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Reliability of T-stub Pre-stressed Connections Using Numerical Model

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ABSTRACT

In this paper, the reliability of T-stub pre-stressed connections is investigated using the numerical model. The T-stub connection is considered as a bolted one, usually in the semi-rigid range. By selecting a test specimen, the T-stub bolted connection is initially simulated in the Abaqus finite element software to determine software validation and the modeling method used in this research. Then, the structural elements, loading, materials and type of analysis used in the test are introduced and 52 samples of T-stub connection controlled with construction and design constraints are determined to specify a series of targeted data through the changes in the geometric configuration and material strength of the T-stub connection elements. Finally, by performing nonlinear analyses in Abaqus finite element software and determining the limit state function of maximum tensile load of bolts in terms of random variables such as the bolt diameter, width and thickness of section flange, width and thickness of section at two performance levels, namely yielding and failure of web plate, the reliability is analyzed by Monte Carlo statistical method. The results of the probability of failure (PF) were zero for all samples under both performance levels. This is because of the requirement for the failure mode not being occurred in the web of T-stub connection was observed when selecting the specimens. Therefore, the determined T-stub connection specimens are of strong bolted type and hence, the probability of failure (PF) becomes zero, which is the probability of the bolt being yielded in the unthreaded section after the web plate is yielded, and the failure of the bolt in the threaded section after the failure of the web plate.

Keywords: Reliability, connections, pre-stressed, T-stub, numerical model

1. INTRODUCTION

One of the most important types of connections is the T-stub connection, which is considered as a bolted one usually in the semi-rigid range. Young and Jackson in 1934 conducted a study to determine the quality and compare the restraint levels provided by the riveted and welded beam-column connections. This study includes several welded connection tests and four tests of riveted T-stub connections. Two connections have the t-stub riveted to a column flange with a given configuration along with two other configurations with the t-stub connections riveted to a plate representing the column web. the loading history includes the cyclic loads limited to the service load levels according to the uniform loading up to failure. The results show that even for service loads, the hysteresis capacity is a considerable energy available in the connections [1]. Rathburn performed 18 beam-column tests. The study includes the results of the tests related to the clip-angle, web-angle and T-stub connections. It is found from these experiments that even the weak moment connections show the restraint levels [2]. Following this work, other studies conducted twenty-seven experiments on a wide-flange beam T-stub in addition to fifteen splice tests to replicate the interaction between the T-stub and the beam flange. Then, the experiments continued with three beam-column tests for verification purposes. A wide range of flange thicknesses and bolt sizes were developed to provide a series of robust data from three prying models of varying complexity. The main results of the study indicate that T-stub connections can be designed to develop full plastic moment in the connected beams, and that the use of thicker T-stub flanges reduces the effects of prying action [3,4]. Nair, Birkemoe and Munse subjected sixteen T-stub connections cut from a W27×160 section to the cyclic loading and considered the fatigue phenomenon as part of a study to determine the behavior of prying action. The 3.4in. A325 and A490 bolts were used in various configurations. The results of the T-stub test were compared with the behavior of bolts that were independently tested to detect the effects of prying action. The finite element models of T-stub connection, including the nonlinear specifications of materials, were used for the development of simplified design equations to predict the strength [5]. Agerskov examined the prying action in the end-plate connections and T-stub by performing four uniformly developed T-stub tests. A method was presented for predicting the yield moment in the T-stub flange based on the von Mises yield criteria, including the shear stresses. Four tests involve the plates of different thicknesses and the bolts of grade 10.9 (A490) [6]. Eight T-stub connections were independently tested by Moore and Slims to determine the impact of backing plates used to reinforce the column flange under the failure. A test is composed of a simple T-stub and column-stub system without any backing plate, and another from a common T-stub and column-stub system using the web stiffeners on the column. The M16 and A325 bolts (M16 = 5.8 in. and A325 = 8.8 in.) were used in the connections to connect the 15mm T-stub flange to the column flange. The backing plates provided different degrees of reinforcement and showed that they provide more support than the old stiffeners [7]. Bursi, Ballerini tested ten samples of the T-stub connection made as part of the research program for the end-plate connection. Four T-stub samples tested under uniform load were compared with similar T-stubs that were cyclically tested. The thickness of T-stub flanges was 12 mm, 18 mm and 25 mm, and the M16, M20 and M24 bolts of grade 8.8 were used. The used cyclic load history includes the loading steps increased from three cycles up to failure. The share of compression from the loading steps always returns the zero displacement (i.e., no real compression was applied to the T-stub). The plastic flange and flange yield mechanisms were obtained along with tensile bolt failure modes [8]. The full-scale T-stub tests performed by Swanson [9] and Smallidge [10] on the rolled T-stubs with flexible flanges (the ratio of size g_t to flange thickness t_f greater than 4.00, i.e. ${}^{g_t}/{}_{t_f} > 4.00$) are limited to the beams up to W24, while those tested by Popov and Takhirov used the W36 beams [11]. The test results reported by Piluso and Rizzano at 2007 [12] with T-stub components of flexible flange stiffness (${}^{g_t}/{}_{t_f} > 4.00$) show that the welding process used to assemble the connection web to the column flange is very important in the sense that it ensures the ductile behavior. The analytical models based on mechanics (finite element and stiffness models) are representative of the deformation-load behavior and are used to replicate the test results, and show a good agreement between the thicknesses of different T-stub flanges. The main objective of the study conducted by Hantouche, Rassati, Kukreti and Swanson is to use the finite element and test data to qualify the T-stub connections for the use in SMF and IMF. The ability to construct T-stub elements with thick (stiff) flanges produced from the plates with ${}^{g_t}/_{t_f} = 3.00$ was presented and described. Using Abaqus finite element software, three-dimensional finite element models were developed for thick-flange T-stub connections and verified by comparing the test results. The finite element and test results emphasize the main differences between the T-stubs produced using complete joint penetration (CJP) and fillet welding, which clarifies the reason for the use of T-stub produced with fillet weld for the convenience construction [13]. It was developed following a similar process recently adopted by Zoetemeijer [14] and Demonceau, Jaspart, Muller and Weynand [15]. Particularly, by setting the work performed by the external load equal to the internal work developed along the yield lines, the equivalent T-stub effective length in tension is determined or all possible failure mechanisms. As a conclusion of this study, a relationship was developed which could provide the strength of a T-stub with four bolts in each row according to the EC3 and verified by a parametric analysis performed in Abaqus software. In a pre-stressed T-stub connection under tension, the load generated in the bolts during the tensile loading depends on the geometry of the connection including several parameters such as the tensile stiffness of bolt, moment stiffness of T-shaped section flange, bolt location, geometric dimensions of T-shaped section, pre-stress levels, etc. Given that it is difficult to analyze the t-stub connections involving the pre-stress in the bolts (which is the most common connection in the modeling of equivalent springs) due to the complexity of deformations in different regions, nonlinear behavior of materials even in small loads, different failure modes, etc. and it is costly, time- consuming and impractical to perform the tests for different samples, therefore, due to the quantitative and qualitative development of finite element software and the great capability to perform complex analyses, using various finite element software such as Ansys and Abaqus is among the most appropriate options available for researchers to study the behavior of these complex connections in such software. In the vast majority of existing methods, due to the high complexity of the tensile and moment behavior of T-stub connections, the behavior analysis is usually accompanied by some simplifications, which in some cases makes the accuracy of results from these analyses controversial.

2. MATERIALS AND METHODS

The experimental and numerical test models are developed to achieve the realistic responses for this type of connection. Since the study of T-stub connection behavior is difficult with classical structural analyses and on the one hand, due to the issues such as the uncertainty of deformations in the connection elements and the load distribution in these elements, and on the other hand, the nonlinear behavior of geometry and materials, therefore, it is not possible to trust the accuracy of results for such analyses. However, performing the test to check the behavior of the connections, though leading to more accurate results, is not feasible for the connection with impractical dimensions due to the incurred costs. In this regard, considering the high capability of finite element software in modeling the behavior of various structures and infrastructures, modeling using the finite element software is among the most appropriate options for researchers, and the studies show that the study and exact modeling of these types of connections can be done in the above software, but it is necessary to examine the parameters affecting the modeling results. In addition to the direct use of T-stub connection in the bolted structures, in many cases, the very complex connections are set equivalent to a series of T-stub connection under tension to allow for the analysis and design. Therefore, the exact study of the behavior of this connection and its elements has been found to be of great importance in the current research. In spite of the ever-increasing use of finite elements for modeling the connections, the standardization or identification of important parameters in the modeling of finite elements for the T-stub connection has not yet been done where the effective parameters are provided in an optimum range. For this purpose, it is desirable and necessary to consider the parametric behavior for one of the connection elements.

Modeling of study structures in Abaqus software

Model verification

In order to validate the numerical models used in this research, there are also test data available for the bolted T-stub connections. This section uses Abaqus finite element software to study the numerical performance of bolted T-stub connections.

Bursi and Jaspart in 1997 conducted a series of T-stub connection tests [8]. These tests were used to generate a numerical T-stub model and have been adopted by many researchers, and therefore, the material properties and geometry are well documented and accessible. The desired specimen designated as T1 has a relatively weak flange plate and therefore, the first failure mechanism is susceptible to be formed in the flange. The geometric properties of T1 are presented in detail in Figure 1. The beams used for the T1 specimen were IPE300 to be a good example of the sections used in the construction works. The connectors were selected from the M12 bolts of grade 8.8. These bolts have a diameter of 12 mm, and the yield stress and ultimate tensile stress are 893 MPa and 974 MPa, respectively, and are among the high-strength bolts. The properties of used materials are shown in Figure 2, in which the flange plates with the yield stress and ultimate tensile stress are 431 MPa and 595 MPa, respectively, and the web plates are used with the yield stress and ultimate tensile stress equal to 469 MPa and 591 MPa, respectively. In the current model, the eight-node cubic C3D8R element was used to model the T-stub web and flange and the bolts where each node has three degrees of freedom. For the contact point of the flange to the bolt head and shank, the surface-to-surface contact element was defined, the regular meshing was used for the meshing of flange, web and bolt elements, and the number of elements was manually selected. The loading is of static type and this tensile load is applied to the element during certain steps and each time a fraction of the load is applied. For the modeling of steel materials in the Abaqus software, the kinematic hardening model is considered for the plastic properties of steel. In this model, the yield surface of steel is moved in the stress space and is considered as the basic idea of the model. The Bauschinger effect is also considered in the kinematic hardening model. The specifications of flange, web and bolt materials are defined as multiline in the software, Figures 1 and 2.

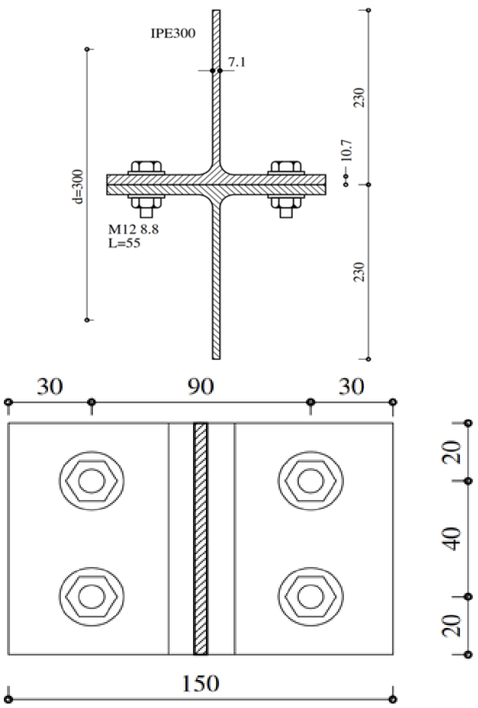


Figure 1. Geometric properties of T1 specimen [8]

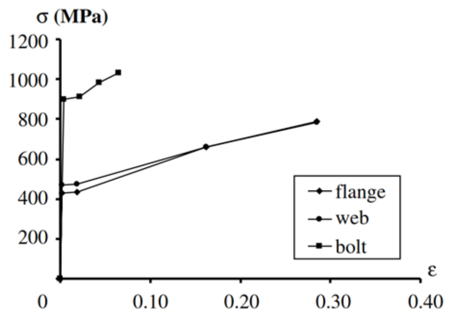


Figure 2. Material properties of T1 specimen [8]

Figure 3 shows the curves (F-d) of the simulated numerical model in the Abaqus finite element software and the test model for the T1 specimen with the pre-stressed bolts. This diagram has a perfect agreement in most points. Comparing the results of the finite element model and the test model, it can be seen that the initial stiffness of the finite element model is slightly higher than the initial stiffness of the test model, and in terms of ultimate strength, the difference is also very small. Comparing two curves (F-d) obtained from testing and modeling in Abaqus software, there is a significant consistency between the two curves (F-d), which is due to the accuracy of the T-stub connection modeling technique in the Abaqus finite element software. In addition, 5.55% error of the numerical diagram was detected compared with the test specimen.

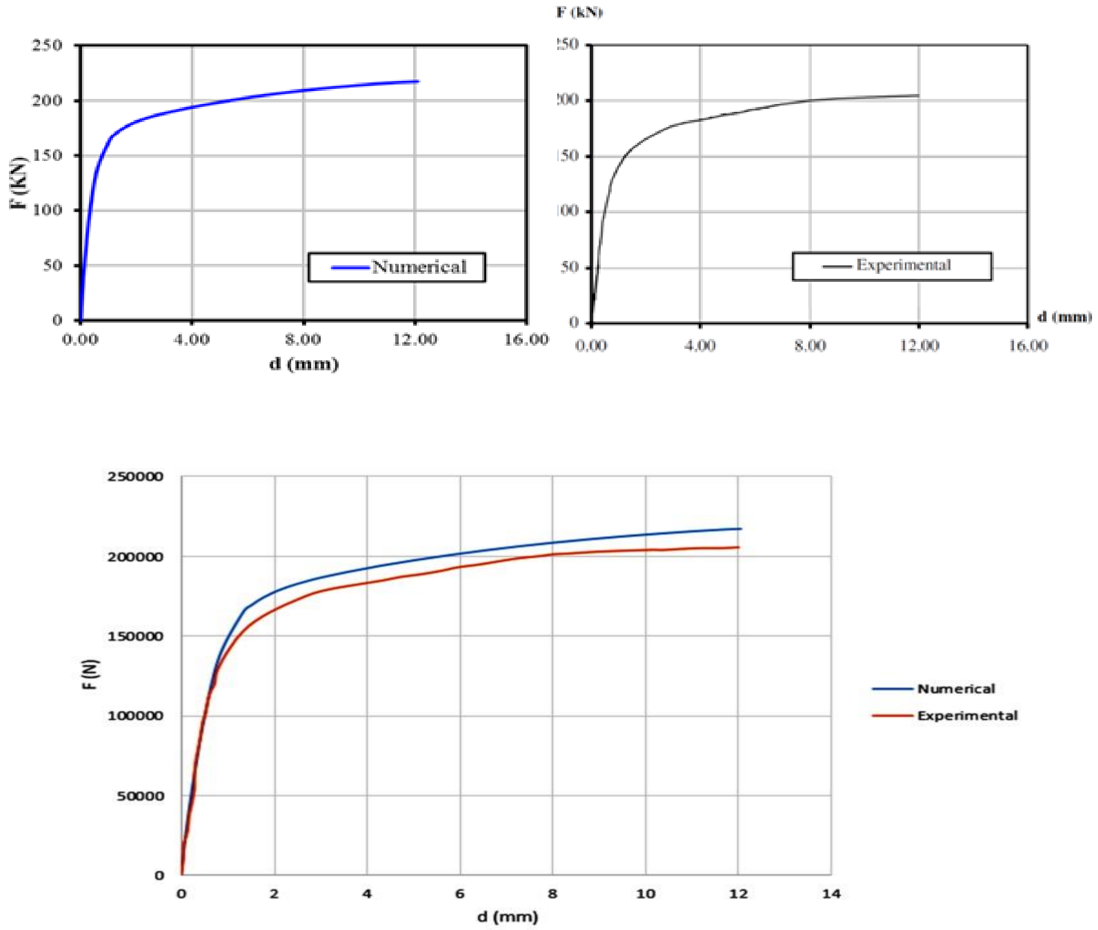
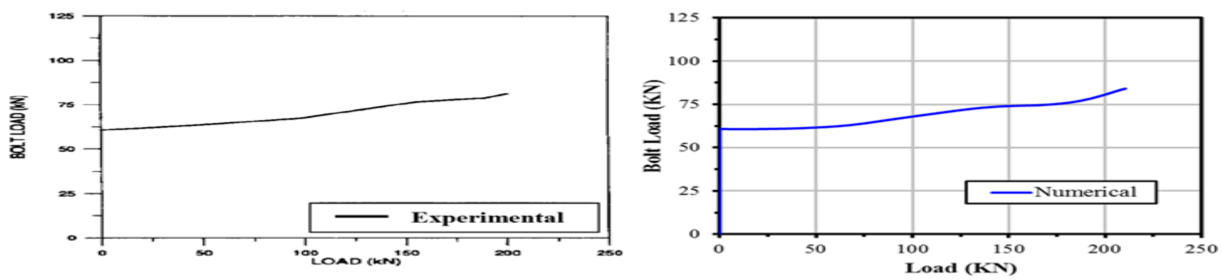


Figure 3. Load-displacement diagram of T1 specimen obtained from simulation in Abaqus software and their comparison [8]

Figure 4 shows the diagram of tensile load applied to a bolt relative to the total tensile load of the T-stub connection simulated in the Abaqus software along with the test results. From the comparison of the two curves in the diagram, the accuracy of the simulated T-stub connection in the Abaqus finite element software can be found. It is noted in this diagram that until the tensile load applied by the test loading is equal to the pre-stress load of 60.7 kN, the bolt resists so that it is not possible to separate two T-shaped flanges from each other, or in other words, to increase the bolt length. In addition, the 7.72% error of the numerical diagram relative to the test specimen was determined.



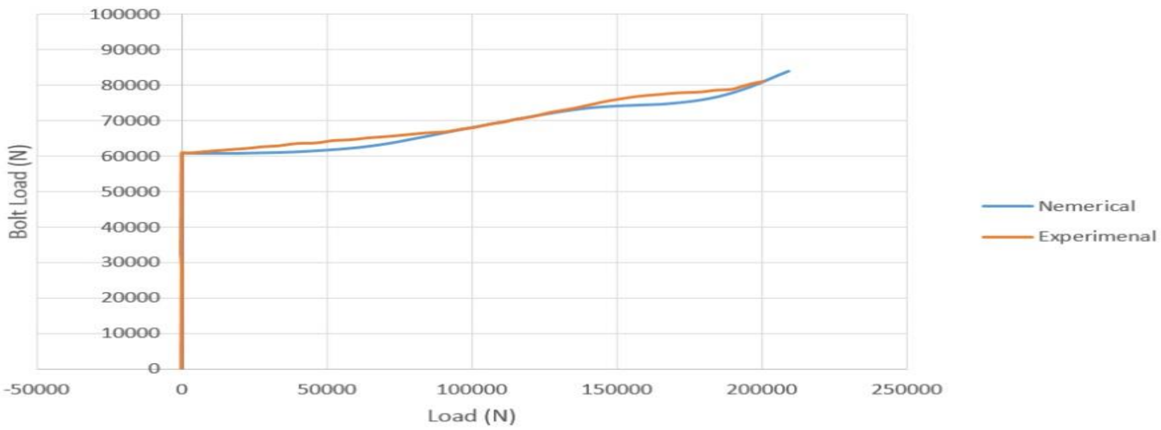


Figure 4. Diagram of tensile load of a bolt and a total load of specimen from simulation in Abaqus software and test and their comparison [8]

Also, Figure 5 shows the deformed state of the T1 specimen with the pre-stressed bolts simulated in the Abaqus finite element software at the end of loading when the separation between two T-shaped plates reaches about 12 mm. As can be seen, all sections of two T-shaped plates, except for the outer edges of the bolt side, reached their ultimate stress. This is for while for the pre-stressed bolts, and only their central part reached the ultimate stress.

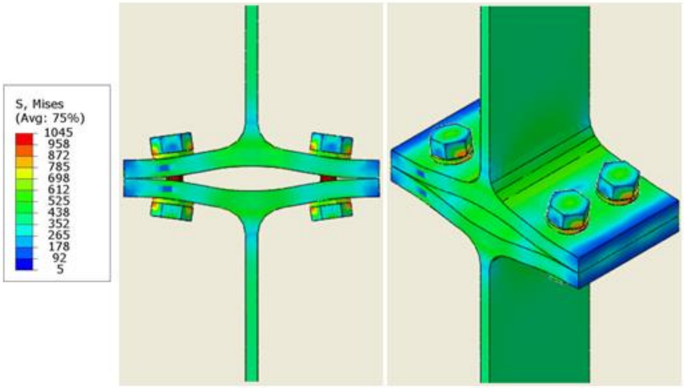


Figure 5: Deformed view of T1 specimen resulting from simulation in Abaqus software at loading end

INTRODUCTION OF SAMPLES USED IN RESEARCH

In this part of the research, the statistical analysis samples are introduced. The samples are the same as the T-stub connection with the high-strength pre-stressed bolts of the previous section, which were tested by Bursi and Jaspart [8], and only the geometry is changed. The geometric changes include those in the thickness of web and flange, flange width of the T-shaped section, diameter of bolts, and distance between the bolts in a single row. The number of bolt rows on each side is one. The web thickness is 6, 8 and 10 mm, the flange thickness is 10, 12, 15, 20 and 25 mm, the flange width is equal to 15, 20, 25, and 30 mm, the ratio of connection length (connection length parallel to the interface of flange and web plate) to flange width is equal to 0.5, 1.0 and 1.5, and finally, the diameter of bolts are 12, 16, 20, 24 and 27 mm. The bolts are in the middle on the sides of the flange so that they are always spaced half the flange width (0.5 h). The A325 bolts (according to the ISO classification) or grade 8.8 (according to ASTM) were selected with the ultimate tensile stress of 800 N/mm^2.

According to Table J3-1M in AISC360-10 [16], the pre-stress load of bolts with the diameter of 12, 16, 20, 24 and 27 mm is 60.7, 91, 142, 205, and 267 kN, respectively. The bolt head and nut have a hexagonal section. The geometry of the bolts and washers used in accordance with DIN 7990 is also given in more detail in Table 1.

Table 1. Introduction of detailed geometric properties of used bolts and washers

Bolt	Washer			Nut Height (mm)	Bolt Head Height (mm)	Bolt Head and Nut Diameter (mm)	Actual Bolt Diameter (mm)
	Thickness (mm)	Inner Diameter (mm)	Outer Diameter (mm)				
M12	3	13	24	10	8	18	11.3
M16	4	17	30	13	10	24	15.3
M20	4	21	37	16	13	30	19.16
M24	4	25	44	19	15	36	23.16
M27	5	28	50	22	17	41	26.16

The number of cases that can be extracted from the variations of the above random variables is equal to 900 T-stub connection cases. Obviously, not all 900 cases of T-stub connection can be executed. Hence, using the Excel software environment and applying the regulation constraints, the 900 cases will be reduced to the lower numbers of available cases for T-stub connection. The regulations used to comply with the design and construction principles include the AISC360-10 and EC3. The flange width (b), flange length (h), bolt diameter (d), flange thickness (t_f) and web thickness (t_w) in T-stub connection are considered as random variables. These variables along with the geometric configuration of samples, are shown in Figure 6.

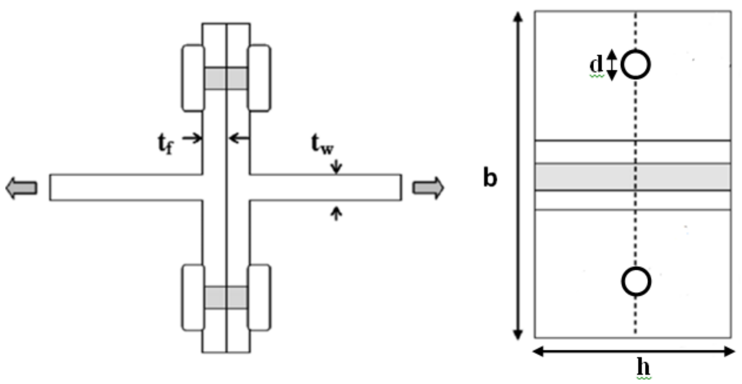


Figure 6. T-stub connection construction samples

This section introduces the regulation constraints for choosing the construction samples of T-stub connection among 900 possible cases.

- Minimum distance between centers of holes:

$$S_{min} = (2\frac{2}{3})d$$

- Minimum distance between centers of holes on both sides:

$$S_{w,min} = 2(k + d)$$

- Minimum distance of center of holes from edge:

$$S_{L,min} = \begin{cases} \text{bolt diameter (mm)} & S_{L,min}\text{(mm)} \\ 12 & 18 \\ 16 & 22 \\ 20 & 26 \\ 24 & 30 \\ 27 & 34 \end{cases}$$

Also, according to the EC3, it is equal to:

$$S_{L,min} = 1.5d$$

- Maximum distance between centers of holes:

$$S_{max} = \min(14t_f, 200mm)$$

- Maximum distance of center of holes from edge:

$S_{L,max} = \min(12t_f, 150mm)$

- Failure mode not being occurred in T-stub web:

$$F_{t,Rd} = \sum B_{t,Rd} = \sum \frac{0.9 f_{ub} A_s}{\gamma_{Mb}}$$

$$F_{t,Sd} < F_{t,Rd}$$

$F_{t,Sd}$ = Tensile load in yielding, equal to yield capacity in tension of web plate

$B_{t,Rd}$ = Design tensile strength of a bolt-plate

$\sum B_{t,Rd}$ = Total value for all bolts in T-stub connection

γ_{Mb} = Partial safety factor for connections, equal to 1.25

f_{ub} = Bolt ultimate tensile strength, equal to 800 N/mm^2

A_s = Bolt cross-section under tensile stress

- Failure mode not being occurred in T-stub flange:

$$t_f \leq 0.36d\sqrt{\frac{F_{ub}}{f_{yf}}}$$

F_{ub} = Bolt ultimate tensile strength, equal to 800 N/mm^2

f_{yf} = Yield stress in T-stub flange

By controlling the constraints described above, the number of samples is reduced from 900 to 52, as shown in Table (2-3) for the sample names along with the respective modified geometric details.

Table 2. Introduction of samples used in this study along with modified geometric details

Sample	Flange Width (b) (cm)	Web Width (h) (cm)	Bolt Diameter (d) (mm)	Flange Thickness (t_f) (mm)	Web Thickness (t_w) (mm)
S-1	15	15	24	12	**6**
S-2	15	15	24	15	**6**
S-3	15	15	27	15	**6**
S-4	15	22.5	27	15	**6**
S-5	15	15	24	20	**6**
S-6	15	15	27	20	**6**
S-7	15	22.5	27	20	**6**
S-8	15	15	24	25	**6**
S-9	15	15	27	25	**6**
S-10	15	22.5	27	25	**6**
S-11	15	15	24	12	**8**
S-12	15	15	24	15	**8**
S-13	15	15	27	15	**8**
S-14	15	15	24	20	**8**
S-15	15	15	27	20	**8**
S-16	15	15	24	25	**8**
S-17	15	15	27	25	**8**
S-18	15	15	27	15	**10**
S-19	15	15	27	20	**10**
S-20	15	15	27	25	**10**
S-21	20	20	24	12	**6**
S-22	20	20	24	15	**6**
S-23	20	20	27	15	**6**
S-24	20	20	24	20	**6**
S-25	20	20	27	20	**6**
S-26	20	20	24	25	**6**
S-27	20	20	27	25	**6**
S-28	25	12.5	20	10	**6**
S-29	25	12.5	20	12	**6**
S-30	25	12.5	20	15	**6**
S-31	25	25	27	15	**6**
S-32	25	12.5	20	20	**6**

S-33	25	25	27	20	**6**
S-34	25	12.5	20	25	**6**
S-35	25	25	27	25	**6**
S-36	30	15	24	12	**6**
S-37	30	15	24	15	**6**
S-38	30	15	27	15	**6**
S-39	30	15	24	20	**6**
S-40	30	15	27	20	**6**
S-41	30	15	24	25	**6**
S-42	30	15	27	25	**6**
S-43	30	15	24	12	**8**
S-44	30	15	24	15	**8**
S-45	30	15	27	15	**8**
S-46	30	15	24	20	**8**
S-47	30	15	27	20	**8**
S-48	30	15	24	25	**8**
S-49	30	15	27	25	**8**
S-50	30	15	27	15	**10**
S-51	30	15	27	20	**10**
S-52	30	15	27	25	**10**

3. RESULTS AND DISCUSSION

The community expects those buildings, bridges and all elements to be designed with a sensible level of safety. In practice, these expectations are achieved by following regulations in which the structural design criteria are considered based on uncertainties. These criteria are usually referred to as "reliability-based design "criteria". The reliability of a structure is, in fact, its ability to meet the design goal for the specified time interval. Reliability is often equivalent to the probability that a structure will not fail to fulfill its required functionality. The term "failure" does not necessarily mean catastrophic failure, but it is used to state that the structure does not act as it was required.

If the state of a building is defined by random variables $X_1, X_2 \ldots, X_n$, each of which representing the variations in the strength and load and the geometric properties such as dead load, live load, length, depth, compressive strength, failure strength, and moment of inertia, the limit state function or the performance function that is actually a function of these parameters is defined as follows:

(1) $g(X_1, X_2, \ldots, X_n)$

(2) $g(X_1, X_2, \ldots, X_n) > 0$, safe mode

(3) $g(X_1, X_2, \ldots, X_n) = 0$, boundary between safe and unsafe

(4) $g(X_1, X_2, \ldots, X_n) < 0$, failure mode

The concepts of structural reliability are used to design new structures and evaluate existing structures. There is a new generation of design regulations based on probabilistic load and resistance models, as in the load and resistance factor design (LRFD) in the AISC for the design of steel structures. Generally, the reliability-based design regulations are very effective, because they meet the following two purposes:

✓ For the desired cost, a stronger structure is designed.

✓ For the desired reliability, a more economical structure is designed.

The reliability of a structure can be considered a reasonable criterion, so that it can provide the appropriate principles for decision-making on repair, reconstruction, or replacement. A structure is not acceptable if the nominal load exceeds the load capacity, but in most cases, the structure is a system of elements; the failure of a member does not mean the failure of the whole system. When a member reaches its ultimate capacity, it may be able to resist the load until there is a redistribution of loads for other elements. The reliability of the system provides a good principle for communicating between the reliability of a member and the reliability of the system.

In this section, the reliability of seismic performance of the T-stub connection with high-strength pre-stressed bolts is evaluated using the nonlinear static analysis (NLSA) and Monte Carlo algorithm. The NLSA is performed using the Abaqus finite element software for fifty-two samples and evaluates the reliability in the Macro space of Excel 2003 software. As such, the geometry and existing sections of the T-stub connection obtained from the previous section are introduced to the program. The limit state derived from the response surface-based methods for the T-stub connection existing in this study includes the maximum bolt tensile load (T_{bolt}) at the time of failure of the T-stub connection, which incorporates the effects of changes in the geometric dimensions of web and flange thickness and the flange and web width for the T-shaped section, and the bolt diameter. The failure of T-stub connection is considered at two performance levels:

Performance level 1: is the case when the web plate reaches its tensile yield limit,

Performance level 2: is the case when the web plate reaches its tensile failure limit.

The flange width (b), flange length (h), bolt diameter (d), flange thickness (t_f) and web thickness (t_w) in the T-Stub connection are considered as random variables. The response surface defined as the maximum tensile load of bolt (T_{bolt}) is expressed using the various combinations corresponding to the values of the random variables extracted from the NLSA as Equation (5.4):

$T_{max} = 591\, t_w.h$

$$g_{bolt}(b;\ h;\ d; t_f; t_w) = T_{c,bolt} - T_{bolt}\ (b;\ h;\ d; t_f; t_w) \quad (5)$$

where the allowable tensile loads according to the steel structure design regulation, Chapter 10 of National Building Regulations for the first and second performance levels are $T_{c;bolt} = 0.38F_{ub}A_b$ and $T_{c;bolt} = F_{ub}A_{br}$, respectively, where F_{ub} is the ultimate bolt tensile strength equal to 800 N/mm^2, A_b is the nominal bolt cross section, and A_{br} is the reduced cross-section in the threaded section of the bolt. The amount of allowable tensile load for the first and second performance levels represents the yield tensile load in the unthreaded section of bolt and the ultimate tensile load of the bolt in the threaded section. Also, the allowable tensile loads of the T-stub connection, $T_{c,\ max}$, for the first and second performance levels are $T_{c.max} = F_{yw}A_w$ and $T_{c.max} = F_{uw}A_w$, respectively, where F_{yw} is the yield stress limit of web plate equal to 469 N/mm^2, A_w is the cross-section of web plate and F_{uw} is the ultimate stress equal to 591 N/mm^2. The amount of allowable tensile load for the first and second performance levels represents the yield tensile load and the ultimate tensile load of the web plate in the T-stub connection, respectively. It should be noted that the value of $T_{bolt}\ (b;\ h;\ d; t_f; t_w)$ for the samples is set in the first and second performance levels for the load generated in the bolt, where the maximum tensile capacity of T-stub connection (T_{max}), or the tensile load generated in the web plate, is equal to Equations (6) and (7), respectively:

$$\mathbf{T_{max} = 469\, t_w.h} \quad (6)$$

$$\mathbf{T_{max} = 591\, t_w.h} \quad (7)$$

Finally, by replacing the values of parameters used in the allowable tensile load, the limit state function on the first and second performance lev $T_{max} = 469\, t_w.h$ els is expressed as Equations (8) and (9):

Performance level 1:

$$\mathbf{g_{bolt}(b;\ h;\ d; t_f; t_w) = 238.64\, d_b^{\,2} - T_{bolt}\ (b;\ h;\ d; t_f; t_w)} \quad (8)$$

Performance level 2:

$$g_{bolt}(b;\ h;\ d; t_f; t_w) = 628\, d_{br}{}^2 - T_{bolt}\,(b;\ h;\ d; t_f; t_w) \qquad g_{bolt}(b;\ h;\ d; t_f; t_w) = 238.64\, d_b{}^2 - T_{bolt}\,(b;\ h;\ d; t_f; t_w) \tag{9}$$

where d_b is the nominal section diameter of the bolt and d_{br} is the reduced section diameter in the threaded section of the bolt.

The maximum tensile load of the bolt (T_{bolt}) represents the demand function, which is expressed as a nonlinear regression of the parameters b, h, d, t_f and t_w. In this study, the normal probability distribution is used. The characteristics of random variables with respect to this type of distribution are shown in Table (3). It should be noted that after controlling the regulation constraints on all formed samples that were reduced to fifty-two, the variations of web thickness (t_w) is 6, 8 and 10 mm, the flange thickness (t_f) is 12, 15, 20 and 25 mm, the flange width (b) is 150, 200, 250, and 300 mm, the web width (h) is 125, 150, 200, and 225 mm, and finally, the bolt diameter (D) is 20, 24 and 27 mm. Using the statistical functions available in the Excel software, the values of mean, coefficient of variation and standard deviation of the random variables with the mentioned variations are determined.

Table 3. Mean coefficient of variation and standard deviation of random variables

Variable	Variations	Mean	Coefficient of Variation	Standard Deviation	Probability Distribution
b (mm)	150,200,250,300	225.00	0.287	64.550	Normal
h (mm)	125,150,200,225	175.00	0.261	45.644	Normal
d (mm)	20,24,27	23.67	0.148	3.512	Normal
t_f (mm)	12,15,20,25	18.00	0.318	5.715	Normal
t_w (mm)	6,8,10	8.00	0.250	2.000	Normal

The Monte Carlo method is used for the maximum bolt tensile load (g_{bolt}) limit state function and the reliability analysis, and 5 simulation samples with 25, 100, 1000, 10000, and 100000 numbers were used in the Monte-Carlo method.

Monte Carlo Simulation Method

The main purpose of simulation as a method for solving structural reliability problems, as its name suggests, is the numerical simulation of some phenomena and then, the observation of number of times some of the desired events occur. The concept of simulation seems simple, but its computational process is very difficult and intensive. The basis of all Monte Carlo simulation methods is the generation of random numbers uniformly distributed between 0 and 1. The tables of uniformly distributed random variables can be produced in many advanced statistical software [17].

In this study, using the Minitab statistical software, 25, 100, 1000, 10000 and 100000 uniformly distributed samples are produced for each of the random variables $b;\ h;\ d; t_f; t_w$. Given the type of normal probability distribution for random variables, the simulated samples associated with this type of probability distribution should be generated. For this purpose, the standard normal random values, Z_1, Z_2, ... , Z_n corresponding to the uniformly distributed randomly values U1, U2, ..., Un between 0 and 1 should be initially generated. Hence, for any U_i value, a Z_i value is generated using Equation (10).

$$Z_i = \emptyset^{-1}(U_i) \tag{10}$$

where $\emptyset^{-1}$ is the inverse standard normal cumulative distribution function. Therefore, for each uniformly distributed random variable, the standard normal values are found as Equations (1) and (3).

$$, \text{For } U_i \le 0.5 \rightarrow Z_i = -t + \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3} \qquad t = \sqrt{-\ln\,(U_i{}^2)} \tag{11}$$

where:

C_0=2.515517, C_1=0.802853, C_2=0.010328, d_1=1.432788, d_2=0.189269, d_3=0.001308.

$$\text{For } U_i > 0.5 \rightarrow Z_i = -\emptyset^{-1}(1 - U_i \qquad (12)$$

Now, considering the standard normal random values generated above, the simulated samples with normal probability distribution are generated for random variables b; h; d; t_f; t_w using Equation (4).

$$X_i = \mu_X + z_i\sigma_X \qquad (13)$$

where:

$$(\sigma_{\ln X})^2 = \ln((v_X)^2 + 1) \approx (v_X)^2 \text{ (For } v_X < 0.2) \qquad (14)$$

$$\mu_{\ln X} = \ln(\mu_X) - 1/2\,(\sigma_{\ln X})^2 \approx \ln(\mu_X) \text{ (For } v_X < 0.2) \qquad (15)$$

As such, the number of 25, 100, 1000, 10000, and 100000 simulated samples with a normal probability distribution for each of the random variables is generated for performing the reliability analysis using the exact Monte Carlo method in the Excel 2003 Macro space. Then, the reliability index (β) and probability of failure (PF) is calculated for the maximum bolt tensile load (g_{bolt}) limit state function using Equations (16) and (17):

$$PF = \frac{N_H}{N} \qquad (16)$$

where N_H is equivalent to the number of times the limit state functions have negative values, and N represents the total number of simulated values for the limit state functions. The limit state function (g_{bolt}) is introduced as g in the following relations:

$$\beta = \frac{\mu_g}{\sigma_g} \qquad (17)$$

Where:

$$\mu_g = {}^{1}/_{n} \textstyle\sum_{i=1}^{n} g_i \qquad (18)$$

$$\sigma_g = \sqrt{\frac{\sum_{i=1}^{n}(g_i-\mu_g)^2}{n-1}} = \sqrt{\frac{(\sum_{i=1}^{n} g_i{}^2)-n(\mu_g)^2}{n-1}} \qquad (19)$$

Interpretation of reliability analysis results

The number of NLSA analyses associated with the five random variables in the Abaqus finite element software used to determine the maximum bolt tensile load (gbolt) and maximum tensile capacity of T-stub connection (gmax) corresponding to each of the first and second performance levels is fifty-two analyses. Therefore, the total number of NLSA analyses used in this study will be equal to fifty-two.

At this step, using the Minitab statistical software and the output results from the NLSA analyses, the limit state functions of maximum bolt tensile load (gbolt) and maximum tensile capacity of T-stub connection (gmax) should be determined for these samples at different performance levels. For this purpose, the nonlinear regression tool in Minitab software was used. In the following, by presenting the results of fifty-two pushover analyses for each sample of this study in terms of the maximum bolt tensile load and the maximum tensile capacity of the T-stub connection, the limit state functions are introduced.

Table 4. Results of 52 nonlinear static analyses at first and second performance levels

Case	b (mm)	h (mm)	d (mm)	t_f (mm)	t_w (mm)	1 PL.		2 PL.	
						T_{bolt} (KN)	T_{max} (KN)	T_{bolt} (KN)	T_{max} (KN)
1	150	150	24	12	6	245.06	422.10	253.39	451.88
2	150	150	24	15	6	233.15	422.10	248.4	473.23
3	150	150	27	15	6	283.95	422.10	291.93	473.86
4	150	225	27	15	6	310.18	633.15	335.54	715.84
5	150	150	24	20	6	220.89	422.10	230.58	474.29
6	150	150	27	20	6	277.25	422.10	286.73	508.73
7	150	225	27	20	6	296.43	633.15	341.79	799.27
8	150	150	24	25	6	216.61	422.10	229.99	525.52
9	150	150	27	25	6	273.96	422.10	282.16	525.73
10	150	225	27	25	6	287.65	633.15	324.76	800.35
11	150	150	24	12	8	285.98	562.80	312.24	639.29
12	150	150	24	15	8	271.18	562.80	323.18	690.25
13	150	150	27	15	8	307.85	562.80	354.02	695.96
14	150	150	24	20	8	246.95	562.80	287.87	699.15
15	150	150	27	20	8	293.22	562.80	325.49	699.83
16	150	150	24	25	8	234.96	562.80	266.68	700.09
17	150	150	27	25	8	285.01	562.80	308.77	700.49
18	150	150	27	15	10	349.9	703.50	409.8	856.93
19	150	150	27	20	10	321.36	703.50	375.53	873.37
20	150	150	27	25	10	306.15	703.50	347.48	874.96
21	200	200	24	12	6	304.17	562.80	304.75	584.59
22	200	200	24	15	6	290.15	562.80	331.42	676.17
23	200	200	27	15	6	322.63	562.80	368.99	691.50
24	200	200	24	20	6	257.52	562.80	304.72	704.76
25	200	200	27	20	6	301.75	562.80	342.17	705.72
26	200	200	24	25	6	241.85	562.80	276.74	706.68
27	200	200	27	25	6	290.45	562.80	319.83	707.15
28	250	125	20	10	6	191.13	351.75	191.13	220.39
29	250	125	20	12	6	217.78	351.75	217.78	309.68
30	250	125	20	15	6	227.15	351.75	236.15	387.56
31	250	250	27	15	6	386.15	703.50	408.17	789.29
32	250	125	20	20	6	187.51	351.75	224.29	431.80
33	250	250	27	20	6	347.45	703.50	422.49	883.21
34	250	125	20	25	6	171.05	351.75	190.73	435.23
35	250	250	27	25	6	322.45	703.50	377.06	892.86
36	300	150	24	12	6	253.16	422.10	253.16	288.34
37	300	150	24	15	6	295.88	422.10	297.98	428.52
38	300	150	27	15	6	342.58	422.10	342.63	447.31
39	300	150	24	20	6	272.42	422.10	319.65	509.86
40	300	150	27	20	6	312.13	422.10	358.88	515.56
41	300	150	24	25	6	243.59	422.10	274.15	523.54
42	300	150	27	25	6	294.82	422.10	320.47	523.49
43	300	150	24	12	8	256.15	562.80	256.15	294.14
44	300	150	24	15	8	308.07	562.80	308.07	449.29
45	300	150	27	15	8	356.37	562.80	356.37	496.28
46	300	150	24	20	8	338.02	562.80	350.21	625.74
47	300	150	27	20	8	382.15	562.80	415.48	647.85
48	300	150	24	25	8	285.35	562.80	341.33	688.24
49	300	150	27	25	8	329.31	562.80	390.32	693.13
50	300	150	27	15	10	381.83	703.50	381.83	513.27
51	300	150	27	20	10	431.45	703.50	434.14	753.38
52	300	150	27	25	10	386.54	703.50	447.28	839.99

Using the results of the above table and utilizing the nonlinear regression tool in Minitab software, the maximum bolt tensile load (g_{bolt}) limit state function for the samples at different performance levels is determined as follows:

Performance level 1:

$$
\begin{aligned}
g_{bolt,1} = {} & (0.23864 \times d^2) \\
& - (589 + 0.44b + 5.83h - 80d - 26.1t_f + 127t_w - 0.00231b^2 + 0.0087h^2 + 2.71d^2 - 0.32{t_f}^2 \\
& + 2.42{t_w}^2 - 0.025b \times d + 0.136b \times t_f - 0.533b \times t_w - 0.275h \times d - 0.162h \times t_f + 1.30d \times t_w \\
& - 6.46d \times t_w + 1.81t_f \times t_w + 0.0756{t_f}^3 + 0.000321b^2 \times t_f + 0.000284b \times h \times t_f - 0.00412b \times d \\
& \times t_f + 0.0147b \times d \times t_f - 0.00841b \times {t_f}^2 + 0.01578b \times t_f \times t_w - 0.0074b \times {t_w}^2 - 0.000718h^2 \\
& \times t_w + 0.0099h \times d \times t_f + 0.00250h \times {t_f}^2 - 0.0592d \times {t_f}^2 + 0.100d \times t_f \times t_w - 0.2035{t_f}^2 \times t_w \\
& + 0.019t_f \times {t_w}^2)
\end{aligned}
$$

Performance level 2:

$$
\begin{aligned}
g_{bolt,2} = {} & \left(0.628 \times {d_{br}}^2\right) - (-1739 + 8.85b - 0.08h + 59d - 25.5t_f + 159.3t_w - 0.014021b^2 - 0.00711h^2 - 1.02d^2 \\
& - 0.557{t_f}^2 + 3.83{t_w}^2 - 0.118b \times d + 0.024b \times t_f - 0.817b \times t_w + 0.066h \times d + 0.048h \times t_f \\
& + 3.09d \times t_w - 3.65d \times t_w - 2.49t_f \times t_w + 0.0553{t_f}^3 + 0.000454b^2 \times t_f - 0.000141b \times h \times t_f \\
& - 0.00124b \times d \times t_f + 0.0216b \times d \times t_f - 0.00793b \times {t_f}^2 + 0.02339b \times t_f \times t_w - 0.0156b \times {t_w}^2 \\
& + 0.000765h^2 \times t_w - 0.0057h \times d \times t_f + 0.00394h \times {t_f}^2 - 0.0324d \times {t_f}^2 - 0.064d \times t_f \times t_w \\
& + 0.0005{t_f}^2 \times t_w + 0.039t_f \times {t_w}^2)
\end{aligned}
$$

The diagram shows the reliability index (β) for the T-Stub connection considered in this research based on two performance levels, namely the yielding of web plate and the failure of web plate. As can be seen, the reliability index (β) for 25, 100, 1000, 10000 and 100000 samples at the first performance level was 1.046, 1.692, 1.513, 1.533 and 1.630, respectively, and at the second performance level was equal to 3.748, 2.951, 2.986, 3.126 and 3.137, respectively. It can be seen that by increasing the number of samples in the Monte Carlo method, an appropriate convergence in the reliability index (β) is achieved at both performance levels and there is no need for a sample with a higher number. It was also found that the reliability index (β) at the second performance level, which is the failure of the web plate in the T-stub connection, is higher than the corresponding value at the first performance level, which is the yielding of the web plate. This means that the tensile load developed in the pre-stressed bolts follows the second failure criterion, or the failure to reach the ultimate tensile load of the bolts in the threaded section until the web plate is failed, with more reliability than the first failure criterion, or the failure to reach the yield tensile load of the bolts in the main body until the web plate is failed. The probability of failure (PF) was zero for all samples under both performance levels. This result is due to the fact that the requirement for the failure mode not being occurred in the web of T-stub connection was observed when selecting the specimens. Therefore, the determined T-stub connection specimens are of strong bolted type and hence, the probability of failure (PF) becomes zero, which is the probability of the bolt being yielded in the unthreaded section after the web plate is yielded, and the failure of bolt in the threaded section after the failure of the web plate.

4. CONCLUSION

In this paper, the reliability of T-stub pre-stressed connections was evaluated using the numerical model.

- By increasing the number of samples in the Monte Carlo method, an appropriate convergence in the reliability index (β) was achieved at both performance levels, and there is no need for a sample with more than 100,000 cases.

- The reliability index (β) at the second performance level, which is the failure of the web plate in the T-stub connection, is higher than the corresponding value at the first performance level, which is the yielding of the web plate. This means that the tensile load developed in the pre-stressed bolts follows the second failure criterion, or the failure to reach the ultimate tensile load of the bolts in the threaded section until the web plate is failed, with more reliability than the first failure criterion, or the failure to reach the yield tensile load of the bolts in the main body until the web plate is failed.

- The probability of failure (PF) was zero for all samples under both performance levels. This result is due to the fact that the requirement for the failure mode not being occurred in the web of T-stub connection was observed when selecting the specimens. Therefore, the determined T-stub connection specimens are of strong bolted type and hence, the probability of failure (PF) becomes zero, which is the probability of the bolt being yielded in the unthreaded section after the web plate is yielded, and the failure of bolt in the threaded section after the failure of the web plate.

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