness, connection degree between steel web and concrete encasement. It was concluded that the ultimate shear strength of steel I-girders increases with increase in the thickness, height and yield strength of corrugated web, while the ultimate shear strength of partially encased composite I-girders increases with the thickness, yield strength of corrugated web and compressive strength of concrete encasement. It was also concluded that the stud stiffness has little influence on the ultimate shear strength.

Jun He et al (2014) developed a partially encased composite I-girder with flat and corrugated web to improve the structural performance of continuous composite girder under hogging moment. The flexural behavior of such structure under two points symmetric loading had been experimentally and analytically investigated. Static flexural loading tests showed that the partially encased girder improved the bending strength in comparison to steel I-girder, as local buckling of steel flange was restricted by encased concrete. It was concluded that the corrugated web girder, the ultimate bending strength increases by 20% and the ductility also increases about 3 times.

2.3 SUMMARY

In this chapter, the literature review pertaining to the performance of hot-rolled steel beams with different corrugations like trapezoidal, triangulation and sinusoidal are discussed. The research on cold-formed steel beams with corrugated web is limited. Hence in this thesis, the behaviour of cold-formed steel beam with trapezoidally corrugated web was carried out.