

Article

Comparison of Structural Performance of T-Flange Joints Using Different Bolt Grades Under Axial Tensile Loading Conditions

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Abstract

This study investigates the effect of bolt grade on the structural performance of T-flange joints used in wind turbine support structures. A nonlinear finite element model was developed to compare Grade 10.9 and Grade 12.9 bolts under identical loading and boundary conditions. The results showed that using Grade 12.9 bolts increased the reaction force by 12.3%, bolt stress by 21%, bolt strain by 18.7%, flange strain by 20.0%, tower shell strain by 18%, and tower shell stress by 11.2% compared with Grade 10.9 bolts. The external-load–bolt-force Z - F_s relationship, where Z denotes the applied external tensile load and F_s denotes the corresponding internal axial bolt force, was used to evaluate bolt-force development and load transfer during loading. The Z - F_s relationship further showed that the internal bolt force increased by 13.7% for Grade 12.9 bolts at the design external tensile load. These results indicate that Grade 12.9 bolts improve load-transfer capacity and joint resistance, but they also increase the stress and strain demand on the connected flange and tower shell. Therefore, higher-grade bolts should be evaluated within the complete joint system rather than based on bolt strength alone.

Keywords: T-flange joint; bolt grade; Grade 10.9 bolts; Grade 12.9 bolts; wind turbine support structure; finite element analysis; bolt pretension; flange strain; tower shell response; Z - F_s relationship

1. Introduction

The increasing global demand for renewable energy has accelerated the development of wind power technology, with wind turbines playing an important role in the transition toward sustainable energy systems [1,2]. Recent reviews have emphasized that wind energy generation is one of the most promising renewable technologies for reducing dependence on conventional fossil-fuel-based energy sources [3]. Offshore wind turbine systems have also gained increasing attention because they can provide high energy output under strong and stable wind conditions [4]. Since the energy crisis of the 1970s, renewable energy technologies have continued to develop as long-term solutions for improving energy security and reducing environmental impacts [5,6]. As turbine capacity, rotor diameter, and tower height continue to increase, wind turbine support structures are required to resist higher axial forces, bending moments, shear forces, and cyclic environmental loads. Therefore, ensuring the structural safety and long-term reliability of wind turbine support structures has become an important engineering requirement.

Recent developments in large-capacity wind turbine systems have increased the need for more reliable structural components and connection systems [7]. Offshore wind



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turbine support structures are exposed to complex environmental loading conditions, including wind, wave, current, and operational loads [8]. These loads are transferred from the rotor–nacelle assembly to the tower, transition piece, and foundation system through a series of structural components and mechanical connections. Among different Offshore foundation types, monopile foundations are widely used because of their simple configuration, mature fabrication process, and economic advantages for large-scale Offshore wind farm installation [9,10]. The development of low-carbon energy systems has further increased the importance of Offshore wind energy as a key component of sustainable energy infrastructure [11]. A review of Offshore wind turbine substructures also reported that monopiles are among the most commonly adopted foundation systems because of their practical advantages in shallow to intermediate water depths [12]. Therefore, reliable load transfer between the tower, transition piece, and monopile foundation is essential for maintaining the structural integrity of Offshore wind turbine systems.

Among the critical connection systems used in wind turbine support structures, bolted flange joints are widely adopted because of their high load-transfer capacity, convenient assembly, and suitability for large tubular steel structures. These joints are commonly used to connect tower cylinder segments, tower-to-foundation interfaces, and monopile-to-transition-piece regions [13,14]. Tran et al. investigated the structural safety of L-type flange joints for wind towers and highlighted the importance of improving flange joint performance in wind turbine support structures [15]. Tran et al. also studied the structural behavior of L-type flange joints under various flatness conditions, showing that connection performance can be strongly affected by geometric and contact-related factors [16,17]. Compared with welded or grouted connections, bolted flange joints provide easier installation, inspection, maintenance, and replacement. However, because these joints are subjected to complex operational and environmental loads, their structural performance directly influences the safety and service life of the entire wind turbine system [18].

Bolted joints are generally assembled using preloaded high-strength bolts to generate sufficient clamping force between the flange surfaces. The review by Mehmanparast et al. emphasized that bolted flange connections in offshore wind structures face several challenges related to fatigue, preload control, installation quality, and long-term reliability [19]. Bolt pretension produces compressive contact pressure at the interface, which improves joint stiffness and reduces the possibility of flange separation under external loading. Okorn et al. examined the effects of preloaded bolts on fatigue life in flange joints and showed that bolt preload is an important factor in connection performance [20]. The design of steel structures also requires careful consideration of connection behavior, bolt resistance, and load transfer mechanisms [21,22]. Lyu et al. demonstrated that bolt pretension significantly influences the bearing behavior of high-strength steel connections [23]. Therefore, proper bolt pretension is necessary to prevent early contact separation, prying action, excessive bolt bending, and fatigue damage.

In offshore wind turbine support structures, bolted flange joints are subjected to axial tensile, bending, shear, and cyclic loading conditions. These loads may cause nonlinear structural behavior such as flange separation, local plastic deformation, bolt elongation, stress concentration, and redistribution of load among the connected components. Manufacturing defects in high-strength bolts can also reduce fatigue life and increase the risk of premature failure in wind turbine applications [24,25]. If connection behavior is not accurately predicted during design, bolt yielding, bolt fracture, flange plastification, or local shell damage may occur. Schaumann and Seidel reported failure-related issues in bolted steel flanges, demonstrating the importance of reliable connection design [26]. Alonso-Martinez et al. investigated wind turbine tower collapse caused by flange failure and showed that flange joint failure can have severe structural consequences [27]. These risks

highlight the need for accurate numerical evaluation of bolted flange joints under realistic loading conditions [28].

The structural performance of bolted flange joints depends on several parameters, including flange geometry, tower shell thickness, bolt diameter, bolt preload, contact condition, friction coefficient, material properties, and bolt strength grade. Among these parameters, bolt strength grade is particularly important because it directly affects bolt tensile resistance, deformation capacity, stiffness, and failure tendency [29]. Zhou et al. investigated the ultimate load-carrying capacity of high-strength bolted structures and showed that bolt strength can strongly influence connection resistance [30]. He et al. numerically and theoretically examined high-strength bolted joints and demonstrated that joint configuration and bolt properties affect the load-carrying mechanism [31]. Li et al. conducted a numerical parametric evaluation of high-strength bolts and emphasized the importance of accurately assessing ultimate resistance under mechanical loading [32]. High-strength bolts such as Grade 10.9 are commonly used in wind turbine flange connections, while Grade 12.9 bolts provide higher tensile strength and may improve the load-carrying capacity of the joint. However, the increase in bolt strength may not produce a proportional increase in overall joint capacity because the connection response is also governed by flange bending, contact pressure, shell deformation, and load redistribution.

Previous studies have investigated bolted flange joints using analytical models, experimental testing, and nonlinear finite element analysis. Madsen et al. performed analytical and numerical investigations of bolted steel ring flange connections for offshore wind monopile foundations and highlighted the importance of bolt force development and flange deformation [33]. Tran and Lee proposed failure mechanisms for L-type flange joints in wind turbine towers and emphasized the role of bolt yielding, flange-to-shell yielding, and bolt bending in determining ultimate resistance [34]. Cabrera-González et al. developed closed-form expressions based on virtual testing for the structural optimization of L-flange bolted connections [35]. These studies have improved the understanding of load-carrying capacity, stiffness, deformation behavior, and failure mechanisms in flange joints. However, most previous research has focused mainly on L-type flange joints or simplified flange segments [36].

L-type flange models are useful for investigating local joint behavior, but they may not fully represent the structural interaction and load redistribution of complete T-flange joints [37]. In a T-flange configuration, the bolts, flange plates, and tower shell components interact simultaneously under axial tensile loading conditions [38]. This creates a more complex load path compared with simplified L-type flange models. Therefore, conclusions obtained from L-type flange configurations may not be sufficient to describe the global behavior of complete T-flange joints. This limitation becomes more important when evaluating the effect of different bolt strength grades on joint stiffness, stress distribution, and failure tendency [39].

In addition, many existing studies have focused primarily on bolt preload, flange geometry, fatigue behavior, contact conditions, and failure-mode prediction. Limited research has systematically evaluated how different bolt grades influence the structural response of complete T-flange joints [40]. Waleed and Lee investigated the influence of Grade 10.9 and Grade 12.9 bolts on the structural integrity of L-type flange joints using finite element analysis [41]. Their study showed that higher-grade bolts can improve joint stiffness and load-carrying capacity. However, the investigation was limited to L-type flange configurations and did not extend to complete T-flange joints. Therefore, a clear research gap remains regarding the comparative structural performance of T-flange joints using different bolt grades under axial tensile loading conditions.

To address this research gap, the present study investigates the structural performance of T-flange joints using different bolt grades under axial tensile and bending loading conditions. A nonlinear finite element model representative of a 5.5 MW wind turbine support structure is developed using ANSYS Mechanical 2026R1. The design background and loading conditions are considered in relation to wind turbine tower and foundation design requirements. Two high-strength bolt grades, Grade 10.9 and Grade 12.9, are compared under identical loading and boundary conditions. The bolt pretension level is considered based on the design principles for bolted steel connections. The numerical model includes material nonlinearity, bolt preload, frictional contact, contact separation, and stress redistribution between the bolts, flange, and tower shell. The structural behavior of the joint is evaluated in terms of force–displacement response, bolt strain, bolt stress, tower shell strain and stress, flange stress, load-carrying capacity, and safety margin.

The main objective of this study is to clarify how increasing bolt strength from Grade 10.9 to Grade 12.9 affects the stiffness, deformation behavior, stress distribution, and failure tendency of T-flange joints. The central hypothesis is that Grade 12.9 bolts can improve joint stiffness and load-carrying capacity while reducing bolt strain and preventing bolt yielding compared with Grade 10.9 bolts. However, because higher-strength bolts possess greater stiffness, they may attract higher load and transfer more stress to the connected tower shell and flange. Therefore, the effectiveness of higher-grade bolts must be evaluated based on the complete joint response rather than bolt strength alone.

The remainder of this paper is organized as follows. Section 2 describes the finite element modeling procedure, including the T-flange geometry, material properties, bolt grade specifications, contact definitions, boundary conditions, bolt preload, and axial tensile loading conditions. Section 3 presents the numerical results, including force–displacement behavior, bolt strain and stress response, tower shell behavior, and flange stress distribution. Section 4 discusses the effect of bolt grade on load transfer, stiffness, yielding tendency, and structural safety of the T-flange joint. It summarizes the main findings and provides conclusions regarding the suitability of Grade 10.9 and Grade 12.9 bolts for T-flange joint applications in wind turbine support structures.

2. Methodology and Variables

2.1. Simulation Approach and Tools

The structural behavior of the T-flange joint was investigated using the finite element method, which provides an effective framework for capturing the complex nonlinear response of bolted flange connections subjected to axial tensile loading conditions. All numerical simulations were performed using ANSYS Mechanical, a commercial finite element software widely used for modeling contact interaction, large deformation effects, material nonlinearity, and bolt pretension behavior. The use of this platform enables accurate evaluation of load transfer mechanisms, local stress evolution, bolt deformation, flange response, and tower shell behavior in bolted flange joints commonly employed in wind turbine support structures.

A detailed three-dimensional finite element model of the T-flange joint assembly was developed, explicitly including the tower shell, flange plates, and high-strength pre-tensioned bolts. The geometry was defined to represent a realistic wind turbine support structural configuration, with the model corresponding to a 5.5 MW-class structural system, as shown in Figure 1. The T-flange configuration was selected because it provides a more complete representation of the joint compared with simplified L-type flange segments. In this configuration, the bolts, flange, and tower shell interact simultaneously, allowing the numerical model to capture load redistribution and stress development under axial tensile and bending loading conditions.



Figure 1. Overall configuration of the T-flange joint specimen used in the finite element analysis.

To evaluate the influence of bolt strength grade on the structural performance of the T-flange joint, two numerical models were considered. In the first case, Grade 10.9 bolts were used in the T-flange assembly. In the second case, Grade 12.9 bolts were used while maintaining the same geometry, boundary conditions, contact definitions, mesh strategy, and external loading conditions. This comparative approach allows the effect of bolt grade to be isolated and evaluated in terms of joint stiffness, bolt stress, bolt strain, tower shell response, flange stress, and load-carrying capacity.

Bolt pretension was applied through the bolt pretension function in ANSYS Mechanical to reproduce the initial clamping force generated during assembly. The applied pretension creates compressive contact pressure between the flange surfaces and establishes the initial stress state of the joint before external loading. Nonlinear surface-to-surface contact formulations were defined at the flange interfaces to capture compression, separation, sliding, and redistribution of contact pressure during the loading process. This contact modeling strategy is essential because T-flange joints may experience local flange opening, contact pressure reduction, and nonlinear load transfer when subjected to axial tensile axial and bending loads.

The numerical simulations were carried out using an incremental nonlinear solution procedure. First, bolt pretension was applied to establish the initial clamping condition. Next, the external axial tensile loading was applied gradually to capture the progressive response of the joint. The numerical results were then extracted and compared for both bolt grades. The main response parameters included reaction force, force displacement behavior, bolt stress, bolt strain, tower shell strain, tower shell stress, flange stress, and deformation pattern. This simulation approach provides a systematic basis for evaluating how increasing bolt strength from Grade 10.9 and Grade 12.9 affects the structural performance and safety of T-flange joints.

2.2. 3D Model

The numerical modeling process began with the development of a detailed three-dimensional representation of the T-flange joint considered in this study. The model consisted of the tower shell, flange plates, bolts, bolt heads, and nuts. The T-flange joint

was modeled as a complete structural assembly rather than a simplified segment, enabling realistic evaluation of the interaction between the connected components. This modeling approach allows the load path between the bolts, flange, and tower shell to be captured more accurately under axial tensile loading conditions, as shown in Figure 2.

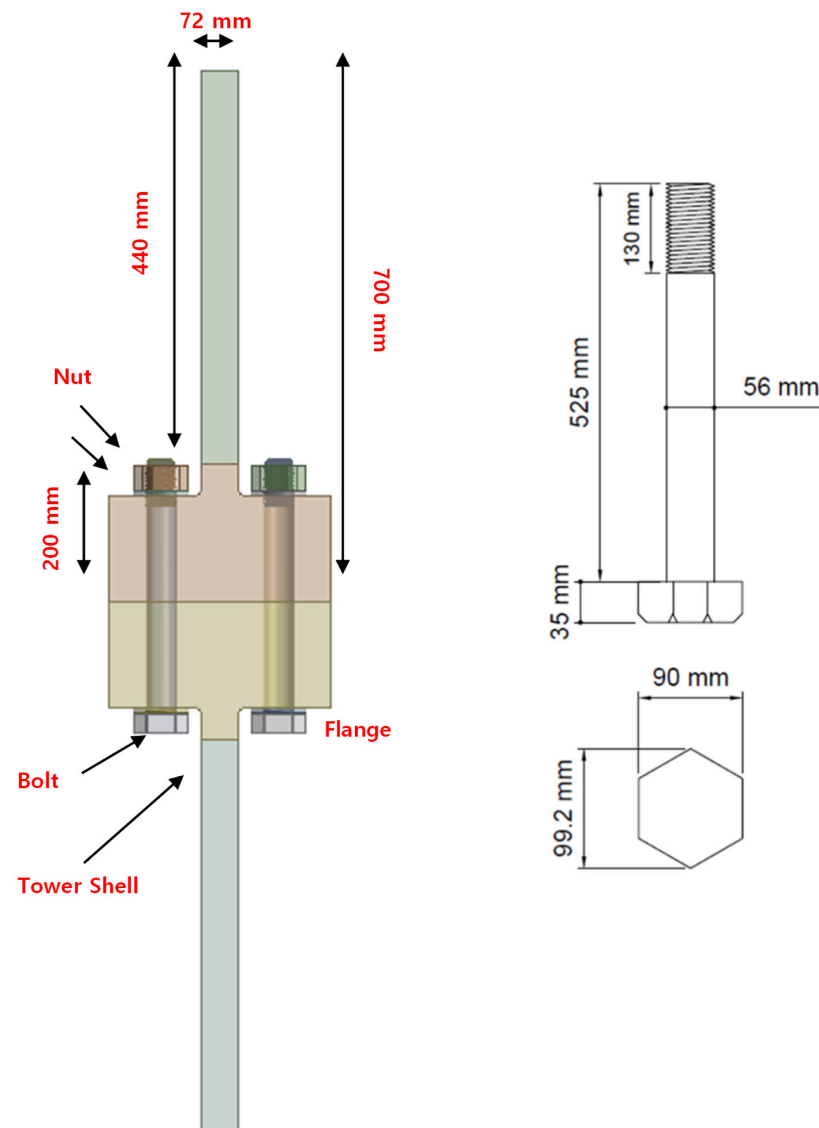


Figure 2. Detailed geometry, component identification, and dimensions of the T-flange joint model.

High-strength bolts were explicitly modeled to represent the mechanical interaction between the bolt components and the flange plates. The bolt shank, head, and nut regions were included to capture local stress development and force transfer. Contact interfaces were defined between the bolt head and flange surface, between the nut and flange surface, and between the mating flange faces. These contact definitions were introduced to simulate realistic compression, separation, and load transfer behavior during the nonlinear analysis.

Material nonlinearity was included using an elastic–plastic constitutive model in ANSYS Mechanical. The initial elastic response of each component was defined by Young’s modulus, and Poisson’s ratio. Beyond the yield point, the bolts, flange, and tower shell were modeled using a bilinear isotropic hardening relationship. The yield strengths of Grade 10.9 and Grade 12.9 bolts were 900 MPa and 1080 MPa, respectively stated in Table 1, while their ultimate tensile strengths were 1020 MPa and 1220 MPa. The flange and tower shell were assigned their respective yield and tensile strengths listed in Table 2. This

formulation enabled the model to capture the onset of yielding, plastic-strain development, stiffness reduction, and stress redistribution during loading.

Table 1. Mechanical Properties of the Investigated Bolt Grades.

Property	Bolt Grade 10.9	Bolt Grade 12.9
Tensile Strength (N/mm ²)	1020	1220
Yield Strength (0.2% offset) (N/mm ²)	900	1080
Elongation (%)	12	14
Reduction in Area (%)	50	54

Table 2. Mechanical Properties of Flange and Tower Shell.

Property	Flange	Tower Shell
Tensile Strength (N/mm ²)	545	548
Yield Strength (0.2% offset) (N/mm ²)	384	394
Elongation (%)	30.3	32
Reduction in Area (%)	70	70.7

Material properties were assigned separately to the bolts, flange, and tower shell. Structural steel was used for the flange and tower shell, while high-strength steel properties were assigned to the bolts. Two bolt grades were considered: Grade 10.9 and Grade 12.9. The mechanical properties of the bolts are summarized in Table 1, while the material properties of the flange and tower shell are summarized in Table 2.

The same material model was used for the flange and tower shell in both bolt-grade cases. Only the bolt material properties were changed between the Grade 10.9 and Grade 12.9 models. This ensured that the differences observed in the numerical results were caused by bolt strength variation rather than changes in geometry, boundary conditions, or material properties of the connected structural components.

2.3. Mesh Generation

A structured meshing strategy was adopted to ensure numerical accuracy while maintaining computational efficiency for the T-flange joint model. Wherever feasible, hexahedral elements were used because of their ability to capture stress gradients and provide stable numerical behavior in contact-dominated regions. Consistent meshing procedures were applied to both Grade 10.9 and Grade 12.9 models to allow direct comparison of the results.

Local mesh refinement was applied to regions expected to experience high stress concentration and nonlinear contact behavior. These regions included the bolt shank, bolt head contact region, nut contact region, bolt holes, flange contact surfaces, and the flange to the tower shell connection area. These locations are critical because stress concentration, contact pressure variation, local deformation, and yielding are most likely to occur near the bolt holes and flange-shell interface. Less critical regions of the tower shell and flange body were meshed more coarsely to reduce computational cost while preserving the overall accuracy of the numerical solution. Mesh sensitivity analysis was conducted using five progressively refined meshes to evaluate the influence of element density on the numerical response of the T-flange joint. The output displacement was examined at two loading levels corresponding to nominal displacements of 5 mm and 8 mm. As shown in Figure 3, the predicted displacement for the 5 mm case increased from 4.62 mm for the coarsest mesh to 5.01 mm for the finest mesh. Similarly, for the 8 mm case, the displacement increased from 7.41 mm to 8.02 mm as the number of elements increased.

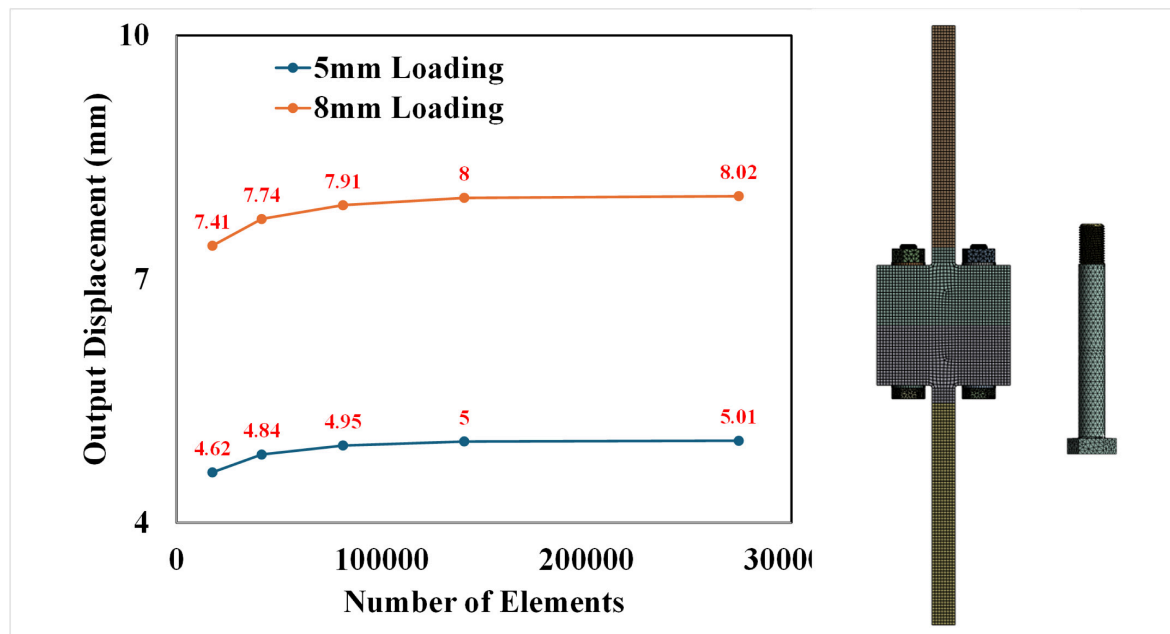


Figure 3. Structured hexahedral finite element mesh used for the tower shell, flanges, bolts, and nuts of the T-flange joint model.

The results changed noticeably for the coarse meshes but gradually stabilized with further mesh refinement. When the number of elements increased from approximately 150,000 to 275,000, the output displacement changed from 5.00 to 5.01 mm for the 5 mm loading level and from 8.00 to 8.02 mm for the 8 mm loading level. These variations correspond to only approximately 0.20% and 0.25%, respectively. Therefore, further mesh refinement produced no significant change in the numerical response, confirming that mesh convergence had been achieved. Based on this result, the mesh containing approximately 275,000 was adopted for the final analyses as an appropriate compromise between numerical accuracy and computational cost. The same mesh configuration was used for both the Grade 10.9 and Grade 12.9 models.

The same mesh density and element size were maintained for both bolt-grade models. This approach ensured that the differences in stress, strain, deformation, and reaction force responses were due to bolt-grade effects rather than mesh-induced numerical variation. The finalized mesh configuration is shown in Figure 3. The mesh was selected to provide stable convergence and reliable prediction of local stress development around the bolts and flange contact surfaces.

The final finite element model used a global element size of 20 mm, while a locally refined element size of 10 mm was applied around the bolt shanks, bolt holes, bolt-head and nut contact regions, flange contact surfaces, and flange-to-tower-shell connection. These regions were refined because they were expected to experience high stress gradients, contact-pressure redistribution, and local deformation. The element sizes were selected based on the mesh sensitivity analysis shown in Figure 3. Further refinement beyond the selected mesh changed the monitored response, indicating that mesh-independent results had been achieved. Therefore, the selected mesh provided an appropriate compromise between numerical accuracy and computational efficiency.

2.4. Contact Definition and Boundary Conditions

Nonlinear contact interactions were defined between all relevant contact surfaces in the T-flange joint assembly. Frictional surface-to-surface contact was assigned between the mating flange surfaces to represent realistic resistance against slip and separation. Contact

definitions were also applied between the bolt head and flange, and between the nut and flange surface. These contact pairs were necessary to accurately simulate the transfer of compressive and tensile forces between the bolts and flange plates.

Bolt pretension was applied before the external loading step to reproduce the clamping force generated during assembly. In ANSYS Mechanical, bolt pretension was introduced using dedicated pretension sections assigned to the bolt shank. The pretension force was applied in the first load step and then locked during the subsequent external loading step. This procedure allowed the model to maintain the initial clamping force while the T-flange joint was subjected to axial tensile loading as shown in Figure 4.

$$F_i = \frac{0.7 \cdot f_{y,b} \cdot A_s}{\gamma_{m7}} \quad (1)$$

where F_i is the initial bolt pretension force, $f_{y,b}$ is the yield strength of the bolt, A_s is the tensile stress area of the bolt, and γ_{m7} is the partial safety factor specified in Eurocode 3. The pretension values were calculated separately for Grade 10.9 and Grade 12.9 bolts because of their different yield strengths. This approach allows the initial clamping force to reflect the mechanical capacity of each bolt grade and the equation is from Eurocode [42].

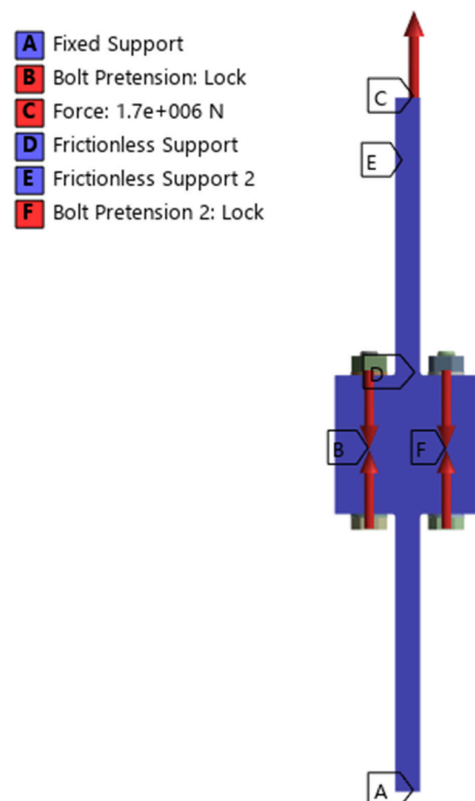


Figure 4. Applied Boundary Conditions.

The use of bolt pretension is important because it affects the initial contact pressure distribution, joint stiffness, flange separation behavior, and bolt force development. Under axial tensile loading, the pretensioned bolts resist flange opening and help maintain load transfer between the connected components. Therefore, accurate modeling of bolt pretension is essential for evaluating the nonlinear response of T-flange joints.

A friction coefficient of $\mu = 0.2$ was assigned to all frictional contact interfaces, including the flange-to-flange, bolt-head-to-flange, and nut-to-flange interfaces. The contact formulation was Augmented Lagrange, with small sliding enabled. These contact settings were kept identical for both bolt-grade models.

Appropriate boundary and loading conditions were applied to reproduce the mechanical response of the T-flange joint under realistic service conditions. The same boundary and loading conditions were used for both bolt-grade models to ensure that the comparison between Grade 10.9 and Grade 12.9 bolts was consistent.

In both cases, one side of the T-flange joint assembly was constrained to represent the connection with the supporting structural component. The fixed support prevented translational and rotational movement at the constrained region, allowing realistic development of internal force, flange contact pressure, and bolt stress under external loading. The opposite side of the model was allowed to deform under the applied load, enabling evaluation of global deformation and local stress response.

After the bolt pretension step, external loading was applied incrementally to the T-flange joint. The applied loading condition consisted of axial tensile and bending actions, representing the load environment experienced by wind turbine support structures during operation. This loading condition was selected because wind turbine flange joints are not subjected to pure tension only; instead, they experience axial tensile axial force and bending moment due to wind, wave, self-weight, and operational effects.

The frictionless supports shown in Figure 4 were applied only to the selected external surfaces of the tower shell as structural boundary conditions. These supports restrained displacement normal to the supported surfaces while permitting tangential deformation, thereby preventing rigid-body motion without fully constraining the natural deformation of the joint. They should not be confused with the contact definitions at the component interfaces. The flange-to-flange, bolt-head-to-flange, and nut-to-flange interfaces were modeled separately using frictional contact. This boundary-condition arrangement was adopted to avoid artificial stiffening of the model while maintaining numerical stability during loading.

Following the bolt-pretension step, a monotonic axial tensile force was applied incrementally to the loaded end of the tower shell, while the opposite end was restrained. Therefore, the numerical analysis was force-controlled. The external load was increased from zero to 1700 kN through nonlinear load substeps, and the resulting displacement, reaction force, stress, strain, and contact response were obtained at each load increment. Load control was selected to represent the prescribed tensile-loading condition and to compare the two bolt-grade configurations under equivalent external load levels.

The axial tensile loading condition generated nonuniform stress distribution in the bolts and flange components. Bolts located near the highly tensioned region experienced greater tensile demand, while contact pressure redistribution occurred along the flange interface. This loading framework enabled evaluation of bolt force development, flange separation, tower shell strain, and load transfer behavior under realistic axial tensile loading conditions. The same loading procedure was applied to both bolt grades to allow direct comparison of structural performance.

2.5. Output Parameters and Post-Processing

After completion of the nonlinear finite element simulations, the results were extracted and post-processed to evaluate the structural performance of each bolt-grade model. The global response was first examined using the force–displacement curve. This curve was used to compare the stiffness and load-carrying capacity of the T-flange joint for Grade 10.9 and Grade 12.9 bolts.

Bolt strain was then evaluated to determine whether the bolts remained within the elastic range or exceeded the yield limit. This parameter was particularly important because bolt yielding can reduce joint stiffness and increase the risk of progressive connection failure. Bolt stress was also examined to identify the load attraction behavior of each bolt grade

and to determine whether higher-strength bolts carried greater internal force under the same external loading.

The response of the connected structural components was evaluated using tower shell strain, tower shell stress, and flange stress. These results were used to determine how the change in bolt grade affected load redistribution from the bolts to the surrounding shell and flange components. Contact behavior was also examined to identify flange separation, contact pressure reduction, and local slip at the interface.

The present analysis considered axial tensile loading because tension promotes flange separation and increases the tensile force, stress, and strain in the preloaded bolts. In contrast, compressive loading generally increases contact pressure between the flange surfaces and reduces the additional tensile demand on the bolts. Therefore, tensile loading was selected as the governing condition for evaluating the influence of bolt grade. The effects of compression, local shell buckling, and cyclic tension–compression loading should be examined in future studies.

The post-processing procedure enabled a detailed comparison of the nonlinear response of the T-flange joint. Through this approach, the influence of bolt grade on joint stiffness, load-carrying capacity, deformation behavior, stress distribution, and safety margin was systematically assessed.

2.6. Validation of FEA Results

The finite element model was verified by comparing its predictions with state the analytical, Identical or comparable geometry, material properties, bolt pretension, contact conditions, and loading were adopted for the benchmark comparison. The present model predicted a Z- F_s of 5% higher compared with reported by analytical approach mentioned in seidel method of IEC-61400-3 Corresponding to a difference of approximately 5%. The close agreement confirms that the numerical model adequately represents the global load-transfer behavior of the bolted flange joint. Nevertheless, local peak stress and strain values may remain sensitive to mesh density and contact discretization; therefore, these quantities are interpreted mainly through comparative trends between the two bolt-grade configurations as shown in Figure 5.

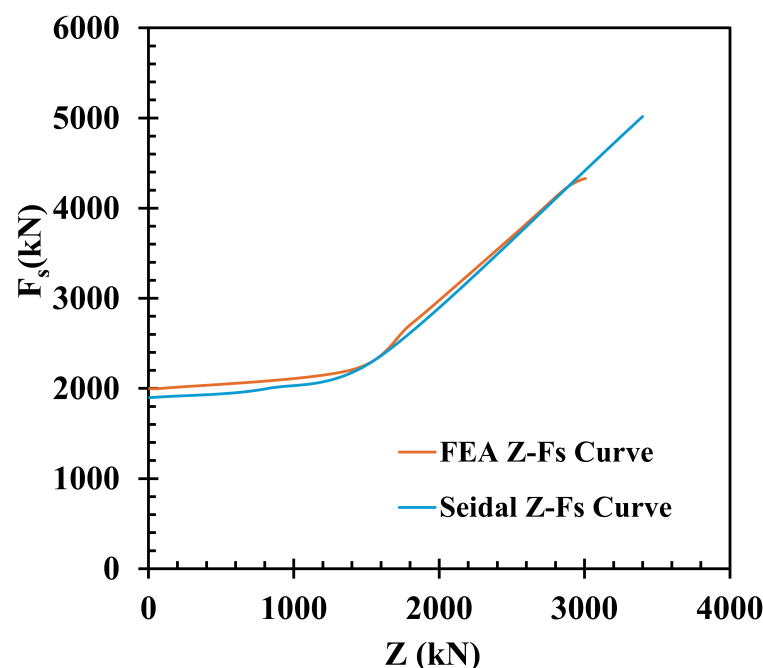


Figure 5. Validation from Analytical Model.

3. Results and Discussions

3.1. Force Displacement Response and Joint Stiffness of T-Flange Connections

The force displacement response of the T-flange joint demonstrates a clear and mechanically consistent dependence on bolt grade, reflecting differences in both material strength and joint stiffness. Under identical loading conditions, the joint assembled with Grade 12.9 bolts exhibits a 12.3% higher reaction force compared to the configuration using Grade 10.9 bolts. This increase is not merely incremental, but indicative of a fundamentally different structural response governed by enhanced stiffness and delayed onset of nonlinear deformation.

In the initial loading regime, both bolt grades exhibit a comparable linear elastic response, suggesting that the global stiffness of the joint is initially dominated by geometric constraints and contact conditions rather than material yielding. However, as the applied displacement increases, divergence between the two curves becomes increasingly evident. The Grade 10.9 configuration begins to deviate from linearity at a lower displacement level, indicating the earlier initiation of localized plastic deformation and micro-slip at the flange interface as shown in Figure 6. In contrast, the Grade 12.9 bolts sustain a steeper force–displacement slope over a larger displacement range, demonstrating their ability to maintain elastic load transfer and resist deformation under higher load levels.

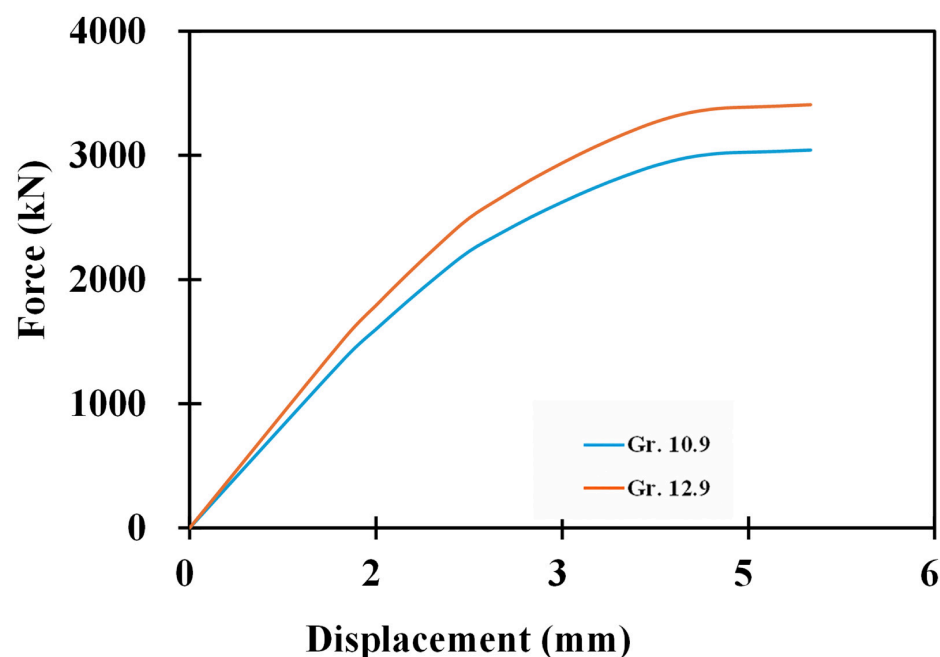


Figure 6. Force Displacement Curve.

The higher reaction force observed in the Grade 12.9 configuration can be directly associated with increased joint stiffness. Mechanically, joint stiffness is governed by the axial tensile stiffness of the bolts, flange plates, and contact interface. Since Grade 12.9 bolts possess higher yield strength and modulus-consistent elastic behavior under elevated stress levels, they provide greater resistance to elongation under tensile loading. This reduced bolt elongation limits relative displacement between the flange plates, thereby maintaining higher contact pressure and frictional resistance at the interface. As a result, the joint behaves more as a rigidly constrained system, leading to higher measured reaction forces.

Conversely, the Grade 10.9 bolts exhibit reduced stiffness due to earlier yielding and increased susceptibility to plastic deformation. As the applied load increases, these bolts undergo greater elongation, which reduces the clamping force and allows partial separation or slip between the flange surfaces. This loss of contact integrity leads to a redistribution of

load from compressive contact zones to the bolts themselves, increasing bending effects and reducing the efficiency of load transfer. Consequently, the overall reaction force is lower, and the joint exhibits a softer mechanical response.

From a load-transfer perspective, the observed behavior highlights the transition from a friction-dominated mechanism to a bolt-dominated mechanism. In the Grade 12.9 configuration, the higher preload retention and stiffness ensure that a significant portion of the applied load is transferred through friction at the flange interface, delaying slip and minimizing stress concentration in the bolts. In contrast, the Grade 10.9 configuration experiences earlier reduction in clamping force, causing a premature shift toward direct load transfer through the bolts. This shift increases localized stresses and accelerates deformation, ultimately reducing the global load-carrying capacity of the joint.

The difference in mechanical performance also reflects the material properties of the respective bolt grades. Grade 10.9 bolts typically have a nominal yield strength of approximately 900–940 MPa, whereas Grade 12.9 bolts exhibit significantly higher yield strength, often exceeding 1100 MPa. This higher strength allows Grade 12.9 bolts to sustain greater levels without entering the plastic regime, thereby preserving structural integrity under higher loads. The delayed yielding behavior contributes to the sustained stiffness and higher reaction force observed in the force displacement response.

Furthermore, the increased stiffness associated with higher-grade bolts enhances the joint's resistance to axial tensile loading effects, including axial tension, shear, and bending. In flange connections, these loading modes often interact, leading to complex stress states within the bolts. The superior mechanical properties of Grade 12.9 bolts enable them to better accommodate these axial tensile stresses without significant deformation, thereby improving the overall robustness of the joint.

The force-displacement curves were evaluated only within the applied loading range and terminated at an approximate displacement of 6 mm. Therefore, the present results describe the pre-peak and progressive nonlinear response of the joint but do not represent complete post-peak softening or structural collapse. Although material yielding was considered, no fracture or damage criterion was included for the bolts, flange, or tower shell. Accordingly, the ultimate collapse state and post-peak load degradation were outside the scope of this study and should be investigated in future work using damage-based material models and an appropriate post-buckling or arc-length solution procedure.

It is also important to note that the relationship between bolt grade and joint performance is not strictly linear. While the 12.3% increase in reaction force reflects improved performance, the underlying mechanisms involve nonlinear interactions between material behavior, contact conditions, and geometric deformation. Enhanced stiffness reduces deformation compatibility within the joint, leading to more efficient load distribution and reduced energy dissipation through plastic deformation.

In practical engineering applications, these findings have significant implications. The use of higher-grade bolts can substantially improve the stiffness, load-carrying capacity, and durability of T-flange joints, particularly in structures subjected to high or cyclic loading conditions such as offshore platforms and wind turbine connections. Conversely, the use of lower-grade bolts may lead to earlier deformation, reduced preload retention, and increased susceptibility to fatigue damage due to fluctuating stresses.

The increase in global reaction force was smaller than the corresponding increase in bolt ultimate tensile strength. The ultimate tensile strength increased from 1020 MPa for Grade 10.9 bolts to 1220 MPa for Grade 12.9 bolts, representing an increase of approximately 19.6%, whereas the total reaction force increased by 12.3%. This sub-proportional improvement is mechanically expected because the global resistance of the T-flange joint is not governed by bolt strength alone.

For bolts with identical geometry and approximately the same Young's modulus, the initial elastic axial stiffness, $k_b = EA/L$, remains essentially unchanged. Therefore, increasing the bolt grade does not produce a proportional increase in the initial elastic stiffness of the connection. Instead, the higher yield and ultimate strengths of Grade 12.9 bolts delay the onset of bolt yielding and allow the bolts to sustain greater internal force before significant nonlinear deformation occurs.

The total joint response is also controlled by flange bending, tower-shell deformation, contact-interface compliance, local flange opening, bolt pretension, and redistribution of load between the bolts and connected components. As the bolt resistance increases, the flange, tower shell, and contact regions contribute a larger proportion of the overall deformation. Consequently, the additional material strength of the Grade 12.9 bolts cannot be fully converted into an equivalent increase in global reaction force. This explains why a 19.6% increase in bolt ultimate strength produced a comparatively smaller 12.3% increase in total joint resistance.

The higher bolt resistance also transfers greater mechanical demand to the surrounding components, which is consistent with the observed increases in flange strain and tower-shell stress and strain. Therefore, the results demonstrate that the structural benefit of a higher bolt grade is limited by the stiffness, strength, and deformation capacity of the complete T-flange joint system.

The increase in global reaction force was smaller than the increase in bolt ultimate strength because the T-flange response is governed by the complete joint system rather than bolt strength alone. Increasing the bolt grade from 10.9 to 12.9 raised the ultimate strength by approximately 19.6%, while the reaction force increased by 12.3%. At the same time, flange strain increased by 20.0%, tower-shell strain by 18%, and tower-shell stress by 11.2%, indicating that part of the additional bolt capacity was transferred to the connected flange and shell. Therefore, flange deformation, shell flexibility, contact behavior, and bolt-flange interaction limited the proportional increase in the overall joint resistance.

Overall, the force displacement analysis confirms that increasing bolt grade enhances joint stiffness, delays the onset of nonlinear deformation, improves load-transfer efficiency, and increases the overall structural performance of the T-flange connection. The results provide clear evidence that bolt material selection plays a critical role in determining both the local and global mechanical behavior of bolted flange systems.

3.2. Bolt Unified Assessment of Force, Stress, and Strain Responses in T-Flange Joints: Impact of Bolt Grade

The mechanical response of the T-flange joint under identical loading conditions reveals a strong dependency on bolt grade, as evidenced by the axial tensile analysis of reaction force, stress distribution, and strain behavior. The integration of these three response parameters provides a comprehensive understanding of how material properties influence both local bolt behavior and global joint performance.

From the force-displacement perspective, the Grade 12.9 configuration exhibits a 12.3% higher reaction force compared to the Grade 10.9 bolts. This increase reflects a higher global stiffness of the joint, indicating that the structure resists deformation more effectively when higher-grade bolts are used. The steeper slope of the force displacement response suggests that Grade 12.9 bolts maintain elastic load transfer over a larger deformation range, whereas Grade 10.9 bolts begin to soften earlier due to material yielding and localized deformation.

This global behavior is directly supported by the stress results. The Grade 12.9 bolts develop approximately 21% higher stress than the Grade 10.9 bolts under the same loading conditions as shown in Figure 7. Rather than indicating a detrimental condition, this higher stress level demonstrates that the stiffer Grade 12.9 bolts attract a larger share of the applied load within the joint. This is consistent with stiffness-controlled load distribution,

where elements with higher rigidity sustain greater internal forces. Additionally, the stress distribution in Grade 12.9 bolts is more uniform, indicating a stable and efficient load-transfer mechanism with reduced stress concentration.

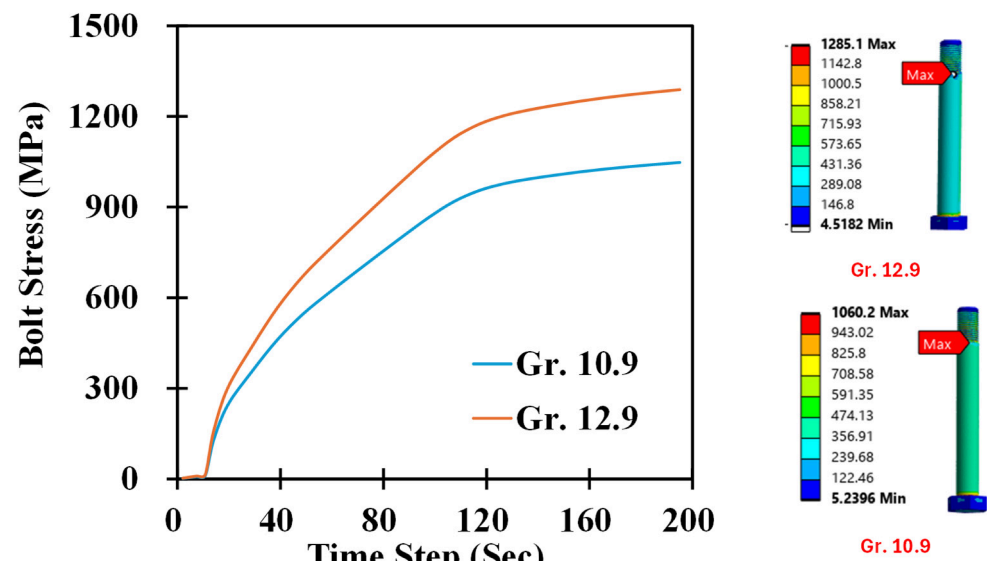


Figure 7. Bolt Stress Under Axial Loading.

The failure response was not governed exclusively by bolt strength. In the Grade 10.9 model, the bolt reached its yield condition earlier, resulting in increased plastic deformation and reduced joint stiffness. Grade 12.9 bolts delayed bolt yielding and sustained higher internal force; however, the additional load was transferred to the flange and tower shell. The flange strain exceeded the corresponding yield strain in both configurations, indicating a coupled bolt–flange yielding mechanism rather than a purely bolt-controlled failure. Consequently, the approximately 19.6% increase in bolt ultimate tensile strength produced only a 12.3% increase in global reaction force because flange bending, local yielding, contact redistribution, and shell deformation progressively controlled the overall joint capacity. Since no fracture criterion was included, the reported failure behavior represents yielding and stiffness degradation rather than physical bolt rupture.

In contrast, the Grade 10.9 bolts exhibit lower peak stress but show clear signs of earlier stress concentration and non-uniform distribution. This behavior is indicative of premature yielding and localized plasticity, which reduces the effective stiffness of the bolt. As yielding progresses, the bolt loses its ability to attract additional load, resulting in stress redistribution and lower measured stress levels despite identical external loading. This phenomenon highlights that lower stress magnitude in this context corresponds to reduced structural efficiency rather than improved performance.

The strain results further reinforce this interpretation. The maximum strain recorded in the Grade 10.9 bolt is $5335 \mu\epsilon$, while the Grade 12.9 bolt reaches a higher value of $6332 \mu\epsilon$. However, when evaluated relative to material capacity, the Grade 10.9 bolt strain exceeds its yield strain by approximately 10–12%, confirming that it has entered the plastic deformation regime. This plastic behavior leads to permanent deformation, reduction in bolt stiffness, and loss of clamping force.

Conversely, the higher strain observed in the Grade 12.9 bolt remains close to its yield limit, indicating that the material is still operating predominantly within the elastic range or at the onset of yielding. This demonstrates that Grade 12.9 bolts can sustain higher deformation levels without significant plastic damage, owing to their superior

yield strength. As a result, they maintain structural integrity and stiffness even under increased demand.

The consistency between force, stress, and strain responses highlights a unified mechanical behavior. The Grade 12.9 bolts, due to their higher stiffness and strength, attract greater load (higher stress), resist deformation more effectively (higher reaction force), and accommodate strain within elastic limits (controlled strain behavior). This leads to a stable load-transfer mechanism, sustained clamping force, and uniform stress distribution across the joint as shown in Figure 8.

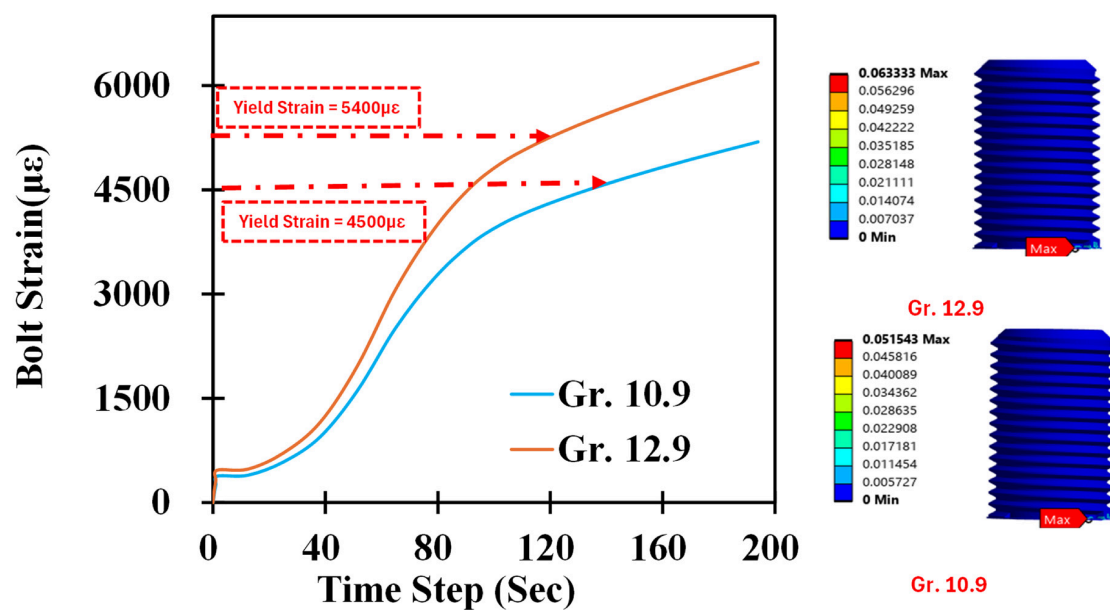


Figure 8. Bolt Strain Performance.

The bolt yield-strain thresholds were calculated using $\epsilon_y = f_y/E$, where $E = 200$ GPa. The resulting yield strains were $4500 \mu\epsilon$ for Grade 10.9 bolts and $5400 \mu\epsilon$ for Grade 12.9 bolts. At the maximum investigated load, the corresponding bolt strains were $5335 \mu\epsilon$ and $6332 \mu\epsilon$, respectively. Thus, both bolt grades entered the plastic range at the final loading stage. However, the higher yield-strain threshold of Grade 12.9 delayed the onset of yielding and enabled the bolt to sustain a greater load before plastic deformation developed.

In contrast, the Grade 10.9 bolts exhibit a coupled degradation mechanism. Earlier yielding leads to increased strain beyond elastic limits, which reduces stiffness and limits stress accumulation. This, in turn, lowers the overall reaction force and promotes non-uniform load distribution. The loss of preload and increased deformation further exacerbate stress concentration, accelerating the transition toward localized damage and reduced structural performance.

Mechanically, this behavior can be explained by the interaction between bolt stiffness, material yielding, and flange contact conditions. In the Grade 12.9 configuration, higher stiffness preserves clamping pressure and frictional resistance at the flange interface, allowing efficient load transfer through both contact and bolt action. In the Grade 10.9 configuration, early plastic deformation reduces clamping effectiveness, causing partial separation and shifting the load-transfer mechanism toward localized bolt loading, which is inherently less efficient and more prone to stress concentration.

From an engineering standpoint, these findings clearly demonstrate that bolt grade plays a critical role in governing the structural response of T-flange joints. The use of higher-grade bolts significantly enhances load-carrying capacity, maintains stiffness, delays yielding, and improves stress distribution, ultimately leading to superior joint performance.

and durability. Conversely, lower-grade bolts are more susceptible to early plastic deformation, reduced stiffness, and localized stress concentration, which can compromise the reliability and service life of the connection.

Although fatigue life was not directly evaluated, the stress results have important implications for cyclic performance. The Grade 12.9 configuration developed approximately 21% higher bolt stress and 11.2% higher tower-shell stress than the Grade 10.9 configuration. If similar increases occur in the cyclic stress range under operational loading, fatigue-damage accumulation in the bolts, flange, or tower shell may increase. Conversely, the higher pretension and delayed flange separation associated with Grade 12.9 bolts may improve contact stability and reduce load fluctuations under some loading conditions. Therefore, higher static strength does not necessarily guarantee improved fatigue life. A quantitative fatigue assessment would require cyclic stress ranges, representative wind and wave load spectra, preload relaxation, thread stress concentration, mean-stress effects, and appropriate S-N curves.

Overall, the axial tensile results confirm that the mechanical performance of bolted flange joints is strongly controlled by bolt material properties, and that higher bolt grades provide a more robust and efficient structural response under identical loading conditions.

3.3. Effect of High-Strength Bolts on Flange Deformation

The flange strain response shows that the bolt grade has a significant influence on the deformation demand transferred to the flange. The maximum flange strain increased from 5091.5 $\mu\epsilon$ for the Grade 10.9 bolt model to 6109.8 $\mu\epsilon$ for the Grade 12.9 bolt model. This corresponds to an increase of approximately 20.0% when Grade 12.9 bolts were used.

This result indicates that the use of higher-strength bolts does not only improve the bolt performance but also changes the load-transfer behavior of the complete T-flange joint. Grade 12.9 bolts have a higher yield strength than Grade 10.9 bolts, so they can resist larger tensile demand without early yielding. Because of this, the Grade 12.9 bolts remain more effective in transferring the external load to the surrounding flange region. As a result, a larger portion of the applied force is transmitted into the flange, causing higher flange strain.

In the Grade 10.9 model, the bolts are more likely to experience earlier yielding or local deformation. Once this occurs, the bolts lose part of their ability to attract and transfer additional load efficiently. This reduces the load transferred to the flange, which explains why the flange strain remains lower in the Grade 10.9 case. However, this lower flange strain should not be interpreted as better structural performance. Instead, it suggests that part of the deformation demand is being absorbed by the lower-strength bolts through earlier nonlinear behavior.

For the Grade 12.9 model, the higher flange strain is a result of stronger bolt action and improved load participation. The Grade 12.9 bolts maintain their load-carrying capacity for a longer loading range, allowing the joint to develop higher resistance. This agrees with the previous results, where Grade 12.9 showed higher reaction force and higher bolt stress. Therefore, the higher flange strain is mechanically consistent: as the stronger bolts carry and transfer more load, the connected flange also experiences higher deformation demand as shown in Figure 9.

Another important reason is bolt pretension. Since bolt pretension is usually calculated based on bolt yield strength, the Grade 12.9 bolts develop higher initial clamping force than Grade 10.9 bolts. This higher clamping force increases contact pressure between the surfaces and improves the engagement of the flange during loading. Consequently, the flange becomes more actively involved in resisting the applied tensile and bending forces, resulting in higher strain.

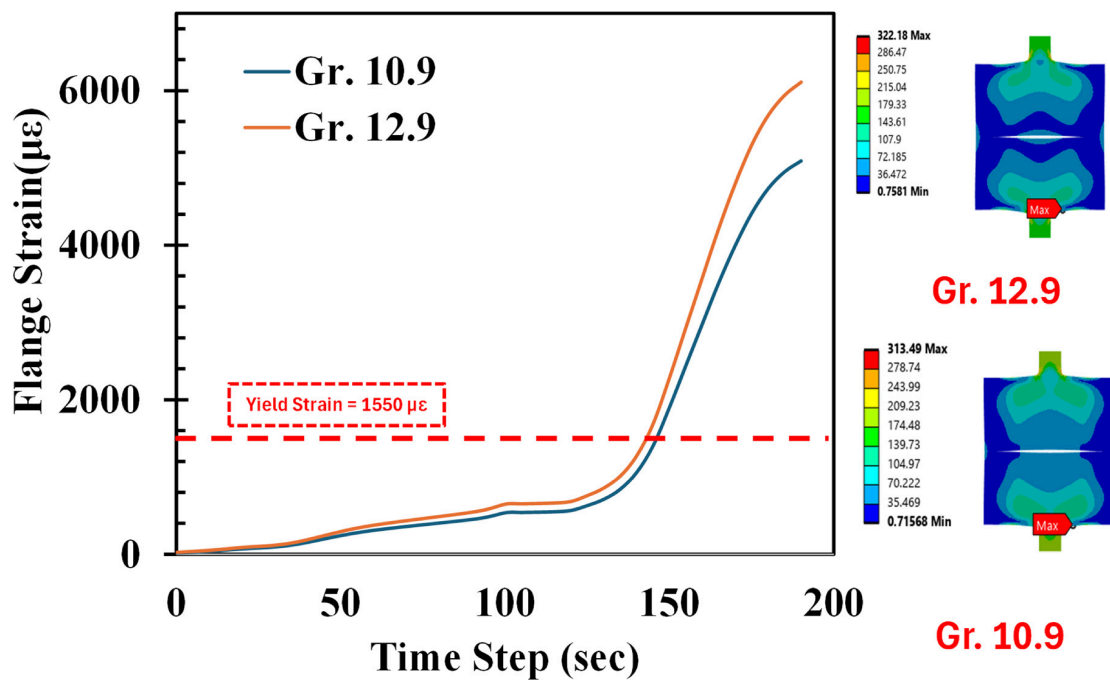


Figure 9. Flange Strain Using Different Bolt Grades.

Overall, the flange strain results show that increasing the bolt grade from 10.9 to 12.9 increases the flange deformation demand by about 20.0%. This confirms that Grade 12.9 bolts improve joint load transfer and overall resistance, but they also transfer greater demand to the flange. Therefore, when Grade 12.9 bolts are used, the flange thickness, flange material strength, local contact region, and bolt-hole area should be carefully checked to ensure that the critical failure mode does not shift from bolt yielding to flange yielding or local flange deformation.

3.4. Effect of Bolt Grade on Tower Shell Strain and Stress Response

The tower shell response was evaluated to understand how the change in bolt grade affects the load transferred from the bolted flange connection to the connected shell structure. The results show that the tower shell strain was higher in the Grade 12.9 bolt model compared with the Grade 10.9 bolt model. The Grade 12.9 configuration produced approximately 18% higher tower shell strain than the Grade 10.9 configuration under identical loading conditions.

This increase indicates that the higher-strength Grade 12.9 bolts transferred a greater portion of the applied load to the tower shell. Since Grade 12.9 bolts have higher yield and tensile strength, they resist bolt yielding and excessive bolt deformation more effectively than Grade 10.9 bolts. As a result, less deformation is absorbed by the bolts, and more load is redistributed to the connected flange and tower shell. Therefore, the tower shell becomes more actively involved in resisting the external tensile and bending loads.

Therefore, the tower shell stress in the Grade 12.9 model was approximately 11% higher than in the Grade 10.9 model as shown in Figure 10.

This higher stress is mechanically consistent with the strain response. Because the Grade 12.9 bolts remain more effective in carrying and transferring load, the surrounding shell receives higher stress demand. In contrast, the Grade 10.9 bolts undergo relatively larger bolt deformation and earlier nonlinear behavior, which reduces the amount of load transferred to the tower shell. Therefore, the lower tower shell stress and strain in the Grade 10.9 model should not be interpreted as better performance; rather, it indicates that more deformation is being absorbed by the bolts.

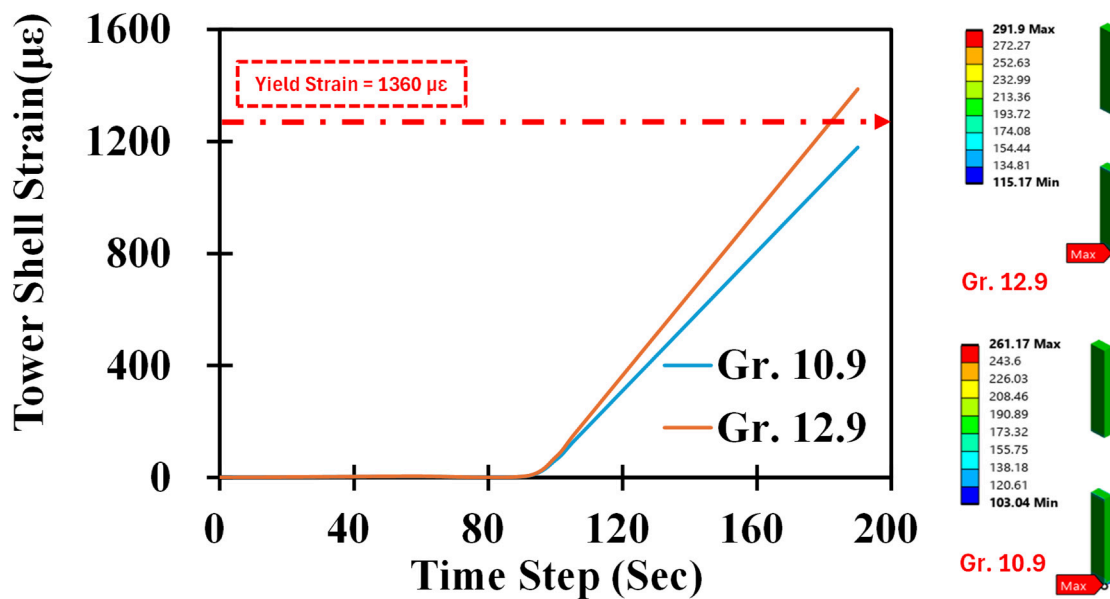


Figure 10. Tower Shell Strain.

However, both cases remain within the elastic range of the tower shell. The maximum tower shell strain remains below the yield strain value of approximately $1876 \mu\epsilon$, which means that no yielding occurred in the tower shell for either bolt grade. This confirms that although Grade 12.9 bolts increase the load demand on the tower shell, the shell still operates safely within the elastic limit.

Overall, the tower shell response shows that increasing the bolt grade from 10.9 to 12.9 improves the load-transfer capacity of the T-flange joint but also increases the stress and strain demand on the connected shell. Therefore, when higher-grade bolts are used, the tower shell and flange should be carefully checked to ensure that the critical failure mode does not shift from bolt yielding to shell or flange yielding.

3.5. Z - F_s Relationship and Bolt Load Transfer Response

The Z - F_s relationship describes the development of internal bolt force, F_s , with increasing applied external tensile load, Z . The value of F_s at $Z = 0$ represents the initial bolt pretension, while the subsequent increase in F_s indicates the additional tensile force attracted by the bolt during external loading. Therefore, the slope and shape of the Z - F_s curve provide information about bolt participation, flange separation, and load redistribution within the preloaded T-flange joint.

The Z - F_s relationship was evaluated to investigate the internal bolt force response, F_s , under increasing external tensile load, Z , for the T-flange joint using Grade 10.9 and Grade 12.9 bolts. This response is important because it describes how the external tensile load is transferred through the preloaded bolt system and how the bolt force develops during loading.

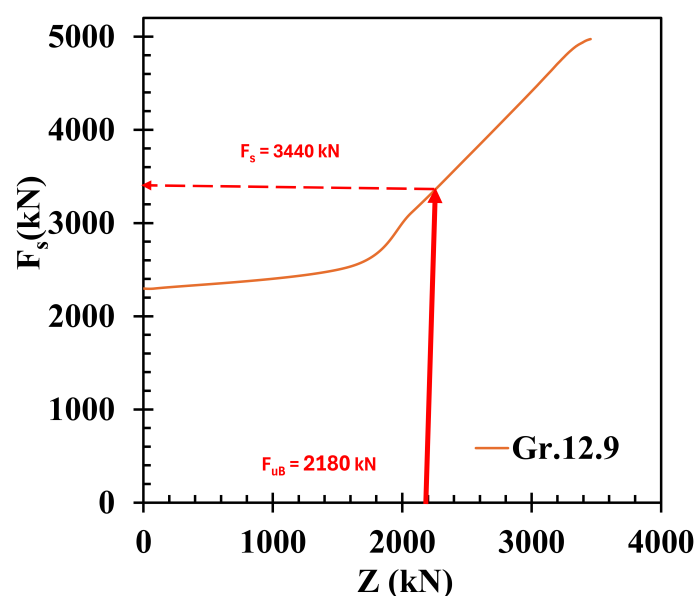
From the Z - F_s curves, both bolt grades show a gradual increase in internal bolt force with increasing external load. At the design external tensile load of $F_{u,B} = 2060$ kN, the internal bolt force was approximately 3160 kN for the Grade 10.9 bolt and 3440 kN for the Grade 12.9 bolt. Therefore, the Grade 12.9 bolt developed an internal bolt force.

This result shows that the Grade 12.9 bolt attracted and carried a greater portion of the applied tensile load. The higher internal bolt force is mainly due to the higher yield and tensile strength of the Grade 12.9 bolt, which allows it to resist larger tensile demand without early yielding. In contrast, the Grade 10.9 bolt shows a lower internal force because

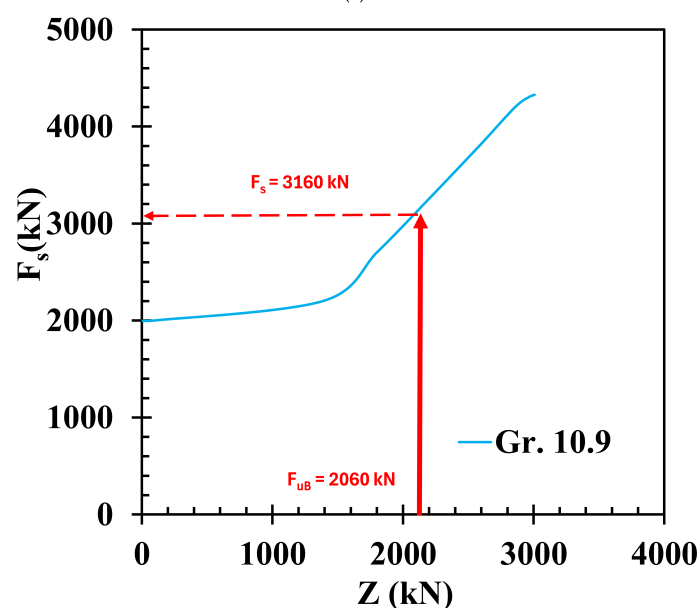
it has lower yield capacity and is more likely to experience earlier nonlinear deformation as the external load increases.

The initial value of F_s at zero external load represents the bolt pretension force. The Grade 12.9 curve starts at a higher internal force level than the Grade 10.9 curve, indicating a higher initial clamping force. This is expected because bolt pretension is related to bolt yield strength. Since Grade 12.9 bolts have higher yield strength, they can develop greater pretension and produce stronger compression between the flange surfaces. This improves the initial contact condition and delays flange separation during loading.

As the external load increases, the Grade 12.9 curve continues to rise to a higher internal bolt force compared with the Grade 10.9 curve. This indicates that the Grade 12.9 bolt maintains more effective load participation throughout the loading process. The higher bolt force is consistent with the previous stress results, where Grade 12.9 bolts showed higher stress than Grade 10.9 bolts. Therefore, the Z - F_s curve confirms that Grade 12.9 bolts are more active in the load-transfer mechanism as demonstrated in Figure 11.



(a)



(b)

Figure 11. Z - F_s Curve (a) Gr. 12.9 (b) Gr. 10.9.

For the Grade 10.9 bolt, the curve shows a comparatively lower F_s value at the same external load. This does not mean that the Grade 10.9 bolt is safer; rather, it suggests that the lower-strength bolt is less capable of attracting additional load once nonlinear deformation begins. Earlier bolt elongation and local deformation reduce the clamping efficiency of the joint, causing partial redistribution of load through flange deformation and contact changes.

Overall, the Z- F_s response confirms that Grade 12.9 bolts improve the bolt load-transfer capacity of the T-flange joint. At the same external load level of 1090 kN, the Grade 12.9 bolt developed approximately 13.7% higher internal bolt force than the Grade 10.9 bolt. This indicates better load participation, higher pretension effectiveness, and delayed yielding behavior. However, the higher internal bolt force also means that greater load is transferred to the surrounding flange and tower shell, which agrees with the flange strain and tower shell response discussed earlier.

4. Conclusions

This study investigated the influence of bolt grade on the structural performance of T-flange joints used in wind turbine support structures. A nonlinear finite element model was developed in ANSYS Mechanical to compare Grade 10.9 and Grade 12.9 bolts under identical geometry, material properties of the connected components, contact conditions, boundary conditions, bolt pretension procedure, and axial tensile bending loading. The main conclusions obtained from this study are summarized as follows.

The force displacement response showed that the T-flange joint assembled with Grade 12.9 bolts developed a 12.3% higher reaction force compared with the Grade 10.9 bolt configuration. This indicates that Grade 12.9 bolts improved the global load-carrying resistance of the joint. The improvement was mainly associated with the higher yield and tensile capacity of Grade 12.9 bolts, which delayed the onset of nonlinear deformation and helped maintain more effective load transfer at higher loading levels.

The bolt stress results showed that Grade 12.9 bolts developed approximately 21% higher stress than Grade 10.9 bolts under the same loading condition. This higher stress does not indicate weaker performance; rather, it confirms that the higher-strength bolts attracted and carried a greater share of the applied load. In contrast, the lower stress observed in Grade 10.9 bolts was associated with earlier nonlinear deformation and reduced load participation.

The bolt strain response further confirmed the difference in mechanical behavior between the two bolt grades. The maximum bolt strain increased from 5335 $\mu\epsilon$ for Grade 10.9 to 6332 $\mu\epsilon$ for Grade 12.9. Although Grade 12.9 bolts experienced higher strain, this occurred together with higher load-carrying capacity and higher material resistance. Therefore, the Grade 12.9 bolts were able to sustain greater load demand before significant degradation of the joint response occurred.

The governing response was identified as a coupled bolt–flange yielding mechanism rather than a purely bolt-controlled failure, which explains why the increase in global joint resistance was smaller than the increase in bolt ultimate strength.

The flange response showed that the maximum flange strain increased from 5091.5 $\mu\epsilon$ in the Grade 10.9 model to 6109.8 $\mu\epsilon$ in the Grade 12.9 model, representing an increase of approximately 20.0%. This confirms that higher-strength bolts transfer greater load demand to the connected flange. Therefore, the use of Grade 12.9 bolts improves bolt load participation, but it also increases the deformation demand on the surrounding flange region.

The tower shell response showed a similar trend. Grade 12.9 bolts produced approximately 18% higher tower shell strain and approximately 11% higher tower shell stress

compared with Grade 10.9 bolts. This indicates that the higher-strength bolts transferred more load into the connected tower shell. However, the tower shell remained within the elastic range in both bolt-grade models, showing that no critical shell yielding occurred under the investigated loading condition.

The Z- F_s relationship also confirmed the improved load-transfer behavior of the Grade 12.9 bolts. At the design external tensile load, the internal bolt force was approximately 3160 kN for Grade 10.9 and 3440 kN for Grade 12.9. This corresponds to a 13.7% higher internal bolt force in the Grade 12.9 model. This result demonstrates that Grade 12.9 bolts provide stronger bolt force development and improved load-transfer efficiency under external tensile loading.

Overall, the numerical results demonstrate that increasing the bolt grade from 10.9 to 12.9 improves the structural resistance, bolt load participation, and load-transfer capacity of the T-flange joint. However, the improvement in bolt performance is accompanied by higher stress and strain demand in the flange and tower shell. Therefore, the use of Grade 12.9 bolts should not be evaluated based only on bolt strength. The complete joint system, including the bolts, flange, contact interface, and tower shell, must be checked to ensure that the critical failure mode does not shift from bolt yielding to flange or shell deformation.

The present comparison is limited to structural performance and does not constitute a complete industrial optimization. Although Grade 12.9 bolts provided higher resistance and delayed yielding, their use may involve higher material and procurement costs, lower availability, and modified tightening and inspection requirements because of the higher pretension level. Practical bolt selection should therefore consider not only mechanical capacity, but also flange and shell resistance, installation equipment, torque–tension control, maintenance, supply availability, and life-cycle cost. Consequently, Grade 12.9 bolts should be regarded as a mechanically advantageous option rather than a universally preferable replacement for Grade 10.9 bolts.

Based on the results of this study, Grade 12.9 bolts can be considered more effective than Grade 10.9 bolts for improving the structural performance of T-flange joints under axial tensile and bending loading. Nevertheless, careful design verification of the connected flange and tower shell is necessary when higher-grade bolts are adopted in wind turbine support structures.

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