CHAPTER ONE
INTROUDUCTION

1.1 General

Structural systems are constructed to transmit structural loads to footings. All structural members work together to do so. Some of these members participate in this mission by carrying loads axially (columns), some others carrying loads flexurally (beams). Most of structural members carry axial and flexural loads (beam-columns). Both columns and beams may be considered special cases of beam-columns. Buckling modes of columns and beams are individual and may be considered principal buckling modes. Beam-columns may be subjected to buckling modes of beams or columns individually. Interaction may also occur between buckling modes of beams and those of columns, and develops a new interactive buckling modes. The deformed shape of the interactive buckling mode combines the buckling deformed shapes of principal buckling modes. So, interaction occurs between individual principal modes having one common degree of freedom (translation or rotation) at least. The critical load of interactive buckling mode is always less than that of the critical load of the individual buckling modes [11, 12, 27].

Purlins are secondary structural members commonly used in the metal industry buildings for roof framing. These secondary structural members are used to transfer gravity and wind loads from the roof panels to rafters. Some of the purlins may be subjected to axial force. This situation occurs when the structure is subjected to wind load. In this case purlin carries flexural load (principally) as well as axial load (additionally). These purlins are called strut purlins, they may be considered an example of beam-columns.

The most common purlin shapes are C- and Z-sections. Cold-formed steel products such as C- or Z-purlins have been commonly used in the metal building construction industry for about half a century. The popularity of these products have dramatically increased in recent years due to their wide range of application, economy, ease of fabrication, and high strength-to-weight ratios. C- or Z-Purlins are predominantly used in light load and medium span situations such as roof systems. As shown in figure 1.1, in roof construction, purlins support either a through-fastened roof panel, Fig. 1.2 or a standing seam roof system, Fig.1.3 [42]. A conventional through-fastened roof system consists of C- or Z-section purlins supporting steel deck. This steel deck is directly fastened to the purlin, usually by self-tapping screws, and therefore provides full lateral bracing to the purlins.

The point symmetric section (a section where the shear center and centroid of the section coincide) properties of a typical Z-section are such that when attached to steel decking and subject to gravity loading, it tends to twist and deflect in both vertical and horizontal directions as shown in figure 1.4. However, this torsional force is partially resisted by the interaction of the deck to the purlin junction. Accordingly, this interaction can increase the lateral buckling strength of the purlin.

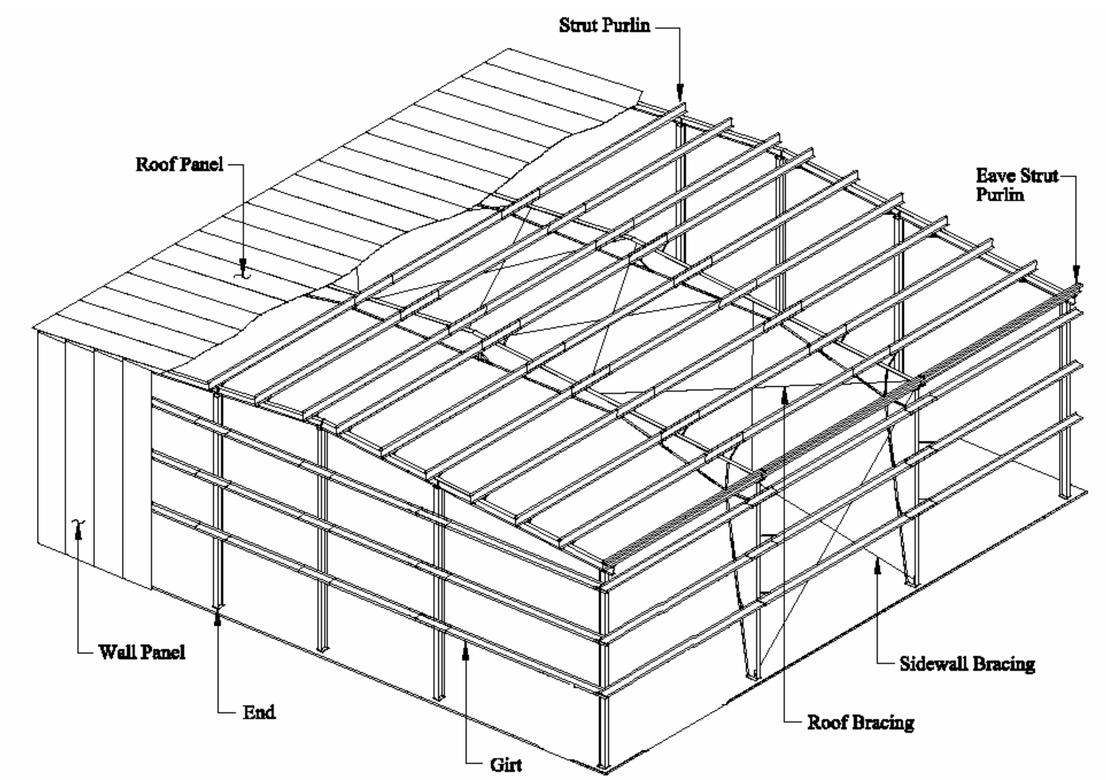


Figure 1.1: Composition of metal building (Stolarczyk et al [42])

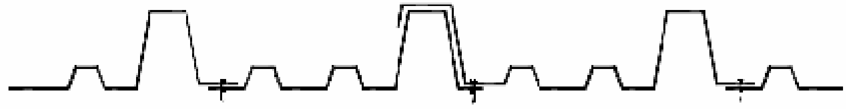


Figure 1.2: Profile of Through-Fastened Roof Panel (Stolarczyk et al [42])

Figure 1.3: Profile of Standing Seam Roof Panel (Stolarczyk et al [42])

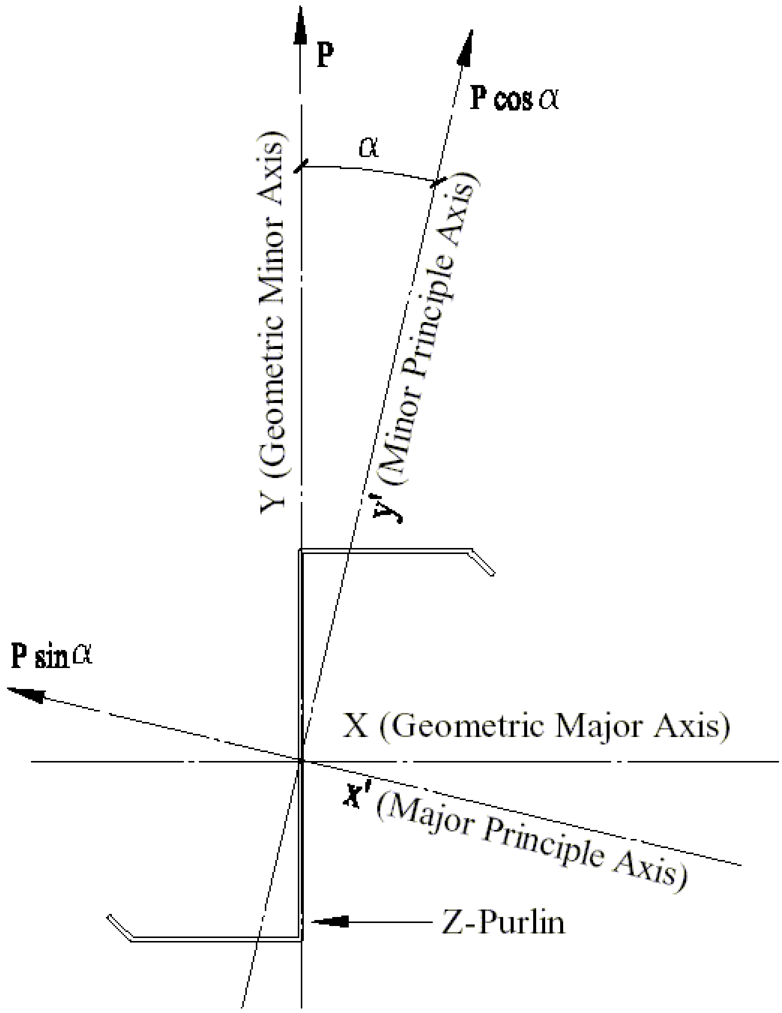


Figure 1.4: Point symmetry of a typical Z-section (Stolarczyk et al [42])

1.2 Aims for Research

Purlin is one of the members used in most of steel structures. It mainly carries flexural loads. These loads may be due to gravity or uplift loading. However, in some cases some purlins are subjected to axial force resulting from wind pressure. This case occurs when wind load acts in the longitudinal direction of the building. Wind causes pressure on walls at one end and suction at the other end. This pressure is transmitted from walls to side girt, which delivers this load to end gables. End gable columns transmit this load to supporting base at the bottom and connection at the top with the frame. This force acts out of frame plane, so that frame does not resist this force and gives it directly to purlin attached at this connection (in case of no strut member used). The force acts in the longitudinal direction of purlin. Purlin carries this force along its longitudinal direction and delivers it to horizontal bracing system. Therefore, strut purlin carries axial force as well as flexural load.

When purlin is subjected to gravity load, the upper flange is compressed in the region of positive bending moment, which is laterally braced by deck or sheeting. While if purlin carries flexural uplift, the bottom flange is compressed in the middle field. The bottom flange is a free flange. The strength of purlin is strongly affected in this case. As the free flange tends to buckle laterally and torsionally, the connection between the top flange and deck or sheeting provides this flange by lateral and torsional restraint. The compression flange of the purlin is not laterally or torsionally restrained, nor completely unrestrained. The whole cross-section including the free flange will be affected by lateral and torsional restraint afforded by purlin to panel connection.

In this research, the international codes design methods for the strut-purlin under different conditions and loads will be investigated. The finite element method eigen value and non-linear elasto-plastic analysis will be applied to investigate the interactive buckling modes and its ultimate resistance, and also to evaluate the effects of the different parameters on the element failure mode and strength. Design recommendations will be presented to help the designer engineers to account for those parameters.

1.3 Scope of Research

Strut purlins subjected to both flexural and axial loads will be investigated. Flange lipped Z-section with inclined edge stiffener will be studied. Several factors affecting the strength of strut purlin including cross-sectional dimension and geometry, member length, purlin to panel assembly stiffness, and tie rods effect will be studied.

Simply supported strut purlin will be considered using finite element analysis. Possible combinations of parameters affecting strength of strut purlins will be modeled. Effect of tie rod on strut purlin strength will be also studied. Comparison between strength of member with and without tie rods will be accomplished. Finite element results will be verified against existing previous experimental work. Also, finite element results will be compared to the provisions of the codes of practice. Treatment of strut purlins according to AISI, 2007 [7], hereafter referred to as AISI, and Eurocode 3, 1993 [20], hereafter referred to as Eurocode3 will be considered.

1.4 Literature Review

Interactive buckling in thin walled sections has attracted the attention of many researchers over the last two decades. Kandil, 1988, [27], investigated the effect of interaction between local and Euler buckling modes on the buckling behavior and strength of axially loaded columns. Bradford and Hancock, 1990, [14] studied the effect of elastic interaction between the local buckling mode and the lateral torsional buckling mode on the buckling behavior and strength of beams. Badawy Abu-Sena et al, 2001 [11 and 12] investigated the interactive buckling in lipped channel sections under axial loads. They concluded that simultaneous occurrence of the distortional/lip and torsional-flexural buckling modes results in significant reduction of critical buckling load and ultimate strength of columns.

Davies et al, 1998 [16], performed a study on buckling modes interaction in cold-formed steel columns and beams. This study detailed how distortional, local, and lateral buckling modes may occur together in conjunction with compression force and bending moment interaction. General beam theory was used as a mean to account for the interactions of buckling modes and axial forces. The authors stated that the main fault of the AISI Specification was described to be its assumption that the failure load is based on the stress in the most highly stressed fiber in compression rather than using a stress gradient throughout the section.

The behavior of purlins supporting roof panels was studied in many previous researches. However, axial strength of purlin through fastened to deck or sheeting has not attracted many researchers to investigate their buckling behavior. Results of previous researches related to buckling strength of strut-purlins are summarized below:

Stolarczyk and Fisher, 2001, [42] studied the axial strength of purlins attached to standing seam roof panels and subjected to uplift load. In most of cases uplift load results from wind suction on roof surface. Under wind load some purlins may be subjected to axial load and flexural uplift. A trial to get the axial strength of purlins undergoing flexural uplift was accomplished. Finite element analysis was used as well as series of verification tests. Numerous finite element models were built to cover practical range of purlin thickness, width, depth, and span length. Effect of purlin to roof panel connection was modeled by axial and rotational springs to restrain the point in the mid width of upper flange. Axially concentrated load and uniformly distributed uplift load was applied individually. The critical axial buckling load and the critical flexural buckling load were calculated using ABAQUS, 2001 [1]. Comparison between the finite element results and the test results showed that finite element models were not able to predict the experimental results of either the axial or the flexural load with reasonable degree of accuracy. Lack of accuracy in the finite element results was attributed to two reasons. The first reason is the approximation in the values of diaphragm stiffness and the diaphragm rotational stiffness. The second reason is that the finite element model can only model the stiffness of standing seam roof system, but it can not model the strength characteristics of the assembly by conducting linear elastic buckling analysis. In order to step over this problem the authors studied a factor that is called the axial to flexural buckling strength ratio. They claimed that this factor eliminates the inaccuracy of the finite element analysis. Accepted correlation between this factor and the section depth to thickness ratio was reported.

The axial capacity of diaphragm braced C- and Z-sections and their application to wall studs were investigated by Simaan and Pekoz, 1976 [40]. Using an energy method approach, the authors predicted the axial capacity of light gage C- and Z-sections, with flanges braced by diaphragms on one and both sides. The analytical results were then verified experimentally. An equation to predict the critical buckling load for a Z-section braced on one side with hinged ends was proposed. The critical buckling load equal the lowest root of the cubic equation of a given section with known shear rigidity and rotational restraint of the diaphragm. Computer programs were developed and presented in Simaan's thesis [39] to overcome the complexity of this design equation.

Hatch, 1991 [25], had conducted similar work in regards to strength evaluation of strut-purlins through-fastened to roof panel. The author aimed to verify that strut-purlin strength could be predicted by using the interaction equation listed in the AISI Specification. The flexural uplift strength of the purlins using the AISI Specification and the axial load strength of the purlins were calculated using the computer programs developed by Simaan and Pekoz, 1976 [39 and 40]. The author concluded that the programs developed by Simaan and Pekoz were generally enough to be applied to strut-purlins in metal building roof systems. A confirmatory testing was accomplished to achieve this conclusion.

The research conducted by Glaser et al, 1993 [21], was the basis of the design criteria listed in Chapter C4.4 of the AISI Cold-Formed Specification, 1996 [5]. The primary objective of the authors was to develop a simplified design equation that would predict the axial load capacity of C- and Z-sections with one flange through-fastened to roof panel. A parametric study was conducted using parameters required in the Simaan equations. The parametric study indicated that in the formulation of the design equation (Eq. C4.4-1) section depth, flange width, member thickness and the rotational stiffness of the deck to flange connection could not be eliminated. The remaining parameters could be ignored provided certain practical limitations were imposed. Member length was determined not to be an important parameter in the research conducted by Glaser et al [21]. This was attributed to the short wave lengths of the buckling modes experienced during failure. The buckling behavior was similar to that of a plate subject to an axial load, for both short and intermediate length purlins. It was observed that strong axis buckling would control for longer purlin lengths.

LaBoube, 1986 [28], conducted a research on through-fastened roof panel. In the determination of the axial and flexural uplift load capacity the rotational stiffness provided by the attachment of the panel and clip to the top flange of the purlin plays a significant role. The author illustrates factors influencing the rotational stiffness of the panel and clip to purlin flange assembly. It was concluded that the rotational stiffness was primarily dependent upon the purlin thickness, roof panel thickness and fastener type and location within the width of the purlin flange.

Cortese and Murray, 2001 [15], investigated single span Z-section purlin supporting standing seam roof system. The authors stated that previous research has determined that the AISI provisions for local buckling strength prediction of cold-formed purlins is not conservative and that the AISI provisions for lateral buckling strength predictions of cold-formed purlins are highly conservative. Comparison between AISI 1996 provisions and Hancock Method, which predicts distortional buckling strengths, was accomplished. Experimental work for 62 third point braced and 12 laterally unbraced standing seam roof system tests were conducted at Virginia Tech. institute. The experimental data were used to determine which of the three buckling methods most accurately predicted the strength of the Z-sections. The authors concluded that Hancock method represents the most accurate method for predicting the strength of third point laterally braced Z-purlins that support standing seam roof systems.

While not initially concerned with the effects of distortional buckling, Willis and Wallace, 1990 [45], accomplished a study to determine if fastener location plays an important role in purlin capacity in through-fastened roof systems. The authors concluded that fastener location is vital to the torsional restraint in C-section purlins, but had no effect in Z-section purlins. Distortional buckling strength predictions for C-sections were affected by fastener location. It was also concluded that the AISI Specification, 1986 [4], over estimate the purlin strengths in the local buckling mode.

The ¼-point bracing requirement by the American Iron and Steel Institute's Specification for the Design of Cold-Formed Steel Structural Members first appeared in the 1956 edition and was further tested in 1992 using different experimental setups at the University of Florida (Ellifritt et al, 1992 [19]). It was concluded that the ¼-point bracing was not required for cold-formed flexural members that are not attached to decking or sheathing. The author stated that this provision was removed in the 1996 AISI specification. It was observed that all un-braced tests failed by translation-rotational buckling and all braced (brace spacing closer than mid-point) tests failed by distortional buckling. The author stated that some of the tests, which failed by distortional buckling, failed at a load less than predicted by the lateral buckling equations of AISI specification.

Lateral buckling strengths of cold-formed Z-section beams was studied by Pi et al, 1997 [32]. A nonlinear inelastic finite element model for analyzing cold-formed Z-sections and the effect of lateral-distortional buckling was discussed. This model takes into account the effects of web distortion, the rotation of a yielded cross-section, pre-buckling in-plane deflections, initial imperfections, residual stresses, material inelasticity, and the effects of a stiffening lip. The authors concluded that cold-formed Z-sections need to be braced at frequent intervals to develop their full moment capacity, and that Z-sections with web distortion have a lower strength prediction than sections without web distortion.

Schafer and Pekoz, 1998 [35], studied the laterally braced cold-formed steel flexural members with edge stiffened flanges. It was concluded that traditional design methods for cold-formed steel takes into account local buckling, but not distortional buckling. The object of their study was to determine a unified width treatment of distortional buckling, and to achieve more accurate results than the slightly conservative Sharp method [38], and modified Lau and Hancock method. The authors presented a new hand design method based on the unified effective width approach for strength prediction considering distortional buckling. New expressions for the prediction of local and distortional buckling were used in this new design method. A new approach for the determination of the web effective width was also presented. A comparison between the developed design method and experimental data was also presented. This resulted in a more accurate and precise strength predictions than the AISI specification.

Neubert and Murray, 2000 [31], estimated the restraint forces for Z-purlin roof under gravity load. They stated that the restraint force for Z-purlin according to 1996 AISI specification for the design of cold-formed steel structures need refinement, the AISI, 1996 [5] formulations are empirical, have an incorrect treatment of roof slope and system effect, and ignore the effect of panel stiffness on restraint force. So that, a new restraint design force procedure was proposed. Elastic stiffness models, with varying roof slope panel stiffness and cross-sectional properties, were used. A new treatment of

Z-purlin has led to a more accurate method of addressing roof slope. Single and multiple span system with five bracing system (support, third-point, midspan, quarter point, and third-point plus support restraint) were examined and included in the proposed procedure.

An experimental program was accomplished by Lee and Murray, 2001 [29], in order to determine the required lateral restraint forces for Z-purlin supported by sloped metal roof systems. Testing was conducted on single span and multiple span metal roof systems. Z-purlin was used with both through-fastened and standing seam roof panel for six roof slopes from 1:12 to 4:12. Restraint forces were measured at five restraint locations in each span; support, third-point, midpoint, quarter-point, and third-point plus support. Based on experimental results, the authors proposed a prediction equation, relying on engineering principles, because the current provisions in the specification are empirical and based on statistical analysis. The authors concluded that the measured restraint forces determined from the experimental test program were inconsistent with the predicted restraint forces.

Bracing requirements of cold-formed steel C-strut subjected to axial compression was studied by Green et al, 2006 [22]. An experimental testing program was carried out on single axially loaded cold-formed lipped C-studs to determine the required flexural and torsional bracing strength and stiffness requirements of the stud. The brace stiffness that was achieved ranged from less than 30 lbs/in. to greater than 4000 lbs/in. The axial load, individual brace forces, axial shortening, and in-plane (weak-axis) and out-of-plane (strong-axis) lateral displacements were measured. The required bracing stiffness was experimentally determined by varying the brace stiffness for a given strut size and was based on the ability of the stud to develop its nominal axial compressive capacity. Figure 1.5 shows the bracing configuration used by Lee et al [29]. The authors stated that the current provisions of the North American Cold-Formed Steel Specification, 2001 do not specify the minimum requirements of the bracing strength and stiffness for structural wall stud assembly systems. Based on the results of this research the authors made valuable observations concerning the axial capacity of cold-formed C-strut, bracing strength and stiffness, partial base fixity, and initial geometric imperfection.

1.5 Overview of Study

Purlins may be considered as a flexural load carrying member. When Z-purlins are subjected to flexural load causing bending moment, their response will be affected by the axis about which the bending moment acts. Each of gravity and wind uplift loadings act nearly parallel to the web. Z-section is a point symmetric section, and its principal axes are not parallel to both the cross-section web and flange. When such section is subjected to flexural uplift, it causes bending moment about X-axis that is perpendicular to the web. The bending moment may be resolved to its principal components about x'- and y'-axes as illustrated in figure 1.4. The purlin will deform laterally and rotationally as shown in figure 1.6. When Z-purlins are through fastened to deck or sheeting, its behavior will be different. The deck or sheeting attached to top flange restrains it laterally and rotationally. The deformation of purlin due to bending moment about X-axis caused by flexural uplift is shown in Figure 1.7. The horizontal deformation is strongly reduced by the presence of deck or sheeting. The rotation of the cross-section is also reduced. The bottom flange is completely free to deflect laterally and rotate about cross-section top flange.

The buckling of Z-purlin due to bending moment about X-axis also will be affected by the presence of deck or sheeting. When Z-purlin is not attached to deck or sheeting, it will tend to buckle in one of three modes of buckling. These modes are local buckling, distortional buckling, and lateral-torsional buckling modes as shown in figure 1.8.

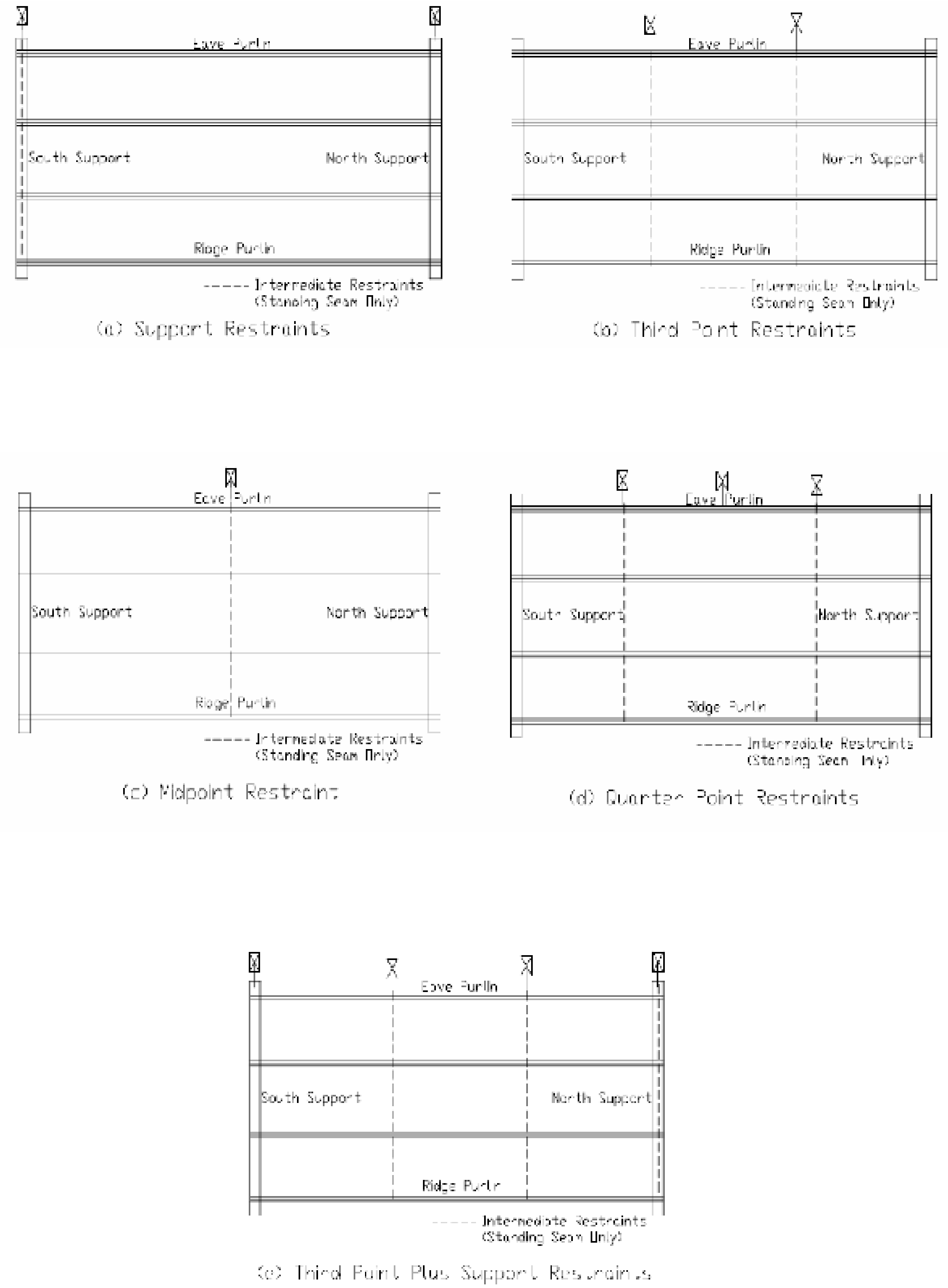


Figure 1.5: Bracing Configurations (Lee et al 2006[29])

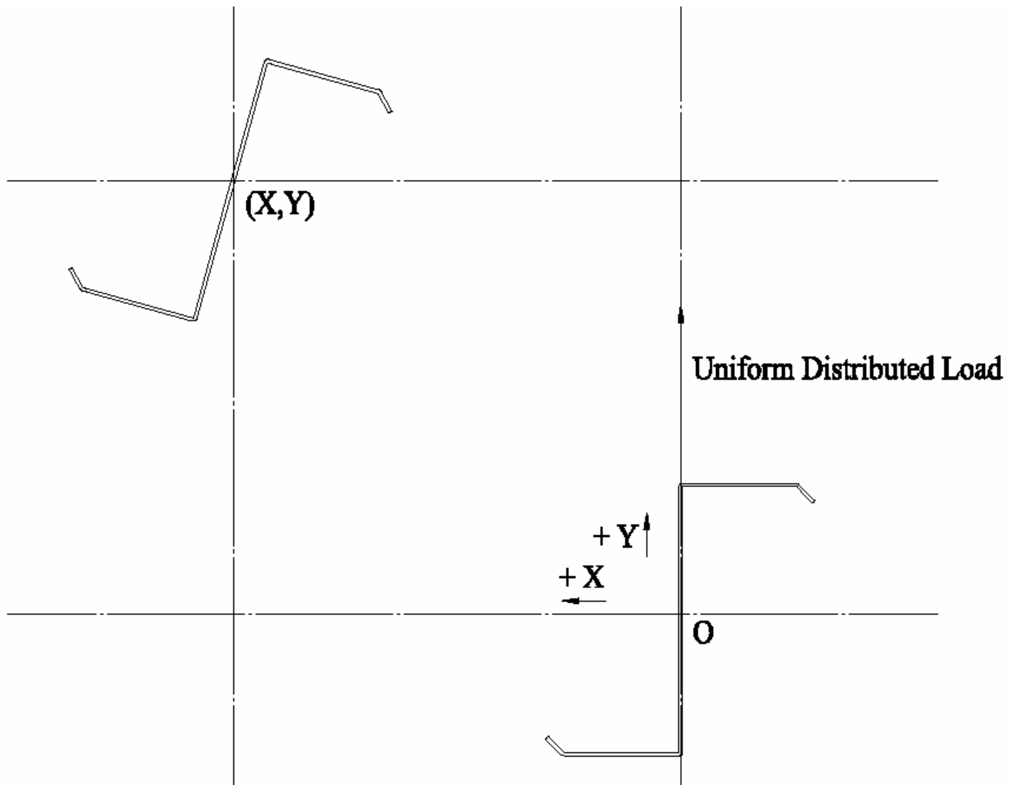


Figure 1.6: Purlin Midspan Deflection without Presence of Panel

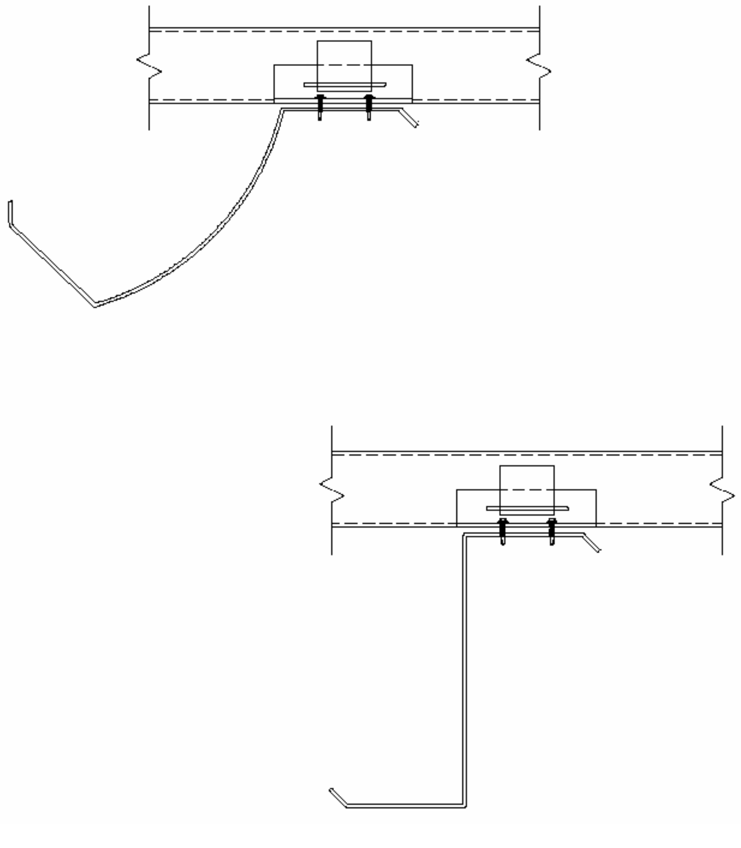
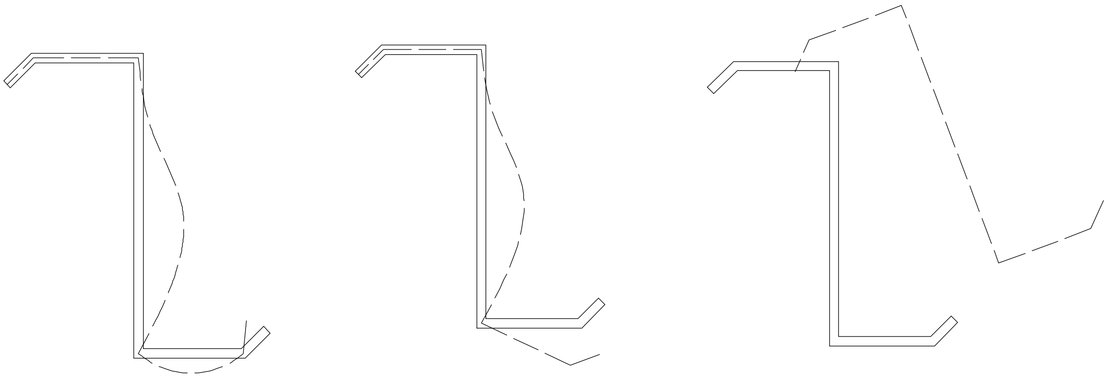


Figure 1.7: Midspan Deflection of Purlin Attached to Panel Subject to Uplift Load



a- local buckling *b- distortional buckling* *c-lateral-torsional buckling*

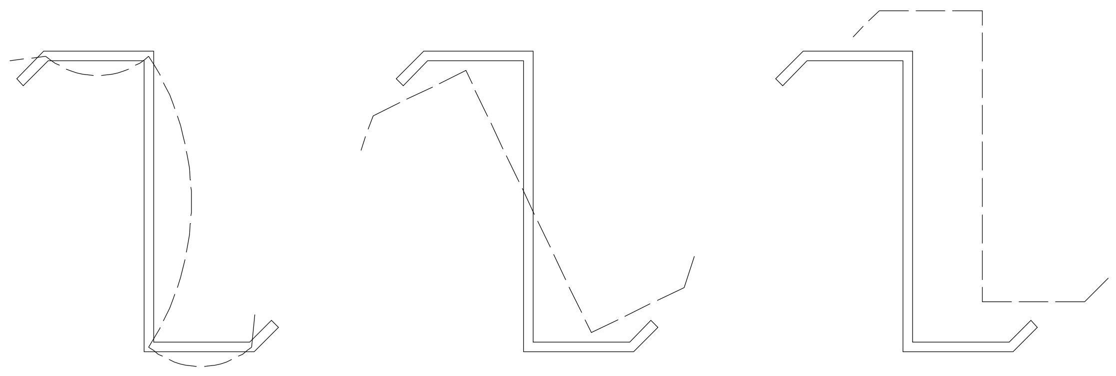
Figure 1.8: Individual Buckling modes of a Z-purlin due to uplift loading

Local buckling of a Z-section purlin is the internal buckling of the section's elements so that there is no relative movement of the nodes; both corners of the compression element remain in longitudinal alignment and the adjoining lip, flange, and web elements buckle by plate flexure at half-wavelengths comparable with the flange width (Rogers and Schuster 1997 [34]). Lateral-torsional buckling is a rigid-body translation of the purlin without any change in the purlin cross-sectional shape (Hancock et al. 1998 [23]). It is important to note that when a cold-formed Z-section under flexure is unrestrained laterally between supports, it is liable to displace laterally and twist after yielding, and the full strength of the cross-section cannot be reached unless the section is laterally braced at frequent intervals (Pi et al. 1997 [32]). Distortional buckling occurs when flange and lip of open lipped section are subjected to compressive stress caused by either axial forces or bending moment. In this case flange and lip are liable to buckle. Restraint against distortional buckling is provided by transverse bending stiffness of cross-section and flexural rigidity of flange and lip itself. Distortional buckling entails deformation of the cross-section, and therefore it can be alternatively referred to as "deformational buckling". Presence of deck or sheeting will not affect the local buckling mode, while the distortional buckling mode will be slightly affected. Overall buckling modes (torsional-flexural buckling, and lateral- torsional buckling modes) will be strongly affected by restraint provided by deck or sheeting.

When Z-purlin is subjected to axial load, it will deform axially. The axial deformation is not be affected by the attachment of top flange to deck or sheeting, while buckling of the member will be affected by the sheeting. If Z-purlin is free, it will experience local, torsional, or flexural buckling modes. Local buckling of Z-purlin subjected to axial force occurs all over the cross-section. Web, flange, and lip plates buckle in the plane of cross-section. This mode is initiated from the web which has the largest height / thickness ratio. In this mode all corners of cross-section does not translate and the maximum translation occurs at middle of web plate. The web buckles such that web height represents the half wave length of buckling wave. In the longitudinal direction the member has several waves of half wave length equal to web height. The torsional buckling mode is an overall buckling mode. The member rotates about its longitudinal axis passing through cross-section shear center. Member has maximum amplitude of rotation at mid-span. The flexural buckling is also an overall buckling mode. It occurs due to the tendency of the member to deform flexurally about the weak principal axis. So, the member has lateral displacement in direction of major principal axis with maximum amplitude at mid-span. In overall buckling modes there is no change in cross-section shape.

In the presence of deck or sheeting, buckling of axially loaded member is affected. Deck or sheeting have insignificant effect on local buckling mode, while torsional and flexural buckling modes are strongly affected due to lateral and torsional stiffness of panel. An interactive buckling mode occurs in the presence of deck or sheeting between torsional and flexural buckling modes. This mode is called torsional-flexural buckling mode. In this mode the member has both translation in the direction of major principal axis and rotation about longitudinal axis. Values of translation and rotation will be affected by panel lateral and rotation stiffness.

In the presence of deck or sheeting, Z-purlin will buckle in local buckling mode without any change. Torsional or flexural buckling modes are affected by the torsional and lateral restraint by deck or sheeting. The different individual buckling modes of Z-section are shown in figure 1.9.



a- local buckling *b- torsional buckling* *c- flexural buckling*

Figure 1.9: Individual Buckling modes of a Z-purlin due to axial compressive force

In the case of Z-section acts as a strut-purlin through fastened to deck or sheeting. Interaction of aforementioned bucking modes will occur. Both of individual buckling modes due to bending moment and individual buckling modes due to axial force will occur and produce new modes. The buckling load of interaction mode will always be smaller than of individual buckling modes.