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Strengthening Method for Thin Steel Roof Batten Subjected To Pull-Through Failure

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Abstract: Cold-formed steel (CFS) sections are commonly used in modern building construction. When used as secondary roof purlins, CFS sections are often attached to trapezoidal sheets through self-drilling or self-tapping screws to form a complete roofing system. The hat shaped cold formed steel sections are commonly used as batten member in light-weight steel constructions, such as residential, industrial and commercial buildings. Failures of the connections of thin-walled steel roof battens to rafters or trusses were increasingly observed in the form of a localized pull-through failure in the batten bottom flanges during recent extreme wind events. Therefore, a detailed numerical study was undertaken by developing suitable finite-element models with the inclusion of a suitable failure criterion to predict the initiation of critical pull-through failures of roof battens. The failure load value of batten is taken from previous experimental results as a base criterion. For this load total deformation, equivalents stresses and maximum principal stresses are compared between all the proposed models. First the analysis is carried out for some existing strengthening methods and then analysis of proposed methods is completed.

Keywords: **Cold-formed steel structure, steel roof batten, Light gauge roofing system, Pull through Failure, Finite Element Analysis, ANSYS software.**

1. INTRODUCTION

A. General

Light-gauge steel roofing systems made of high-strength and thin (0.42 to 1.20 mm) steel roof sheeting and battens (Fig. 1) are highly susceptible to premature failures during extreme wind events, such as tropical cyclones, tornadoes, and thunderstorms. Past wind damage and research investigations showed that connections of roof sheeting to battens (Fig. 1) prematurely failed at their screw fastener connections, causing substantial losses of roof sheeting (Morgan and Beck 1977; Beck and Stevens 1979) [1]. In most cases, pull-through failures of roof sheeting were observed in which the screw fasteners connecting thereof sheeting to the battens pulled through the thin steel roof sheeting as shown in Fig. 2. However, many research studies (Xu and Reardon 1993[2]; Mahendran 1994[3], 1995a [4]; Xu 1995[5]; Mahendran and Tang 1998[6]; Mahendran and Mahaarachchi 2002[7]; Mahaarachchi and Mahendran 2004[8], 2009[9]) investigated the pull-through failures of roof sheeting and developed suitable test and design methods to enhance the safety of these roof connections. In addition, the use of cyclone washers (Fig. 1) was identified as an effective strengthening method to further enhance the safety of connections of roof sheeting to batten since extreme wind events (Xu and Reardon 1993[2]; Mahendran1995b).

However, roof failures continued to occur, notably as observed during recent extreme wind events. Previous wind-damage researches (Henderson and Leitch 2005; Henderson et al. 2006; Boughton and Falck 2007, 2008) [1] showed that the location of failure had moved to the connections of the roof battens to rafters or trusses (Fig. 1), which resulted into loss of roof sheeting as well as battens. It has been observed that the connection failed in the form of a localized pull-through failure in which the screw fastener connecting roof battens to rafters or trusses pulled through the bottom flanges of the roof battens, as shown in Fig. 3.

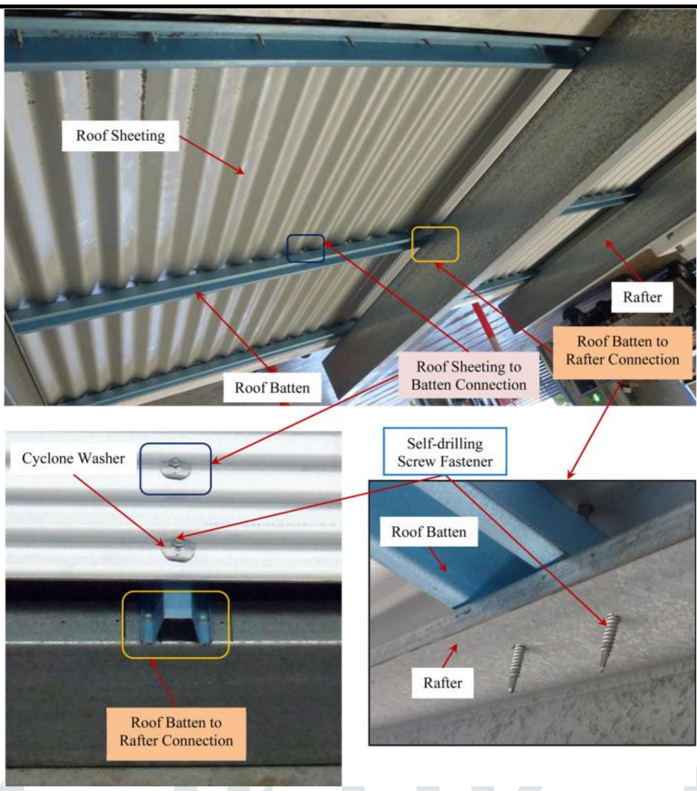

Figure 1. Typical thin-walled steel roof structure and connections

The wind-uplift load acting on the batten top flange via fastener connections of the roof sheeting to the batten screw created large stress concentrations in the batten bottom flange at the edge of the screw fastener head closer to the batten web (Fig. 3).This led to a tearing failure around the edge of the screw fastener head in a semi-circular shape and a complete disengagement of both roof sheeting and battens. This pull-through failure mode of roof battens significantly differs from the previously researched pull-through failure mode of roof sheeting, which is related to a splitting failure mechanism (Fig. 2). Therefore, an extensive research study consisting of experimental investigations was undertaken at Queensland University of Technology (QUT), and suitable test and design methods were proposed to accurately determine the pull through capacities of roof battens (Sivapathasundaram and Mahendran 2016a, b, 2017) [1]. The presence of large stress concentrations including high longitudinal membrane strains around the screw connections under wind uplift loading was the main reason for pull-through failures. Local pull-through failures can be caused by simple static or low cycle fatigue loading that occurs during high wind events [23]. An inspection of trapezoidal steel roofs has shown that roofing has been split in the transverse direction due to accidental or poor workmanship-caused overtightening of screw fasteners [26].

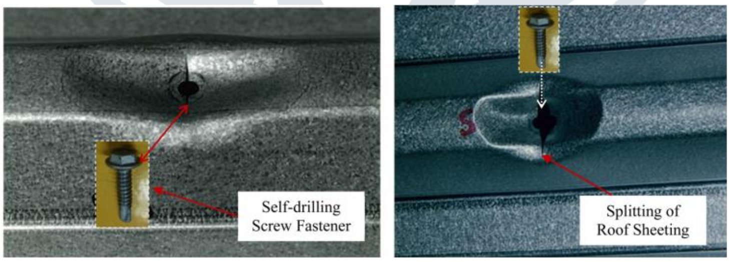

Figure 2. Roof sheeting pull-through failures [1]

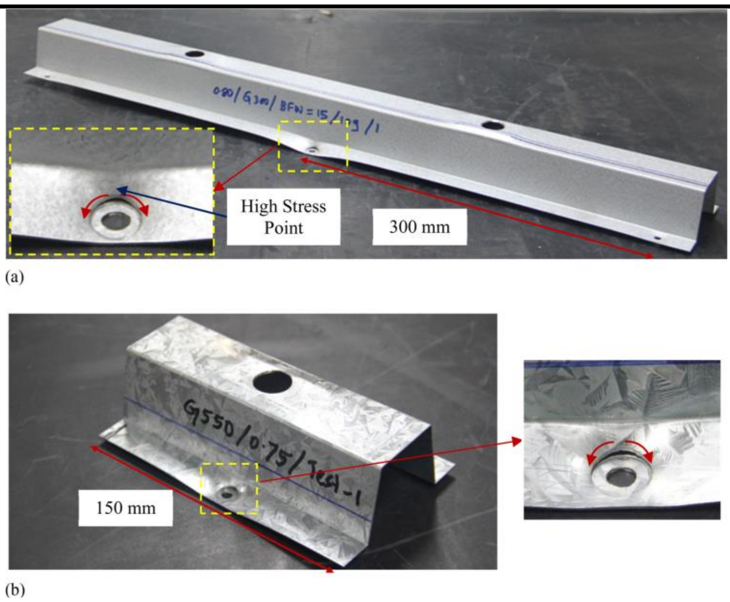

Figure 3. Roof batten pull-through failures [1]

B. Cold-formed steel (CFS)

Cold-formed steel (CFS) sections are commonly used in modern building construction. When used as secondary roof purlins, CFS sections are often attached to trapezoidal sheets through self-drilling or self-tapping screws to form a complete roofing system. Most purlin members are of thin-walled open cross section, which means that they are susceptible to buckling when subjected to roof loading at the top flange in either an upward or a downward direction. The load application points, where the sheeting/purlin connections are located, are often eccentric to the shear center, and thus inevitably generate a torsional moment that will induce twisting and/or warping deformations in addition to bending deflection. This type of complexity associated with the loading conditions will be exacerbated by the occurrence of single- or mixed-mode buckling (e.g. overall, distortional and local buckling) due to compression flanges tending to move sideways. The connections between purlin and roof sheeting provide a restraining effect on purlin members by preventing such lateral and twisting movements, and thus have a beneficial effect on their load-carrying capacity. InDesign practice, this effect should be taken into account from a design-efficiency perspective. In the analysis and design of thin-walled cold-formed steel elements, rules and methods normally applicable for joints made of hot rolled or welded sections cannot be applied. Failure modes of shear and tensile joints of cold-formed steel elements differ from failure modes occurring in traditional steel structures [30].

C. Finite Element Analysis

The objective of FEM analysis is not to describe reality as accurately as possible, but to find the simplest model resulting in a sufficiently accurate description of reality [17]. In a typical finite element model, there are over 2000 nodes, 1200 solid elements and 1000 contact elements [18]. It is observed that the magnitude of critical damage parameter decreases with the increase in mesh size [19]. ANSYS is capable of conducting three-dimensional finite element analysis considering both geometric and material non linearity. It includes contact elements and constraint conditions necessary for modeling complex systems [21]. FE analysis provides a relatively inexpensive and time efficient alternative compared with physical experiments. Itis essential to have a sound test data on which to calibrate a FE model.

D. Aim

To perform a numerical analysis to get strengthening method for thin steel batten subjected to pull through failure to delay or prevent localize connection failure and improve pull through capacity.

E. Objectives

- To determine pull-through capacity of thin steel roof batten using ANSYS software.
- To set a base criteria to validate the experimental test results with ANSYS software results.
- To check various models of batten using suitable attachments for improving pull-through capacity.
- To compare results based on stresses induced at bolt location and suggest the best suitable method to improve pull-through capacity.

2. PROBLEM STATEMENT

A topspan 4055 hat section thin steel roof batten of material Aluminium Zinc alloy coated steel is used as a test specimen. The material and section is selected according to previous study. By varying the parameters there are total 8 models that have been tested. Models are needed to be tested for tensile loading (Pull due to wind loading). Finally according to stress generated at bolt location in bottom flange the pull-through capacity has to be determined.

The section is having dimensions as follows:

Top flange width = 32 mm Bottom flange width = 14 mm
Total bottom width = 75 mm Height = 40 mm
Length of test specimen = 150 mm Thickness of section = 0.55 mm

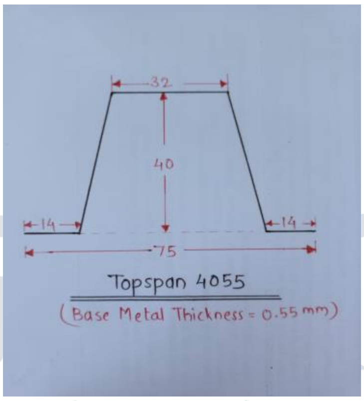

Figure 4. Topspan4055 Hat Section

3. THEORITICAL CONTENT

There are four currently used strengthening methods.

1. Four Screw Fastener Connections:

Many roof batten manufacturers recommend using four screw fastener connections (fig. 6) (two screw fasteners on each bottom flange side) instead of the typical two screw fastener connections(one screw fastener on each bottom flange side) to improve the roof batten performance under high wind uplift loads. The benefit of using four screw fastener connections over two screw fastener connections was assessed by comparing the total failure loads. (Mayooran Sivapathasundaram and Mahen Mahendran 2018) [1]. Topspan 4055 roof batten tests conducted with four 10-gauge screw fastener connections and a screw fastener spacing of 20mm provided a mean total failure load of 6.79 kN, whereas Topspan 4055 roof batten tests conducted with two 10-gauge screw fastener connections provided a mean total failure load of 4.02kN (Sivapathasundaram and Mahendran 2016a) [10]. Hence, the total capacity-improvement factor of using four screw fastener connections over two screw fastener connections was determined to be 1.69. The first pull-through failure mode is always initiated by a tearing fracture of the thin steel batten bottom flange around the edge of the screw fastener head that carries the highest load among the four screw fasteners. The premature failure of one screw fastener connection triggers the complete failure of a connection with four screw fasteners. Equal load sharing among all four screw fasteners is applicable only until the first pull-through failure. These findings again portray an important fact that the use of connections with four screw fasteners instead of conventional connections with two screw fasteners does not double the failure loads as anticipated. Hence, suitably reduced capacity-improvement factors are reported based on the test results in this section.

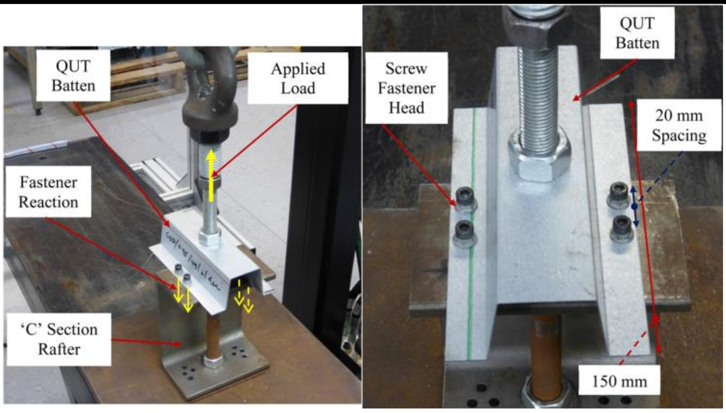

Figure 5. Four screw fastener connection

2. Rectangular-Shaped Screw Fastener Head Connection:

Because increasing the screw fastener head size (from 10 to 12 gauge) did not significantly increase the pull-through capacities of G550 steel roof battens (Sivapatha sundaram and Mahendran 2016a) [10], roof batten tests were conducted using10 X 15mm rectangular-shaped screw fastener heads The width of 10mm was chosen based on the minimum bottom flange width of 12mm, and the length of 15mm was chosen based on the size of the larger screw fastener head (12-gauge screw fastener head diameter of 14.5mm). The tests were conducted using G550 0.55- and 0.7-mmsteel roof battens. The test with the G550 0.75-mmsteelroof batten showed a pull-through failure mode, whereas the test with G550 0.55-mm steel roof batten showed a pull-through failure mode and a splitting failure mode at the corner of the bottom flange and web (Fig. 7). The pull-through failure loads of 3.38 and4.97 kN were determined for G550 0.55- and 0.75-mm steel roof battens, respectively (i.e., improvements of 63.3 and 39.6%).Although this fastening method gave a higher strength improvement for G550 steel roof battens compared with the connections with four screw fastener, specific screwdrivers are needed to install them properly in the bottom flanges (without damaging the batten web as a result of the rotation of the rectangular screw fastener head). In addition to this practical concern, the use of this particular fastener arrangement indicated the possibilities of localized failure moving to the corner of the web and bottom flange in the form of a splitting failure (Fig. 7). Further, there was a larger variation in the strength improvement.

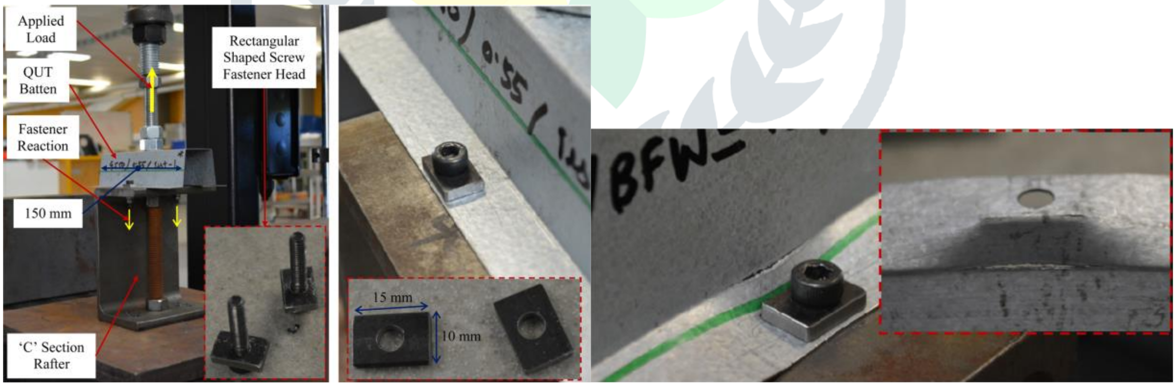

Figure 6. Rectangular-Shaped Screw Fastener Head Connection

3. Raised Fastener Head Connection:

Because the pull-through failure of roof sheeting is caused by the screw fastener head pulling through the screw fastener hole compared with the pull-through failure of the roof batten caused by the screw head pulling around the edge of the screw head, some roof batten tests were also attempted using fasteners with raised screw heads (Fig. 8). Despite the expectation that the use of raised fastener heads may change the failure mode to be similar to that observed with roof sheeting connections and possibly lead to higher failure loads, the tests showed a different ultimate failure mode in which the fastener shank caused an edge-tearing failure (Fig. 9). Because the raised fastener head was not in full contact with the bottom flange to form a firm connection (i.e., typical connection of roof batten to rafter or truss), the failure mode observed in these tests was dominated by shear forces in the fastener instead of tensile forces. Because the edge distance was small, it was governed by a shear action and associated failure. The failure loads (per screw fastener) of 2.80 and 3.76 kN were determined for G550 0.75- and 0.95-mm roof battens, respectively. Because these failure loads are significantly lower than the pull through failure loads (Sivapathasundaram and Mahendran 2016a) [10], it is recommended that this type of fastener connection is not used with roof battens.

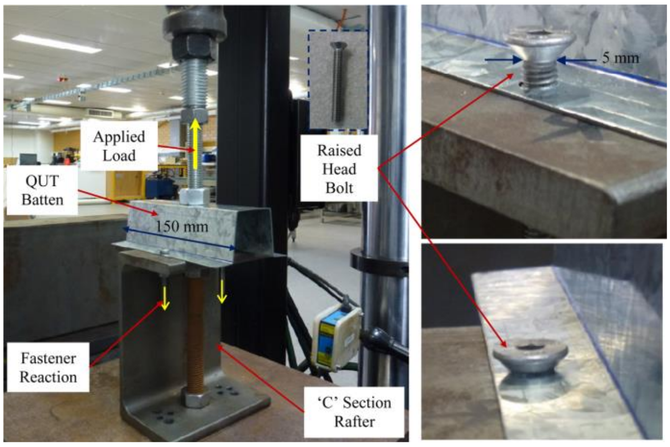

Fig. 8(a) Raised head bolt connection [1]

Figure 7. Raised head bolt connection failure pattern [1]

4. Use of bracket at connection:

A suitable solution was to strengthen the entire roof batten section at the connections of the batten to the rafter or truss. Hence, author used 150-mm-long roof battens as brackets at the connections of the roof battens to the rafters or trusses and conducted two-span batten tests to determine improvement of the pull-through capacity as a result of the presence of two bottom flanges. Also assumed that it can eliminate or delay other failures, such as splitting failures at the corner of the web and bottom flange and the bending failure of battens. The tests conducted without brackets showed typical pull through failure modes of the roof battens. However, the tests conducted with brackets showed member failure modes of the roof battens at the loading points (midspan). Because the use of bracket at the critical central support delayed the pull-through failure mode, it caused the member to fail at midspan. Although the screw fastener head initiated a typical pull-through failure mode in the bracket section at the critical central support, it was not able to completely pull through both the bracket and the main roof batten because of the occurrences of member failures. Despite the fact that a complete pull-through failure mode was not observed in the tests conducted with brackets, the critical central support reaction at the member failure point was considered in the failure load comparisons. The average central support fastener load of 3.76 kN at failure for Topspan 6160 battens with brackets was54.5% higher than that of the same battens without brackets (2.43 kN). Similarly, the average central support fastener load of5.26 kN for Topspan 6175 battens with brackets was 58.5% higher than that of the same battens without brackets (3.32 kN) [1]. These two comparisons indicate that the use of brackets at the critical central support of a two-span batten system delayed the typical pull through failure mode with a consistent strength enhancement of more than 50%[1].The pull-through capacity of roof battens with brackets could not be determined from the two-span batten tests because such failures did not occur. However, the pull-through capacity can be determined using suitable small-scale test results without assuming it as twice the pull through failure load from the roof batten tests conducted without brackets. Therefore, a set of short batten tests was conducted. This finding implies that a capacity improvement of 85% is achievable[1] by employing the recommended strengthening method using 150-mm-long brackets at the connections of the roof batten to the rafter or truss for the commonly used shorter roof batten spans (450 or 600 or 750mm) that are very likely to be governed by localized pull-through failures.

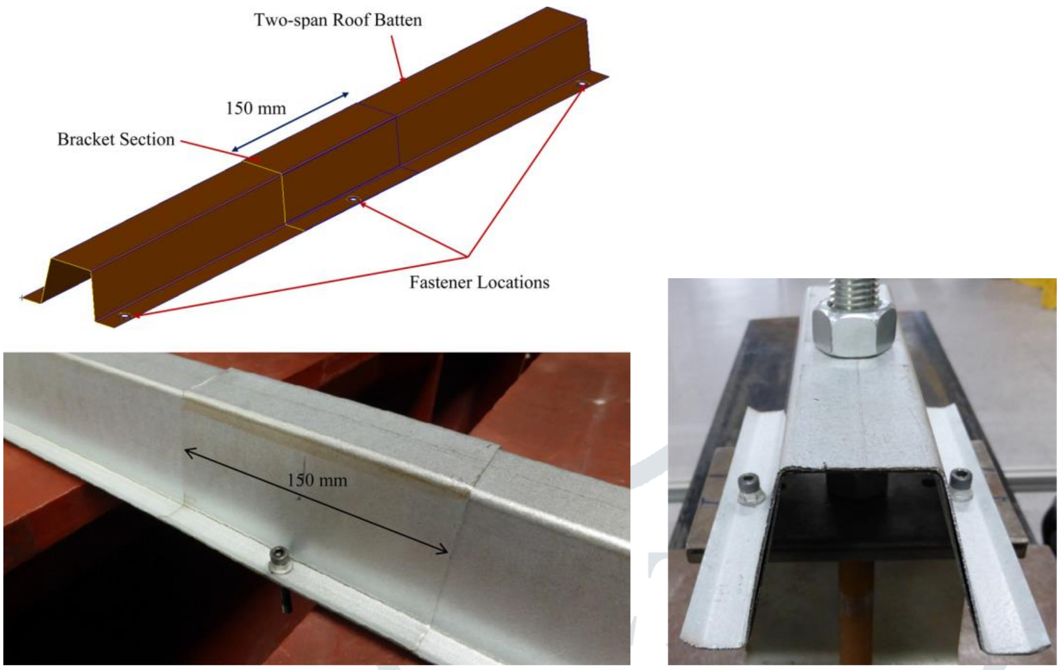

Figure 8. Two span batten with bracket and Short span batten with bracket [1]

4. METHODOLOGY

By taking into account all the existing methods of strengthening the roof battens and their limitations, it is decided to determine the pull through capacity of the battens which are strengthened by various attachments. As experimental analysis is time consuming numerical analysis method is used with the help of "ANSYS" software. The models with different attachments are generated using "Solid Works" software. They are converted in required format and imported into ANSYS software and analyzed by giving specific inputs.

There are total eight models generated using solid works software. The hat section roof batten is the specimen on which analysis is carried out. Topspan 4055 hat section is used as a reference from previous work which is most commonly used industrial roof batten section in Australia. Topspan 4055 refers to height of section as 40 mm and base metal thickness as 0.55 mm. Overall section dimensions are as height of section is 40 mm, width of top flange is 32 mm, width of two bottom flanges are 14 mm each and overall bottom width is 75 mm. As we have to analyze the section as a short batten the length of section is taken as 150 mm. The material used for section is Zinc-Aluminium alloy coated structural steel generally indicated as (G550) having yield strength of 550 MPa. In a making of G550 grade steel sheet annealing is carried out in a hot dip coating line prior to application of either a zinc or an aluminum/zinc coating.

In proposed eight models four models are connected to the principal rafter or roof truss by two screw fasteners (one screw fastener on either side of section at bottom flange) and remaining eight models are connected using four screw fasteners (two screw fasteners on either side of section at bottom flange). There are total four variations in the attachments used for creating models. First model is simply a section as per specified dimensions without any attachment (Fig. 11). Second model consist of 150 mm long bracket made up of same material as roof batten placed over a main member (Fig. 12). In third model two flange plates are used (Fig. 13) to support the bottom flanges which are the critical location of pull through failures. Fourth model also consist a bracket as in second model but having extended bottom flanges to increase the thickness of bottom flange (Fig. 14). All this four models are connected to principal rafter with the help of two screw fasteners. The next four models are exactly same in geometry as first four models but they are connected to principal rafter using four screw fasteners.

All these eight models are fixed at its bolt connection location. The tensile load in the form of surface loading is applied at the top flange as wind load is acting on it. The output of results is in the form of Equivalent (von-Mises) stresses and maximum principal stresses. As we do not directly get the value of failure load, this method is treated as indirect method of analysis. Numerical analysis is carried out with the help of using software. According to stress values the load carrying capacity is compared between various models. The variations of models are as given below:

Model 1: Roof batten connected with two screw fasteners
Model 2: Roof batten with bracket and connected with two screw fasteners
Model 3: Roof batten with flange plates and connected with two screw fasteners
Model 4: Roof batten with bracket having extended flanges and connected with two screw fasteners
Model 5: Roof batten connected with four screw fasteners
Model 6: Roof batten with bracket and connected with four screw fasteners
Model 7: Roof batten with flange plates and connected with four screw fasteners
Model 8: Roof batten with bracket having extended flanges and connected with four screw fasteners

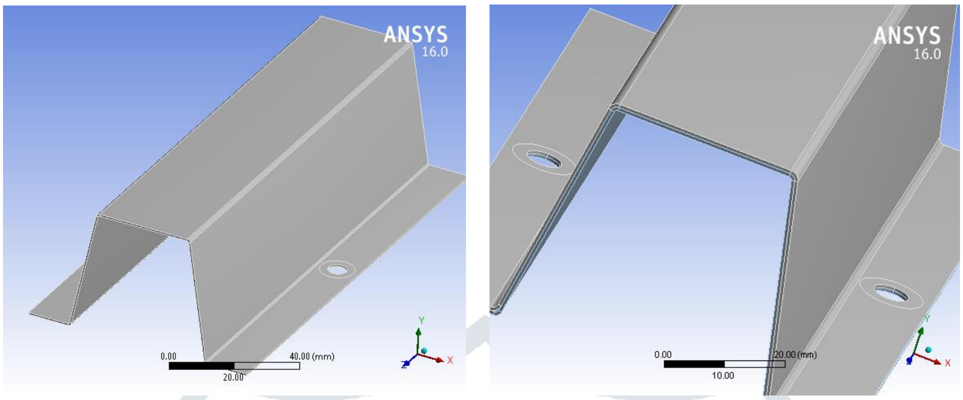

Figure 9. Model 1 & 2

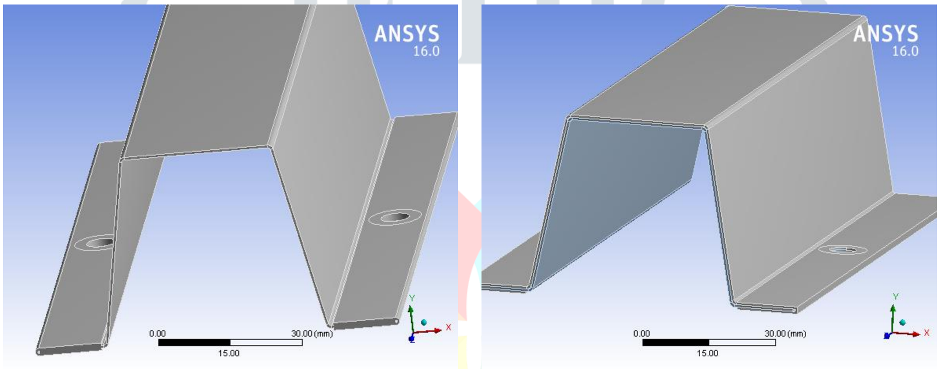

Figure 10. Model 3 & 4

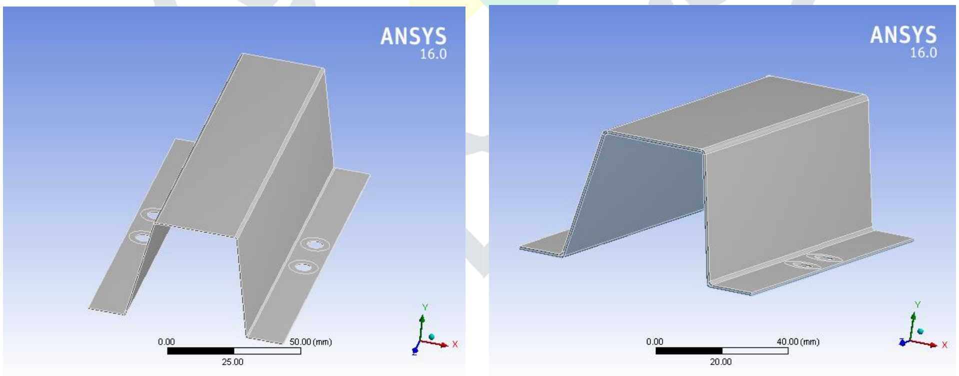

Figure 11. Model 5 & 6

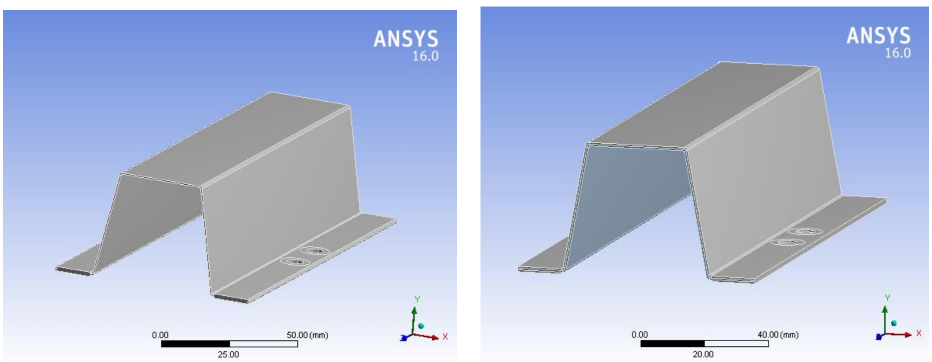

Figure 12. Model 7 & 8

Topspan 4055 roof batten tests conducted with two 10-gauge screw fastener connections provided a mean total failure load of 4.02kN (Sivapathasundaram and Mahendran 2016a). As per these previous experimental results the value of tensile load of 4000N applied on the specimen in this study for a single section (in model 1). As the previous research work aimed at improving the pull through capacity up to double, for analysis of every model with additional attachments the tensile load is considered as 8000N.

After starting ANSYS the material is added as zinc aluminum alloy coated steel of grade (G550) by giving the properties of material as density equal to 6300 kg/cu.m, Young's modulus equal to 214 GPa, and poisson's ratio equal to 0.29. After adding material the model is imported from solid works to ANSYS. For finite element analysis meshing is generated. The location and intensity of load is given to section. Fixed support at specific location is provided. Outputs are defined in the form of Equivalent (Von-Mises) stresses, Maximum Principal Stresses and Total Deformation which are the main parameters for comparing results. Same procedure is followed for analysis of all the models. Finally results are discussed.

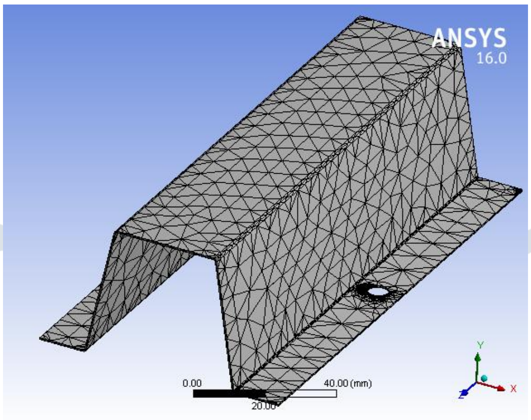

Figure 13. Meshing generated in ANSYS

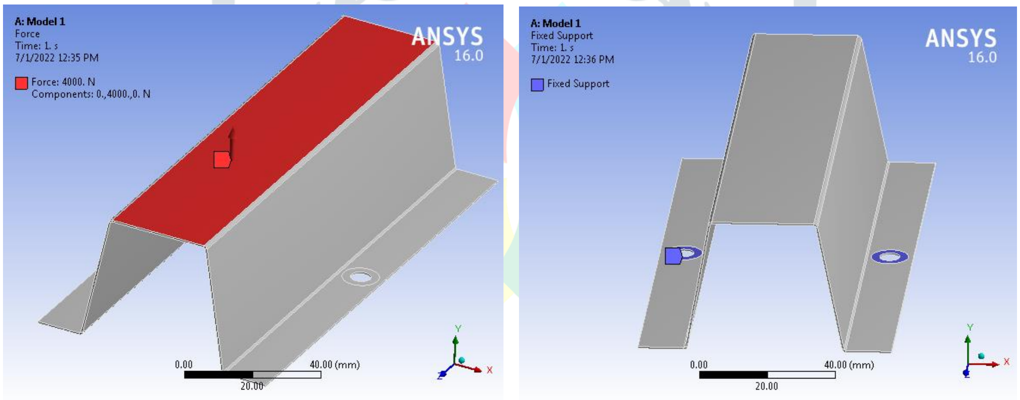

Figure 14. Tensile Loading and Fixed Support Location

5. RESULTS

After the numerical analysis using ANSYS software we get the following results.

Table 1 shows the result obtained from the four models which are connected to principal rafter with the help of two screw fasteners. For all models material used is Aluminium-Zinc alloy coated steel of grade G550. There are four models which are prepared with different geometrical arrangements.

Table 1: Comparison of Equivalent stresses and Maximum Principle stresses obtained from numerical analysis for different models connected with **two** screw fasteners.

Model No	Description	Applied Load (kN)	Maximum Equivalent Stress (MPa)	Maximum Principal Stress (MPa)	Location of maximum stress
1	Single Batten	4	2653.6	2692.7	At screw fastener in bottom flange
2	Batten with bracket	8	1871.5	1304.6	At screw fastener in bottom flange
3	Batten with flange plates	8	2201.2	2600.8	Centre of top flange
4	Batten with bracket having extended flange plates	8	1351.9	1104.7	In the top flange

Table 2 shows the result obtained from the four models which are connected to principal rafter with the help of four screw fasteners. For all models material used is Aluminium-Zinc alloy coated steel of grade G550. This table also consists of four models as table 1 but having only variation in their connection type.

Table 2: Comparison of Equivalent stresses and Maximum Principle stresses obtained from numerical analysis for different models connected with **four** screw fasteners.

Model No	Description	Applied Load (kN)	Maximum Equivalent Stress (MPa)	Maximum Principal Stress (MPa)	Location of maximum stress
5	Single Batten	8	2350.7	2559.0	Centre of top flange
6	Batten with bracket	8	909.36	1054.4	Centre of top flange
7	Batten with flange plates	8	2116.5	2591.8	Centre of top flange
8	Batten with bracket having extended flange plates	8	1135.5	1072.8	At the top flange edge

Results of model 1:

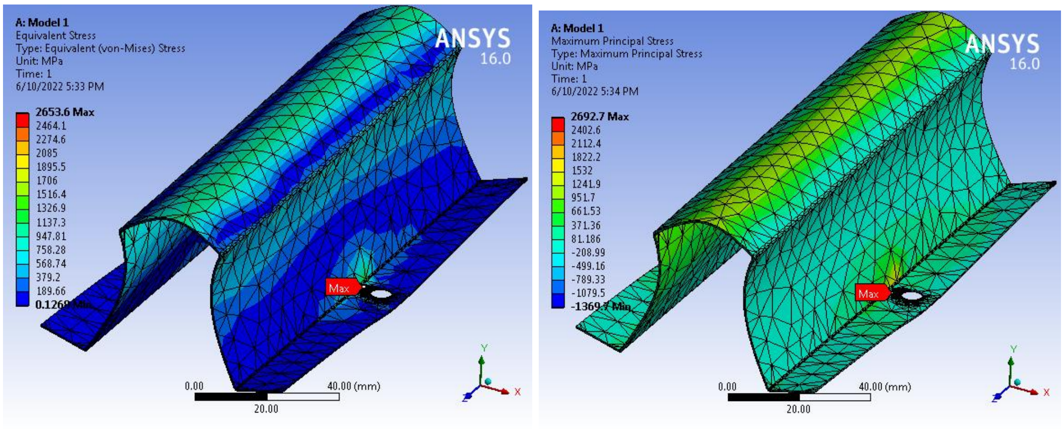

Figure 15. Model-1 Equivalent Stress, Maximum Principal Stress

Results of model 2:

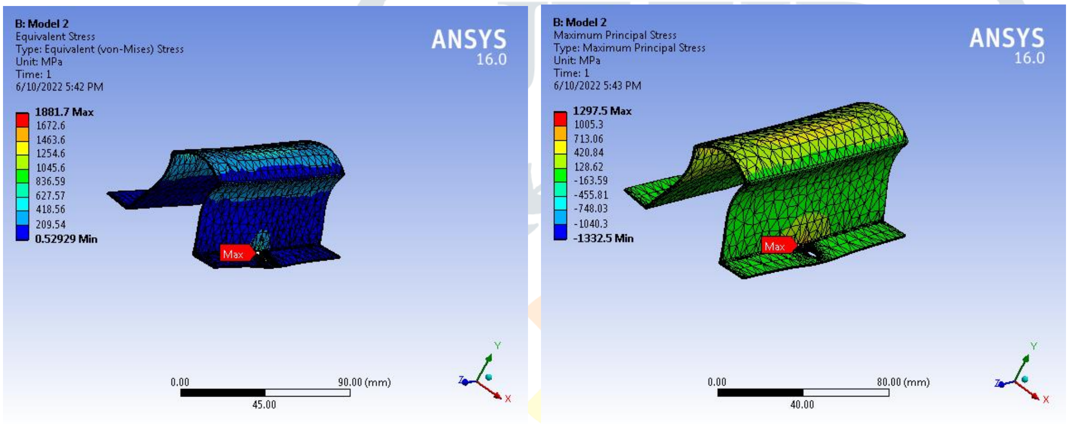

Figure 16. Model-2 Equivalent Stress, Maximum Principal Stress

Results of model 3:

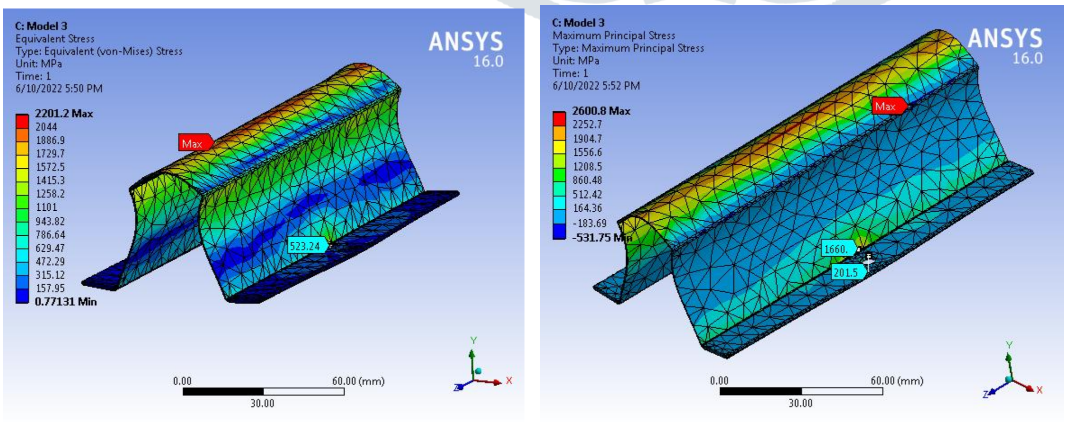

Figure 17. Model-3 Equivalent Stress, Maximum Principal Stress

Results of model 4:

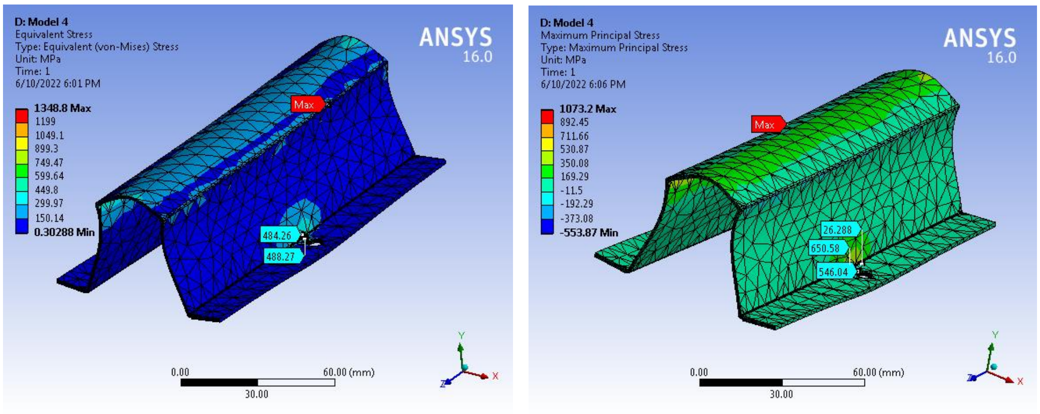

Figure 18. Model-4 Equivalent Stress, Maximum Principal Stress

Results of model 5:

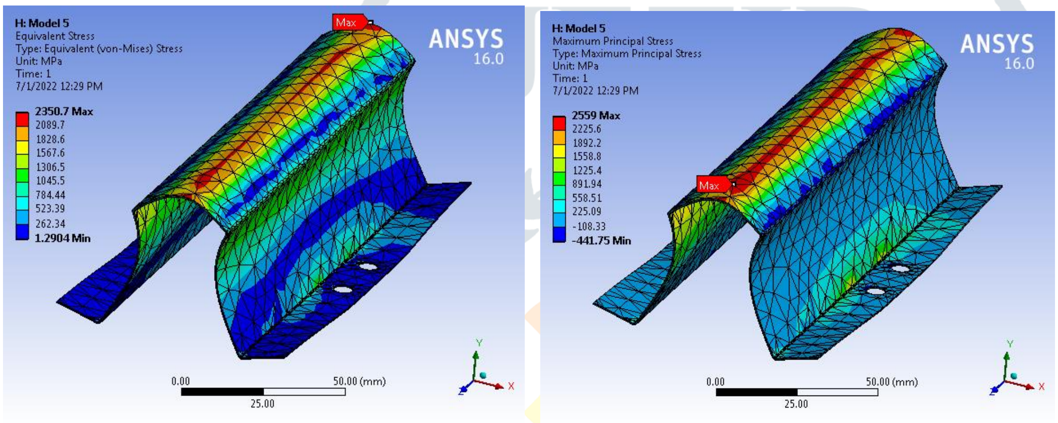

Figure 19. Model-5 Equivalent Stress, Maximum Principal Stress

Results of model 6

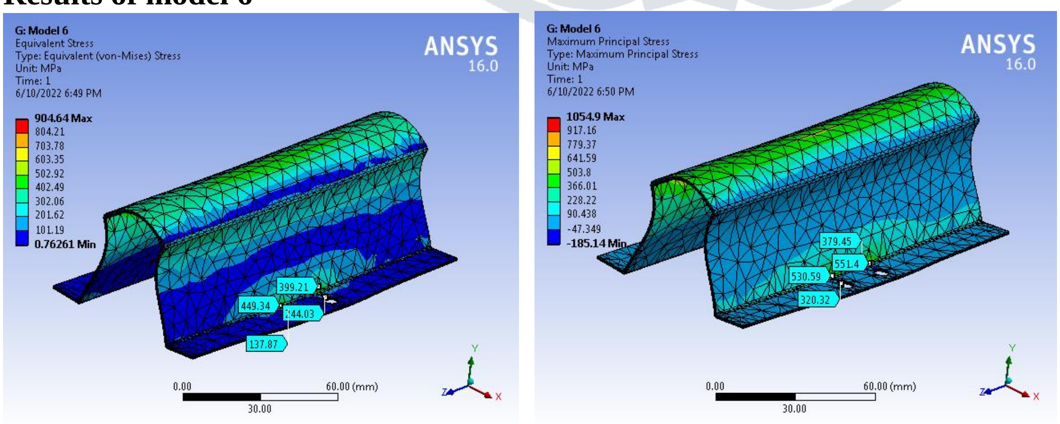

Figure 20. Model-6 Equivalent Stress, Maximum Principal Stress

Results of model 7:

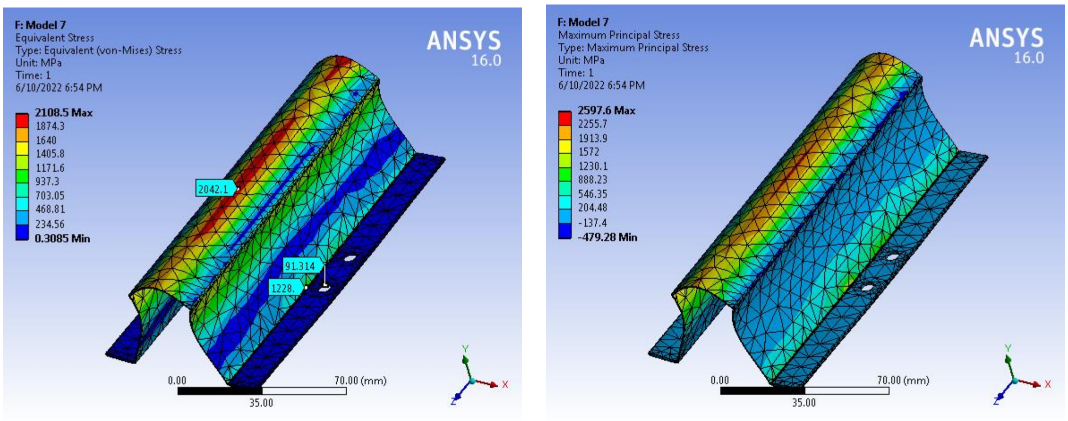

Figure 21. Model-7 Equivalent Stress, Maximum Principal Stress

Results of model 8:

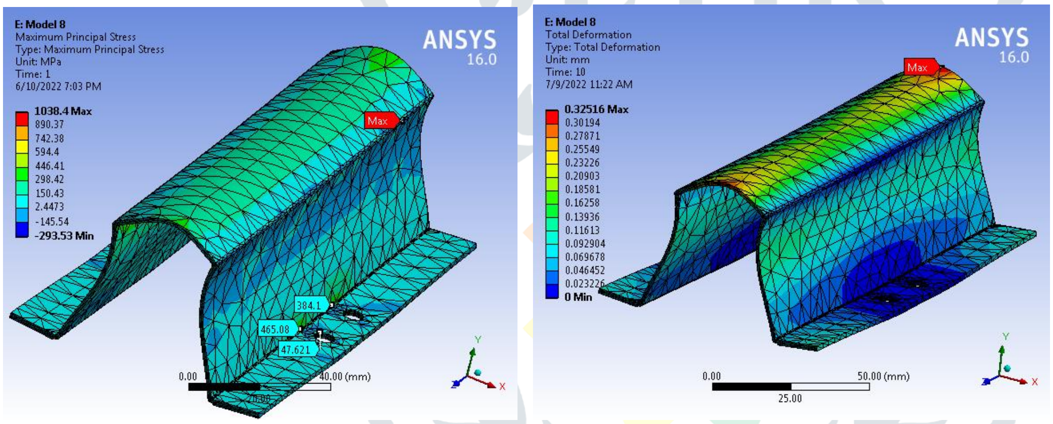

Figure 22. Model-8 Equivalent Stress, Maximum Principal Stress

6. DISCUSSION

Results in terms of Equivalent Stresses, Maximum Principal Stresses and Total Deformation are compared between 8 models and their graphs are prepared for better understanding.

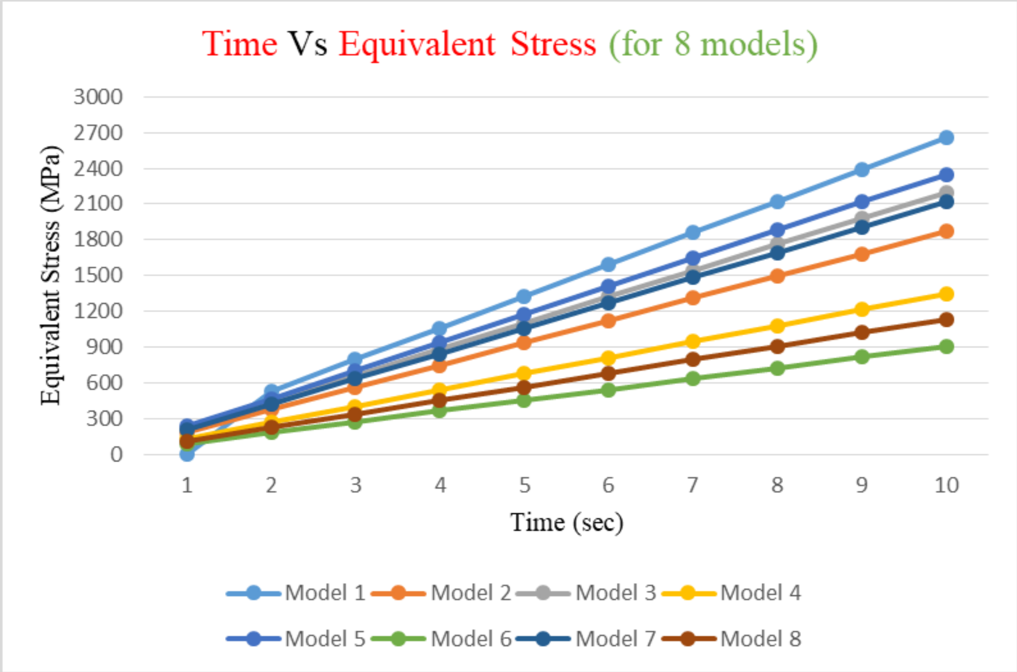

Figure 23. Comparison of Equivalent Stresses between 8 models

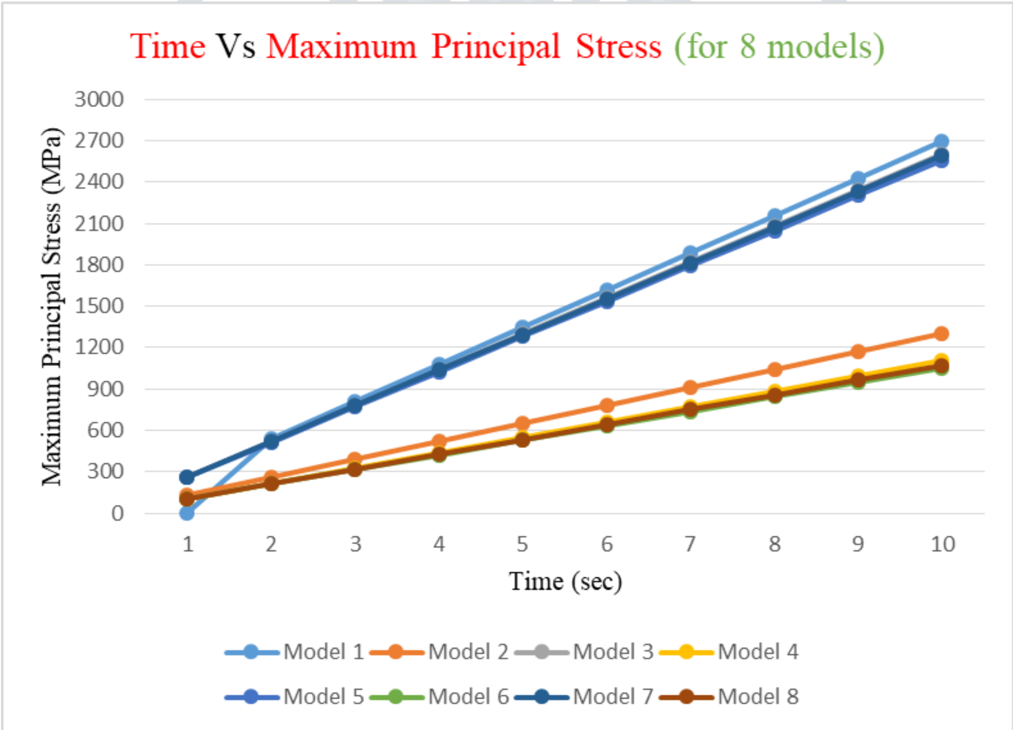

Figure 24. Comparison of Maximum Principal Stresses between 8 models

Model 1: It consists of a single batten section. Models 1, 2, 3 & 4 are connected to principal rafter of a truss with the help of two screw fasteners. According to previous experimental studies [1] which shows the failure load of 4.02 kN, the load of 4 kN tensile in nature is applied on the specimen. The values of maximum equivalent stress and maximum principal stress obtained are 2653.6 MPa and 2692.7 MPa respectively. These values are taken as base values for further comparison. The analysis shows critical pull through failure modes of roof batten as the maximum stresses are generated near screw connection at the bottom flange of a section. For improving pull thorough failure capacity analysis of other models has been carried out.

Model 2: It consists of main batten section and a bracket of length 150 mm which is made up of same batten section placed over a main section. As the aim to improve the pull through capacity of section up to double, the load of 8 kN is applied on second test specimen. The values of maximum equivalent stress and maximum principal stress obtained are 1871.5 MPa and 1304.6 MPa respectively. The analysis also shows critical pull through failure modes of roof batten as the maximum stresses are generated near screw connection at the bottom flange of a section. In this method thickness of bottom flange is improved to two times as a result it shows less stresses at the screw connection though the load applied is twice the reference load. The pull through capacity is improved to considerable point.

Model 3: In model 3 instead of attaching whole bracket to main section, considering the failure location it is decided to strengthen the bottom flange of section which is the critical location, the flange plates are attached to either sides of bottom flanges. As a result the flange thickness is improved to three times. The values of maximum equivalent stress and maximum principal stress obtained are 2201.2 MPa and 2600.8 MPa respectively. Despite of fact that complete pull through failure mode was not observed in the analysis conducted the maximum stress value is considered for section failure. The failure location is shifted to top flange where actually load is applied. Though the pull through capacity is improved, this method is not suitable practically as it weakens the top flange and ultimately stress values are very close to model 1. It means that it improves the capacity of section but do not reach ultimate aim to carry twice load than first model.

Model 4: This method is combination of bracket and flange plate which is attached to main batten to improve pull through capacity. It also improves the bottom flange thickness to three times. The values of maximum equivalent stress and maximum principal stress obtained are 1351.9 MPa and 1104.7 MPa respectively. These stress values are much lesser as compared to first model also after applying twice loading. It also don't show the typical pull through failure mode. The maximum stress value is considered for comparison of failure of section though the failure location is at top flange of a section. This section can take more load than twice of failure load in model 1. It can be used efficiently as the best strengthening method.

Model 5: This is one of the previously used strengthening method. In this method the batten section is connected to principal rafter of a truss with the help of four screw fasteners (two screw fasteners on each bottom flange side). As per experimental results use of four screw fasteners increases the capacity of section by 50 to 70%. The values of maximum equivalent stress and maximum principal stress obtained are 2350.7 MPa and 2559.0 MPa respectively. Numerical analysis also shows stress values very closer to that of model 1. So we do not get the required results of improving the capacity by 100%. Stiffness of flange and rafter also get increased which results in failure of a section at top flange. The maximum values of stresses are considered for comparison. This method does not proved to be an effective strengthening method.

Model 6: It is the same model as model 2 which consists of a bracket but connected to principal rafter with the help of four screw fastener (two screw fasteners on each bottom flange side). This variation of model is checked for enhanced pull through capacity of a section by combining two previously using strengthening methods. The values of maximum equivalent stress and maximum principal stress obtained are 909.36 MPa and 1054.4 MPa respectively. This model shows the best results among all the models. It has minimum stresses generating in the section confirming that it has maximum load carrying capacity. Though maximum stresses are not generating at bottom flange the maximum stress values are considered for comparison as they ultimately lead to section failure. Failure location is at center of top flange.

Model 7: Model 7 is identical to model 3, just difference is in connection with principal rafter. In model 3 two screw fasteners were used whereas in model 7, four screw fasteners are used. The values of maximum equivalent stress and maximum principal stress obtained are 2116.5 MPa and 2591.8 MPa respectively. It definitely help to improve pull through capacity of a section as it strengthens the bottom flange but it ultimately provides in comparatively weak top flange. The stress values are closer to model 1 which shows this method is not suitable to improve the capacity by 100%.

Model 8: When model 4 is connected to rafter with the help of four screw fasteners instead of two screw fasteners we get model 8. Though it is geometrically strongest model, it is subjected to slightly more stresses as compared with model 6. The values of maximum equivalent stress and maximum principal stress obtained are 1135.5 MPa and 1072.8 MPa respectively. It is also proven as a suitable option to improve the capacity of a section but as the attachment used in this model is slightly difficult to manufacture it is not suitable for practical use.

7. CONCLUSION

1. "Use of flange plates" as a strengthening method increases the pull through capacity of a section but it weakens the top flange and failure of section occurs. It does not improve overall strength of section. Its deformation is also comparatively greater (3.6 mm).

2. Use of bracket with extended bottom flanges can improve the strength of section but as this type of section takes more manufacturing efforts, practically it is not much suitable.

3. After the numerical analysis of hat section topspan 4055 with the help of ANSYS software, it can be concluded that the bracket of 150 mm length of same material as of main batten connected to principal rafter with four screw fasteners will provide maximum pull through capacity of a section. This method will provide strengthened connection and is easy to apply. As compared to previously used strengthening method of using bracket with two screw fasteners, this method (bracket with four screw fasteners) provide improved load carrying capacity.

4. Proposed method "Use of bracket with four screw fastener" is the combination of two previously used strengthening methods "Four screw fastener connection" and "Use of bracket at connection".

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