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A study on strengthening thin roof battens subjected to pull through failure

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Abstract

cold formed steel is frequently used in contemporary construction, especially as a secondary roof purlin. These sections are typically connected to trapezoidal roofing sheets using screws that self-drill or self-tap, forming an integral part of lightweight roofing systems. Hat-shaped CFS sections are commonly employed as batten members in industrial, commercial and residential buildings due to their structural efficiency and ease of installation. However, recent extreme wind events have revealed a recurring issue: localized pull-through failures occurring at bottom flanges of batten sections where they connect to rafters or trusses. To investigate this failure mechanism, a comprehensive numerical study was conducted using finite element modeling. The analysis incorporated an appropriate failure criterion to accurately forecast when pull-through will begin failure in roof battens. The failure load values, obtained from previous experimental studies, were used as input for the simulation. Key parameters such as total deformation, equivalent (von Mises) stresses, and the highest primary stresses were assessed and compared across various models. These models were initially developed in SolidWorks and later imported into ANSYS for detailed analysis. All material properties, boundary conditions, and loading configurations were appropriately defined. The study first analyzed several existing strengthening techniques before evaluating the performance of newly proposed methods. The results revealed that a combination of two existing strengthening approaches significantly improved the pull-through resistance of the battens, offering the most effective solution among the tested models.

Keywords: Cold-Formed Steel Structure; High Wind Uplift Load; Steel Roof Battens; Light Gauge Roofing System; Pull Through Failure; Finite Element Analysis; ANSYS Software

1. Introduction

A truss is fundamentally a triangulated framework composed of typically straight, interconnected structural elements. This configuration is also commonly referred to as an open web girder. The individual members are joined at nodes, which are often assumed to behave as pinned connections. Both the externally applied loads and the support reactions are generally considered to act at these nodal points.

Light-gauge steel roofing systems constructed using high-strength, thin steel roof sheeting and battens ranging in thickness from 0.42 to 1.20 mm (Fig.) are particularly vulnerable to premature failure under extreme wind conditions such as tropical cyclones, tornadoes, and severe thunderstorms. Historical wind damage reports and various studies have indicated that failures often originated at the connections between roof sheeting and battens, particularly at the screw fastener points (Morgan and Beck, 1977; Beck and Stevens, 1979). In most documented cases, a pullthrough failure was observed in which the fasteners tore through thin roof sheeting, as illustrated.

Several researchers (Xu, 1995[4]; Mahendran and Tang, 1998[10]; Mahendran and Mahaarachchi, 2002[11]; Mahaarachchi and Mahendran, 2004[8], 2009[7]) have investigated these pull-through failures and proposed various testing and design methodologies to improve the reliability of these connections. The addition of cyclone washers (Fig.)

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has been recognized as a highly effective method of enhancing the resistance of sheeting-to-batten connections under extreme wind loads (Xu and Reardon, 1993[15]; Mahendran, 1995b).

Roof failures have persisted in being reported in spite of these developments, particularly during recent high-wind storms. The location of failure shifted from sheeting-to-batten connections to connections between roof batten and rafter or trusse, according to later wind damaged evaluations (Henderson and Leitch, 2005; Henderson al., 2006; Boughton and Falck, 2007, 2008) (Fig.). The majority of these failures took the shape of localized pull-throughs, in which screw ripped through roof battens' bottom flanges

Significant stress concentrations were created in the battens' bottom flange, especially close to screw head next to the battens web, as result of the uplift pressures that were transferred through the sheeting-to-batten fasteners Both the roof sheeting and the battens eventually detached as result of tearing failure around the screw head brought on by this stress concentration, which frequently formed a semi-circular rupture. The previously investigated mechanism seen in roof sheeting, which usually entailed a splitting failure, is significantly different from this type of pull-through failure.

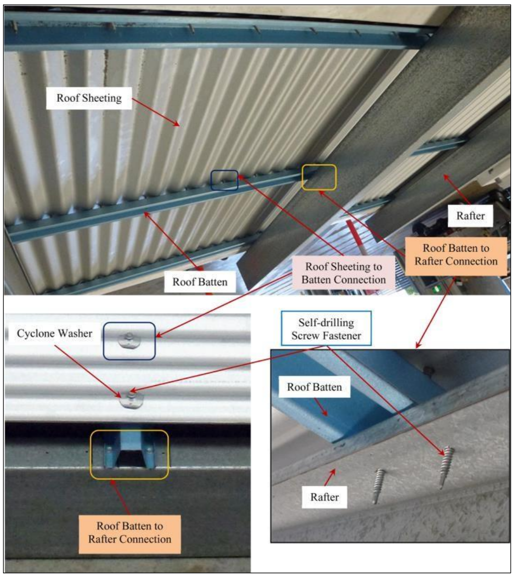

Figure 1 Typical thin-walled steel roof structure and connection

1.1. Cold formed steel

In modern building construction, cold formed steel section is frequently used, especially as secondary roof purlins. To create a full roofing system, this thin walled, open cross section element is usually fastened to the trapezoidal roof sheeting using screws that self-drill or self-tap. CFS purlins are prone to buckling under roof loading because of their thin geometry, particularly when forces are applied to top flange in either an upward or downward direction. Torsional moments are created at the sheeting/purlin connection points, which are frequently eccentric to the shear center. This results in bending deflections as well as twisting and/or warping deformations. This complexity is increased by presence of the single or mixed mode buckling, including to distortional, local and overall buckling. Due to the tendency of compression flange to slide sideway. In order to limit the lateral and twisting movements of purlin members and increase their load-carrying capability, the connection between the purlins and roof sheetings are essential. To increase design efficiency, design processes should take this restraining influence into account. Conventional techniques that are relevant to junctions constructed of hot-rolled or welded sections are not directly transferable to the study and design of thinwalled CFS elements. In CFS elements, shear and tensile joints fail in different ways than in conventional steel constructions. High buildability, high yield strength, and long-term durability are benefits of employing CFS. HRS sections are frequently utilized as main structural frameworks in building construction. On other hand, CFS sections form external building envelopes by supporting claddings as secondary structural components. CFS sections can be used effectively as principal floor beams, roof trusses, stud walls, and partitions due to their versatility in a range of shapes and sizes. Additionally, CFS sections are increasing being used as a beam and columns in structural frames for low-rise residential buildings. Bolts are the most widely utilized fastener type in practice among the different kinds of fastenings between cold-formed steel components. They are very appealing in all kinds of steel buildings because of their affordability and simplicity of use. Bolts offer a dependable and effective way to join components in cold-formed sections when holes are punched during forming.

1.2. Hat Shaped Section

Cold-formed steel sections with a hat shape are frequently utilised in lightweight steel structures, including commercial, industrial, and residential buildings. Hat sections have a higher resistance to lateral-torsional buckling and are more torsionally rigid than other sections. Usually, cold-formed steel parts have thin walls. In cold formed buildings, steel sheet is typically 1 to 3 mm thick, with a maximum thickness of 12.5 mm. Cold rolling, press brake, or bending brake methods are used to make the cold formed steel parts. C and Z sections are the most frequently found sections of cold-formed steel flexural members. These days, supplementary members like purlins and grits are typically used for hat and sigma sections. The ultimate strength is impacted by the intricate stability behaviour of hat-shaped sections, includes lateral torsional and distortional, and local buckling. The constituent components of the section buckle at relatively small wavelengths, causing local buckling. Lateral-distortional buckling occurs in cross section, whereas distortional buckling is caused by translation and rotation at the member's compression flange. Along with advantageous effects like stressed-skin action, the top hat part has certain advantages in terms of simplicity of installation on site. A cost comparison between the thinner gauge top-hat portion and the zed-section would be more advantageous.

1.3. Finite Element Analysis

The primary objective of Finite Element Method (FEM) analysis not replicate reality with absolute precision, but rather to develop the most straightforward model that provides a sufficiently accurate representation of the physical system. In a typical finite element model, the complexity can be substantial, often comprising over 2,000 nodes, 1,200 solid elements, and 1,000 contact elements. It has been observed that the magnitude of critical damage parameters tends to decrease as the mesh size increases. ANSYS software is capable of performing three-dimensional finite element analyses that account for both geometric and material nonlinearities. This includes the integration of contact elements and the application of appropriate constraint conditions, which are essential for modeling complex systems. offers a time-efficient and reasonably priced substitute for physical experiments.A reliable test set is necessary in order to calibrate a FE model. It is feasible to use the FE model to examine the structural behavior against a variety of factors if the validity of the FE Length test specimen = 150 mm Thick. section = 0.55 mm analysis is guaranteed. Design guidelines for complicated structural components may be developed using contemporary numerical analysis tools of the kind that are currently easily accessible to the research community. This method keeps realistic and secure coverage of all significant structural concerns while significantly reducing the requirement for costly and time-consuming laboratory studies. The finite element approach is commonly used in software applications for integrated structural analysis and design, have been becoming more and more popular in, while ensuring that all significant structural issues are covered in a realistic and secure manner. In the design business, integrated structural analysis and design software packages, which usually use the finite element method for analysis and design, have been gaining popularity since they have reduced the time-consuming calculation process to only inputting input values.

1.4. Aim

To investigate pull-throughs failure behavior of thin roof batten and to develop effective strengthening techniques to enhance their resistance under wind uplift loading or prevent localize connection failure and improve pull through capacity

1.5. Objectives

The current study's goals are stated as follows:

- To look into how wind uplift forces cause thin steel roof battens to pull through.
- Roof batten pull-through behavior is simulated using ANSYS software's Finite Element Analysis (FEA).
- To identify stress concentration zones around fastener locations and evaluate their impact on failure.
- To explore various strengthening techniques and attachment configurations to improve pull-through resistance.
- To compare results based on stresses induced at bolt location and suggest the best suitable method to improve pull-through capacity.

1.6. Problem Statement

Extensive A Topsan 4055 hat-section thin steel roof batten, fabricated from Aluminium-Zinc alloy-coated steel, has been selected as the test specimen based on prior studies. Eight distinct models, incorporating variations in key parameters, have been developed for testing. These models are subjected to tensile loading to simulate pull-through failures induced by wind uplift forces. By examining the stress distribution at the bolt positions on the batten's bottom flange, the main goal is to ascertain the pull-through capacity. The section is having dimensions as follows:

- Top flange width = 32 mm   Bottom flange width = 12mm
- Total bottom width = 75 mm   Height = 40 mm
- Length test specimen = 150 mm Thick. section = 0.55 mm

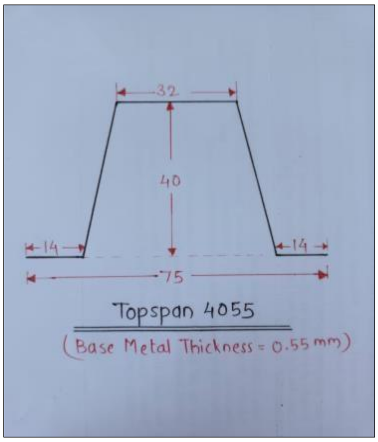

Figure 2 Topspan4055 Hat Section

2. Methodology

2.1. General

Eight FEA models were created using SolidWorks and examined in ANSYS to examine the pull throughs capacity of thin steel roof batten. These models simulate various strengthening attachments to enhance batten's resistance to pull-through failures. for analysis of every model.

2.1.1. Model Specifications

- **Section Profile:** Topspan 4055 hat section, 40 mm height, 75 mm bottom width, 32 mm top flange, 14 mm bottom flanges, 150 mm length.
- **Material:** G550 grade steel (0.55 mm thickness, yield strength 550 MPa).
- **Attachment Variations:** Different strengthening attachments are incorporated into four variants with two screw and four models with four screws.

2.1.2. Attachment Configurations

- **Base Model:** Standard batten section without any attachment.
- **Bracket Attachment:** 150 mm long bracket placed over the main member.
- **Flange Plates:** Two flange plates supporting the bottom flanges.
- **Extended Bracket:** Bracket with extended bottom flanges to increase thickness.

2.1.3. Analysis Procedure

- **Software Used:** SolidWorks for modeling; ANSYS for finite element analysis.
- **Boundary Conditions:** Fixed bolt connection locations; tensile load applied at the top flange to simulate wind uplift.
- **Output Parameters:** Equivalent (von-Mises) stresses and maximum principal stresses.

By evaluating different strengthening techniques and their effect on the pull through capability of roof batten, this numerical method offers a time- and money-efficient substitute for actual testing. The best strengthening configurations to improve structural integrity of roof battens under wind uplift circumstances can be found by analyzing stress distributions across several models. The variations of models are as given below:

- Model 1: The roof batten is fixed in place with two screws
- Model 2: The roof batten, along with a bracket, is attached using two screw fasteners.
- Model 3: The roof batten features flange plates and is fastened with two screw connections.

- Model 4: The roof batten, supported by a bracket with extended flanges, is connected using two screws
- Model 5: The roof batten is fixed in place with four screws
- Model 6: The roof batten, along with a bracket, is attached using four screw fasteners.
- Model 7: The roof batten features flange plates and is fastened with four screw connections
- Model 8: The roof batten, supported by a bracket with extended flanges, is connected using four screws

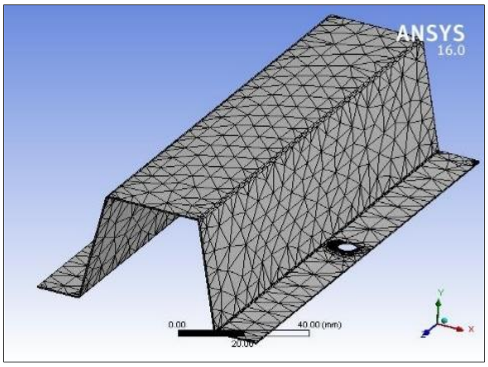

Figure 3 Meshing Generated in ANSYS

For the finite element analysis, a mesh is generated, and the load is applied to the section with specified location and intensity. Fixed support is assigned at designated locations. The analysis outputs are defined in terms of Equivalent stress, Maximum Principal Stress, and Total Deformations, which serve as key parameters for result comparison. Same procedure is consistently applied across all models. Finally, the results are evaluated and discussed.

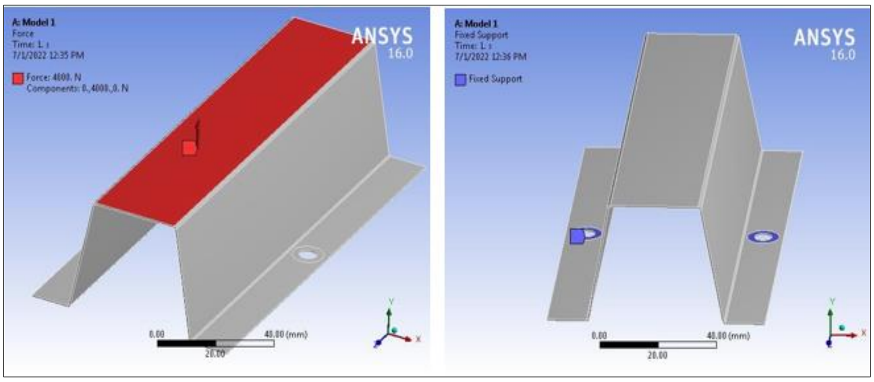

Figure 4 Tensile Loading and Fixed Support Location

3. Results

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

Table 1 presents the results obtained from four models, each connected to the principal rafter using two screw fasteners. All models were fabricated from G550 grade Aluminium-Zinc alloy coated steel. These models were designed with varying geometrical configurations to assess their performance under pull-through failure conditions.

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

Model No.	**Description**	**Applied Load**	**Max. Principal Equivalent (mpa)**	**Max. Principle Stress (mpa)**	**Location Of Max. Stress**
1	Single Battens	8	2653.6	2692.7	At screw in lower flange
2	Batten with bracket	8	1871.5	1304.6	At screw in lower flange
3	Batten with flange plate	8	2201.2	2600.8	Center at top flange
4	Battens with bracket having extended flange plates	8	1351.9	1104.7	In the top flange

Table 2 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**	**Max. Principal Equivalent (mpa)**	**Max. Principle Stress (mpa)**	**Location Of Max. Stress**
1	Single Battens	8	2350.7	2559.0	At screw in lower flange
2	Batten with bracket	8	909.36	1054.4	At screw in lower flange
3	Batten with flange plate	8	2116.5	2591.8	Center at top flange
4	Battens with bracket having extended flange plates	8	1135.5	1072.8	In the top flange

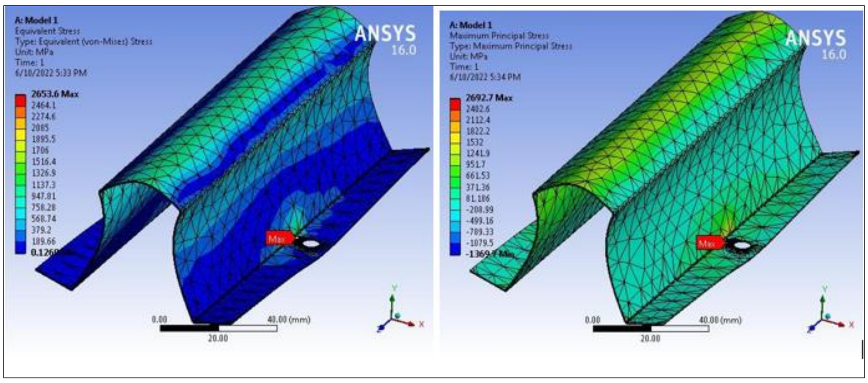

Figure 5 Model-1 Equivalent Stress, Maximum Principal Stress

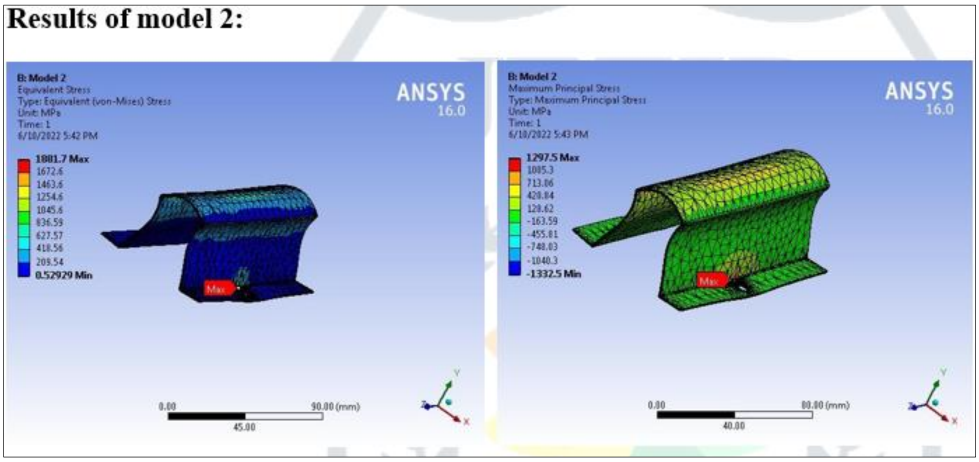

Figure 6 Model-2 Equivalent Stress, Maximum Principal Stress

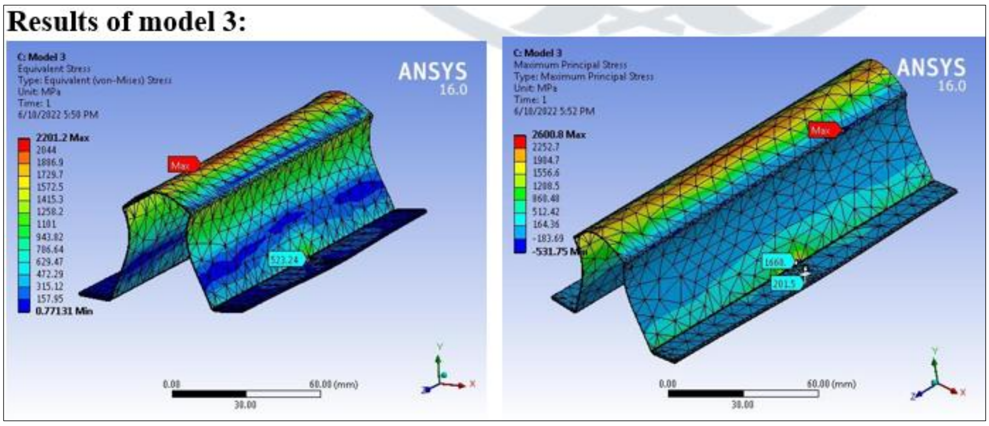

Figure 7 Model-3 Equivalent Stress, Maximum Principal Stress

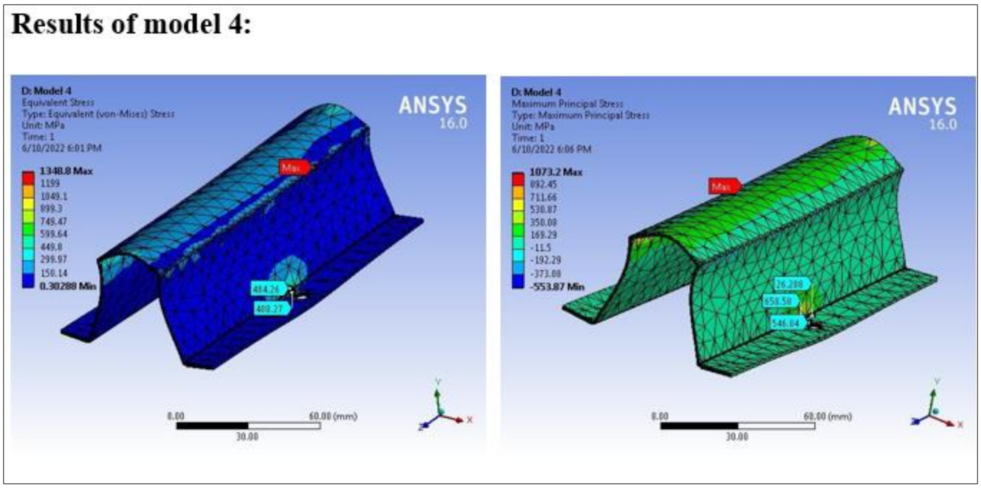

Figure 8 Model-4 Equivalent Stress, Maximum Principal Stress

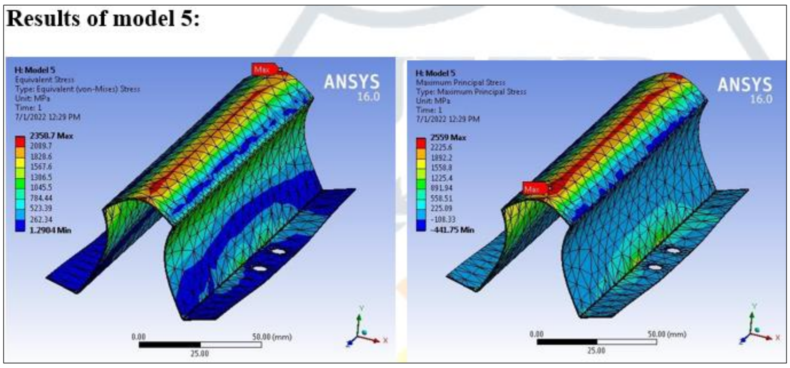

Figure 9 Model-5 Equivalent Stress, Maximum Principal Stress

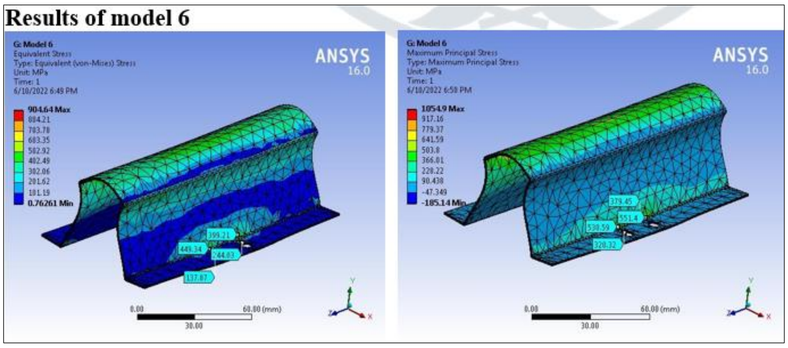

Figure 10 Model-6 Equivalent Stress, Maximum Principal Stress

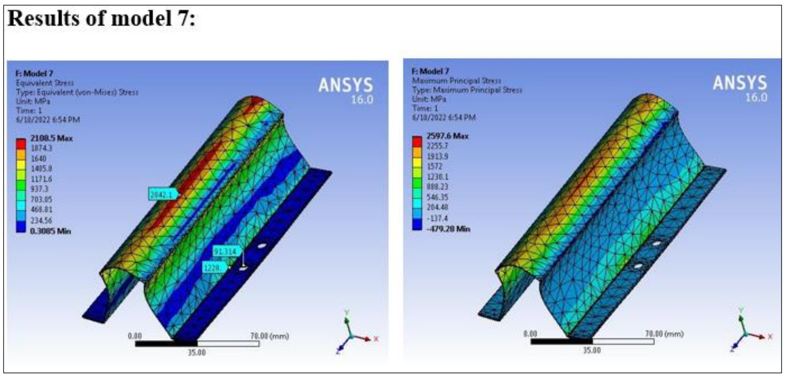

Figure 11 Model-7 Equivalent Stress, Maximum Principal Stress

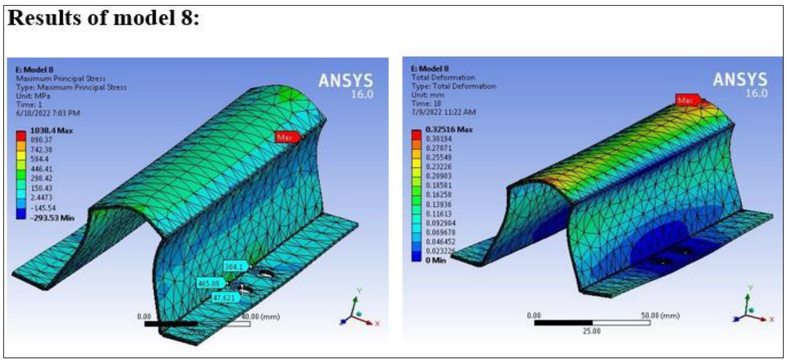

Figure 12 Model-8 Equivalent Stress, Maximum Principal Stress

4. Discussion

The results in terms of Equivalent Stresses, Maximum Principal Stresses, and Total Deformation are compared across eight models, with graphs prepared to facilitate better understanding.

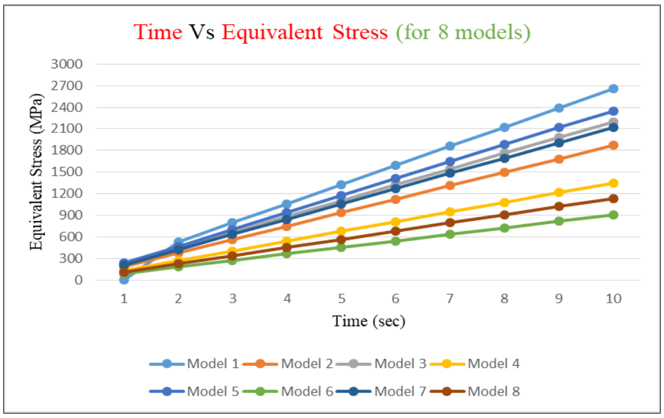

Figure 13 Comparison of equivalent stresses between eight model

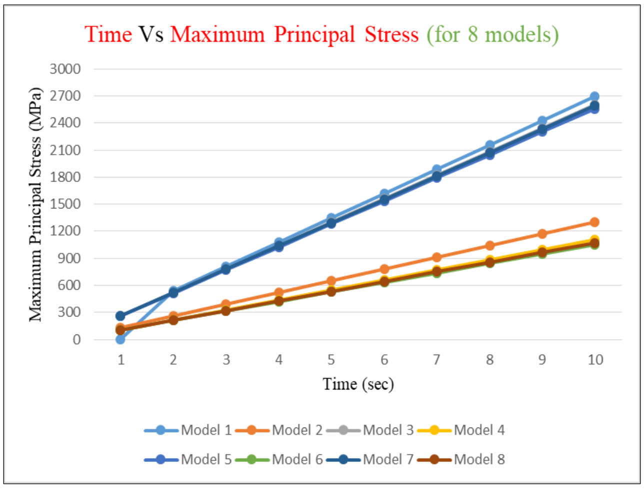

Figure 14 Comparison of maximum principal stresses between eight model

- **Model 1**: This arrangement uses two screw fasteners, one on either side of the bottom flange, to secure a single Topspan 4055 hat-section roof batten to the main rafter. A tensile load of 4 kN was applied, based on prior experimental studies indicating a failure load of 4.02 kN. The resulting maximum equivalent and principal stresses were 2653.6 MPa and 2692.7 MPa, respectively. These values serve as baseline references for subsequent comparisons. The analysis identified pull through failure initiating at screw connections on bottom flange, highlighting ritical nature of this location.
- **Model 2**: This model introduces a 150 mm long bracket, fabricated from the same G550 material, placed over the main batten section. With an applied load of 8 kN—double that of Model 1—the maximum equivalent and principal stresses were reduced to 1871.5 MPa and 1304.6 MPa, respectively. Despite the increased load, the stresses near the screw connection were lower, indicating a significant improvement in pull-through capacity.
- **Model 3**: In this configuration, flange plates are attached to both sides of the bottom flanges, tripling their thickness. The analysis revealed maximum equivalent and principal stresses of 2201.2 MPa and 2600.8 MPa, respectively. While the pull-through failure mode shifted to the top flange, the stress values approached those of Model 1, suggesting limited enhancement in capacity.
- **Model 4**: Combining the bracket from Model 2 with the flange plates from Model 3, this model also triples the bottom flange thickness. The analysis showed significantly reduced stresses—1351.9 MPa (equivalent) and 1104.7 MPa (principal)—even under the doubled load. The failure mode remained at the top flange, but the capacity was notably higher than Model 1, indicating this as an effective strengthening method.

- **Model 5**: In this style, the batten is attached to the rafter using four screw fasteners, two on each side of the bottom flange. The analysis indicated maximum stresses of 2350.7 MPa (equivalent) and 2559.0 MPa (principal), with failure occurring at the top flange. While the capacity increased by 50–70% compared to Model 1, it did not achieve the desired doubling of capacity.
- **Model 6**: This configuration combines the bracket from Model 2 with four screw fasteners. The analysis revealed the lowest stresses among all models—909.36 MPa (equivalent) and 1054.4 MPa (principal)—indicating the highest pull-through capacity. The failure mode occurred at the top flange, confirming its suitability for enhancing capacity.
- **Model 7**: Identical to Model 3 but with four screw fasteners, this model showed maximum stresses of 2116.5 MPa (equivalent) and 2591.8 MPa (principal). Despite the increased screw count, the capacity did not meet the target of doubling that of Model 1, and the failure mode remained at the top flange.
- **Model 8**: This configuration combines the bracket from Model 2 with flange plates and four screw fasteners. The analysis showed stresses of 1135.5 MPa (equivalent) and 1072.8 MPa (principal), slightly higher than Model 6. While it offers increased capacity, the complexity of manufacturing the attachments may limit its practical application.

5. Conclusion

- The use of flange plates as a strengthening technique increases the pull-through capability of a segment by making it stiffer. However, this approach introduces a significant drawback: it compromises the integrity of the top flange, leading to potential failure under load. This is due to the redistribution of stresses, which can cause the top flange to become the critical failure point. Additionally, the deformation at the connection site increases notably, with values reaching approximately 3.6 mm, indicating a reduction in the overall structural efficiency.
- 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.
- Based on numerical analyses conducted using ANSYS software, it has been determined that a 150 mm long bracket, fabricated from the same G550-grade steel as the main batten, and connected to the principal rafter with four screws, greatly increases hat-section Top span 4055 roof batten pull-through capacity. This configuration provides a robust connection that is straightforward to implement. When compared to the previously utilized method involving a bracket with only two screw fasteners, the four-screw fastener approach offers a substantial improvement in load-carrying capacity, making it a more effective solution for strengthening roof batten connections.
- The proposed method, "Use of a bracket with four screw fasteners," integrates two previously established strengthening techniques: the "Four screw fastener connection" and the "Use of a bracket at the connection." The technique increases the section's pull-through capability by combining both strategies, providing a more robust and efficient connection. This combined strategy leverages the benefits of both individual methods, resulting in improved structural performance and load-bearing capacity.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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