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Reliabilities of distances describing bolt placement for high strength steel connections

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Abstract. In the bolted connections, bolt placements are generally described and are generally made in the direction of design effects and in the perpendicular direction to design effects. In these both directions, the reliability of the distance of bolts to the edges of connection plate and the distance of bolts to each other is investigated for high strength steel connections built up with high strength bolts in this study. For this purpose, simple *SL* (bearing type shear connection) and *SLP* (bearing type shear connection for body-fit bolts) type steel connections with *St 52* grade steel plates with *8* different thicknesses and with *8.8D* grade high strength bolts (*HV*) were constituted and analyzed under *H* (*Dead Loads+Live Loads+Snow Loads+ Roof Loads*) and *HZ* (*H Loads+Wind Loads+Earthquake Loads*) loadings. Geometric properties, material properties and design actions were taken as random variables. Monte Carlo Simulation method was used to compute failure risk and the first order second moment method was used to determine the reliability indexes of those different distances describing the placement of bolts. Results obtained from computations have been presented in graphics and in a Table. Then, they were compared with some values proposed by some structural codes. Finally, new equations were constituted for minimum and maximum values of distances describing bolt placement by regression analyses performed on those results.

Keywords: reliability analysis; bolted connection; bolt distance; bolt placement; monte carlo simulation

1. Introduction

Probability and risk calculations take place in the base of structural reliability calculations. There is no absolute reliability at the probabilistic designs. It is required that an acceptable risk level has to be defined before structural designs. This requirement is also necessary for economic structural designs. For this reason, an acceptable risk level or a desired reliability level is defined before the structural reliability designs and then it is expected from the designed structure or structural element that they provide the desired reliability level (Bayazıt 1998, Bayazıt 2006, Nowak and Collins 2000).

Reliability based structural designs started to be used widely with the development of structural reliability theories and methods. Especially, using the Monte Carlo Simulation (*MCS*) methods in computations provides more accurate results in more complex structural reliability designs (Bayazıt 1998, Bayazıt 2006, Nowak and Collins 2000). However, this simulation method requires

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large number of structural analyses and time. For this reason, structural analysis programs and codes could find wide application area with the *MCS* method by using only computers.

For example; Huh (1999), Huh and Haldar (2000) developed an algorithm including finite element method *(FEM)* in order to determine reliabilities of structures having nonlinear geometry under earthquake effects. They also compared the algorithm with the *MCS* method in their study. Tsompanakis and Papadrakakis (2000) presented a robust and efficient methodology for treating large scale reliability-based structural optimization problems. Evolution strategies were used in optimization studies. The *MCS* method incorporating the importance sampling technique was used to reduce the sample size. Lee (2000), Lee and Haldar (2003) wrote a computer program using the *FEM* to investigate reliabilities of framed and shell walled structures. Then they compared the results obtained from their own computer program with the results obtained from *MCS* methods. Papadrakakis *et al.* (2004), presented a robust and efficient methodology for performing a reliability-based structural optimum design of steel frames under seismic loading. They used the *MCS* method and Latin Hypercube Sampling Technique together to reduce the sample size. Papadrakakis Lagaros (2002), Papadrakakis (1996) used artificial neural networks and the *MCS* in his other studies successfully. Basaga and Bayraktar (2006) used analytical equations and the *FEM* comparatively and they specified that the *FEM* can be used effectively with the reliability analysis. Basaga *et al.* (2007) incorporated the *MCS* method and the *FEM* for the reliability analysis of structures subjected to earthquake effects. Cardoso *et al.* (2008) performed a reliability based optimization study using the *MCS* method and genetic algorithm. They included artificial neural networks to their own study to reduce the computation time while necessary numbers of numerical analysis are performing. Bolandim *et al.* (2013) performed a reliability analysis for rupture in the net section of bolted connections in cold-formed steel angles and channels. According to their study, reliability indices are found to be less than the target reliability levels recommended in some structural codes. The authors also presented some suggestions for improvement of some structural codes in that study.

Although many reliability studies have been performed about structural reliability, there are no studies in technical literature about the reliability of distances describing the placement of bolts. In addition, no information about reliability levels of those distances describing the bolt placement is presented at the current the structural codes.

Providing structural reliability is aimed at with criteria recommended by many structural codes for element sizes, material properties and displacements. The criteria for distances between bolts and the criteria for distances between the bolt and plate edge or plate end at the bolted connections of steel structures can be given as examples. The lower and upper limits of distances describing bolt placement were determined at the structural codes. Although limit values for some of those distances are given separately for bridges and buildings in some structural codes, they have been used widely without taking account of the structural element strength, the loading type, type of usage of structure and reliability levels.

For these reasons, the reliabilities of distances describing bolt placement were investigated in order to design not only bolted connections but also steel structures with bolted connections constituted using the high strength grade steel and bolt at the desired reliability levels in this study. In addition, the validations of these equations proposed for traditional steel structure design by structural codes were investigated for those of steel structures and bolted connections with high strength grade steel plates and bolts. For these purposes, simple bolted connections with 8 different plate thicknesses (t=4, t=5, t=7, t=10, t=15, t=20, t=25 and t=30 mm) were modelled analytically. *St* 52 grade of steel plates, 8.8*D* grade *HV* bolts were used in modelling *SL* and *SLP*

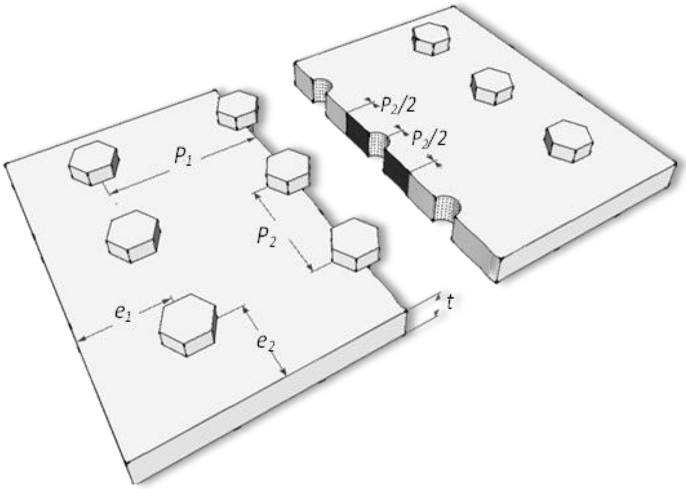

Fig. 1 Bolt placement representations

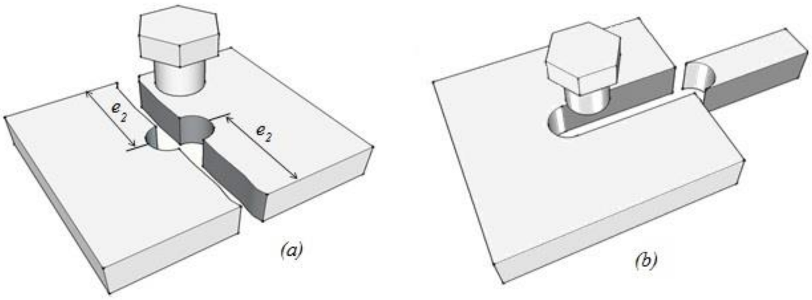

Fig. 2 Edge distances (a), Shear surfaces at the end of plate (b)

types simple bolted connections. All bolted connection models were analyzed under *H* and *HZ* loadings separately to determine the reliabilities of different distances describing bolt placement.

2. Designing of bolt placement

Distances describing bolt placement in the direction of the design action are defined differently and designed in different lengths in the designing of bolted connections. The first of them is the distance between the end of the plate with the bolt, which is the closest to the end of the plate. This distance is symbolized with e_1 as shown in Fig. 1 and called *the edge distance*. Distances between bolts placed in the direction of the design action are called *Pitch* and are showed with the P_1 symbol. Distances between bolts placed in the perpendicular direction to the design actions are shown as P_2 in Fig. 1. e_2 (Fig. 2(a)) is the last length and is defined as the distance from the edge of plate (Uzgider *et al.* 2008, EN 1993-1-8: Eurocode 3 2005, TS648 1980).

Two shear surfaces shaded in Fig. 2(b) are taken into account in mechanic calculations to determine the minimum e_1 distances. According to this figure, e_1 distance can be determined by Eq. (1).

$$e_1 \geq min\begin{cases}\frac{\frac{\pi d_b^2}{4}\tau_b}{2.t.\tau_p}\\ \\ \frac{d_b.t_{min}.\sigma_c}{2.t.\tau_p}\end{cases} \tag{1}$$

In this equation, τ_b, τ_p, d_b, $t_{\min}$ and σ_c are shear strength of bolts, shear strength of plates, bolt diameter, minimum plate thickness and crushing strength of bolts respectively.

For the calculation of the minimum value of P_1 distance, no exact equations are given in the technical literature. However, it is also stated in the technical literature that the calculation procedure of e_1 can be used in calculations of distance of P_1 and when actual force distributions are taken into account; this calculation procedure produces safer values for P_1 distances than e_1 distances (Omurtag 2010). Conversely, bolt heads and nuts have to be taken into account for ease of montage in the determination of P_1 value. For these reasons, although e_1 and P_1 distances are calculated similarly, P_1 distances are generally bigger than e_1 distances in actual. Assuming an equal distribution of the forces on the bolts, P_1 distances can be calculated by Eq. (2).

$$P_1 \geq min\begin{cases}\frac{\frac{\pi d_b^2}{4}\tau_b}{2.t.\tau_p}\\ \\ \frac{d_b.t_{min}.\sigma_c}{2.t.\tau_p}\end{cases} \tag{2}$$

In this equation d_b is bolt diameter.

As shown in Fig. 2(a), distance of e_2 in the perpendicular direction to design actions can be determined with Eq. (3) by considering the state of rupture of plate.

$$e_2 = \frac{1}{2}\left(\frac{Q}{t_{min}.\sigma_p} + d_h\right) \tag{3}$$

In this equation, Q, d_h and σ_p are design load carried by connection, hole diameter and tensile strength of plate respectively.

Calculation of P_2 distance can be made similarly to the distance of e_2. If the design actions are distributed uniformly to cross-sections of plate in Fig. 1, formulation given by Eq. (4) can be used for the calculation of P_2.

$$P_2 = \left(\frac{Q}{t_{min}.\sigma_p} + d_h\right) \tag{4}$$

While the maximum values of e_1 and P_1 distances are determined, buckling effects are taken into account. Buckling equations given with Eqs. (5)-(6)-(7)-(8)-(9) were used for determination of maximum values of e_1 and P_1 distances in this study (Uzgider *et al.* 2008, Omurtag 2010). However, no method for the determination of maximum values of e_2 and P_2 distances has been encountered in the technical literature.

$$\sigma_{pb} = \frac{\left[1-\frac{1}{2}\left(\frac{\lambda}{\lambda_p}\right)^2\right]\sigma_y}{n} \tag{5}$$

$$\lambda < 20 \ \rightarrow n = 1.67 \tag{6}$$

$$\lambda_p \leq \lambda \ \rightarrow n = 1.5 + 1.2\left(\frac{\lambda}{\lambda_p}\right) - 0.2\left(\frac{\lambda}{\lambda_p}\right)^3 \tag{7}$$

$$\lambda > \lambda_p \ \rightarrow \ n = 2.5 \tag{8}$$

$$\lambda_p = \sqrt{\frac{2\pi^2 E}{\sigma_y}} = \frac{6438.4}{\sqrt{\sigma_y}} \tag{9}$$

Here, in this equation, all units are in kg/cm^2.

2.1 Bolts placements in the structural codes

During the design of bolted connections of steel structures, e_1, e_2, P_1 and P_2 distances have been determined within the limits specified in the structural codes. Some special values for those

Table 1 Proposed values for e_1, e_2, P_1 and P_2 distances in some the structural codes

Codes	P_1		e_1		P_2		e_2	
	min	max	min	max	min	max	min	max
EU-3	$2.2d_h$	$14t$ 200 mm	$1.2d_h$	40 mm+$4t$ $12t$, 150 mm	*$3d_h$	$14t$ 200 mm	$1.5d_h$	40 mm+$4t$ $12t$, 150 mm
AISC and CAN/CSA SP16-01	$2\frac{2}{3}d_b$ $2.7d_b$	$24t$ 305 mm (12inch)	d +mm ++mm 16 28 22 20 34 26 22 38 28 24 42 30 27 48 34 30 52 38 36 64 46 >36 $1.75d$ $1.25d$	12t 150 mm (6inch)	$2\frac{2}{3}d_b$ $2.7d_b$	24t 305 mm (12inch)	d +mm ++mm 16 28 22 20 34 26 22 38 28 24 42 30 27 48 34 30 52 38 36 64 46 >36 $1.75d$ $1.25d$	$12t$ 150 mm (6inch)
BS 5950-1	$2.5d_h$	$14t$ 200 mm	$1.25d_h$ xx$1.4d_h$	$11t\varepsilon$ 40 mm+$4t$	$2.5d_h$	16t 200mm	$1.25d_h$ xx$1.4d_h$	$11t\varepsilon$ 40 mm+$4t$
TS648	$3d_h$	$8d_h$ 15t	$2d_h$	$3d_h$ $6t$	$3d_h$	$8d_h$ 15t	$1.5d_h$	$3d_h$ $6t$
IS 800	$2.5d_b$	#$16t$, #20 mm ##$12t$, ##200 mm	+$1.7d$ ++$1.5d$	$12t\varepsilon$	$2.5d_b$	4t+100 200mm	+$1.7d$ ++$1.5d$	$12t\varepsilon$
AS 4100	$2.5d_b$	$15t$ 200 mm NX32t NX300 mm NY$4t$+100 NY200 mm	x1$1.75d_b$ x2$1.50d_b$ x3$1.25d_b$	$12t$ 150 mm	$2.5d_b$	15t 200mm NX32t NX300mm NY4t+100 NY200mm	$1.75d_b$ $1.50d_b$ $1.25d_b$	$12t$ 150 mm

*This Spacing may reduced to 2.4dh , see EU3 Section 8, + At sheared edges, ++ At Rolled edge of plates, Shapes or bars or thermally cut Edges, # For Tension, ## For Compression, x1 Sheared or hand flame cut edge, x2 Rolled plate, flat bar or section: machine flame cut, sawn or planed edge, x3 Rolled edge of a rolled flat bar or section, *NX* For fasteners which are not required to carry design actions in regions not liable to Corrosion, *NY* For an outside line of fasteners in the direction of the design action, (ε=250/f_y)$^{1/2}$)

distances are proposed for some special situations by some structural codes. Those special values are given as a footnote below Table 1. However, any mechanical or mathematical formulas are not specified for the calculation of the maximum value of e_1, e_2, P_1 and P_2 distances in structural codes. Minimum and maximum value ranges of e_1, e_2, P_1 and P_2 distances proposed by some structural codes (Eurocode 3 2005, AISC 2005, CAN/CSA SP16-01 2001, BS 5950-1 2000, TS648 1980, IS800 2007, AS4100 1998) have been presented in Table 1.

3. Reliability analysis and the Monte Carlo simulation method

Structural reliability is defined as calculation of the probability of failure under limit state conditions. Limit states of a structure are specified basically by limit state function or performance function given in Eq. (10) (Bayazıt 1998, Bayazıt 2006, Nowak and Collins 2000).

$$g(R,Q) = R - Q \tag{10}$$

Where R is load bearing capacity and Q is load effect. This function is also expressed as $g(X_1, X_2, X_3, \ldots., X_N)$, where X_1, X_2, …., X_n are random variables of R and Q Loads (Nowak and Collins 2000).

Limit state is boundary between desired and undesired performance. In other words, limit state function produces zero value at limit state. If the value of limit state function is bigger than zero, structure is safe. Contrary, failure occurs at the minus values of limit state function. These three states are given with the following three equations (Bayazıt 1998, Bayazıt 2006, Nowak and Collins 2000).

$$g(R,Q) = R - Q > 0 \quad \text{Safe} \tag{11}$$

$$g(R,Q) = R - Q = 0 \quad \text{Limit State} \tag{12}$$

$$g(R,Q) = R - Q < 0 \quad \text{Failure} \tag{13}$$

Depending on the limit state conditions, probability of failure of a structure or any structural elements (p_f) is expressed by the following expression (Bayazıt 1998, Bayazıt 2006, Collins 2000).

$$p_f = P[g(X_1, X_2, \ldots, X_n) \le 0]$$

$$= \iint_{g(X_1,X_2,\ldots,X_n)\le 0} \cdots \int f_{X_1,X_2,\ldots,X_n}(x_1, x_2, \ldots., x_n)dx_1 dx_2 \ldots. dx_n \tag{14}$$

In this equation, $f_{X_1,X_2,\ldots,X_n}(x_1, x_2, \ldots., x_n)$ is joint probability density function of (x_1, x_2, ..., x_n) random variables.

According to the MCS method, estimation of probability of failure can be determined by

$$P_f = \frac{1}{N}\sum_{i=1}^{N} I\,(X_1, X_2, \ldots, X_n) \tag{15}$$

Where $I(X_1, X_2, \ldots, X_n)$ is a function and defined by

$$I(X_1, X_2, \ldots, X_n) = \begin{Bmatrix} 1 & if & g(X_1, X_2, \ldots, X_n) \le 0 \\ 0 & if & g(X_1, X_2, \ldots, X_n) > 0 \end{Bmatrix} \tag{16}$$

Basic procedure of the *MCS* Method begins by producing x_1, x_2, ..., x_n independent sets of randomized values using their probability distributions. Calculation of value of limit state function

Table 2 Reliability index (β) and probability of failure (P_f)

β	1.28	2.33	3.09	3.71	4.26	4.75	5.19	5.62	5.99
P_f	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}

according to the randomized values of x_1, x_2, ..., x_n is second step. In third step, value of $I(X_1, X_2, \ldots, X_n)$ is determided according to the value of $g(X_1, X_2, \ldots, X_n)$. Those three steps are repeated until sufficient number of solutions *(N)* is performed. Finally, probability of failure is obtained by $P_f = N_f / N$ (Eq. (15)) where N_f is total number of failure cases.

The estimation of failure probability improves as the number of simulation increases in the *MCS* Technique. That is why the determination of a sufficient number of solutions (*N*) is very important. For the determination of sufficient number of simulations, Eq. (17) has been suggested by Soong and Grigoriu (1993).

$$N = \frac{1-P}{V_p^2 . P} \tag{17}$$

Where P is theoretically correct probability, V_p is coefficient variation of estimated probability. The reliability index is defined as the shortest distance between origin of reduced variables and the line drawn by using reduced variables in limit state function and its calculation is made by taking the inverse of probability function.

$$\beta = -\Phi^{-1}(P_f) \tag{18}$$

In this equation, Φ( ) shows the function of standard normal distribution tabulated statistically. There are lots of different methods for the calculation of the reliability index. First Order Second-Moment, Second Order Reliability Method, Advanced First Order Second-Moment, Hasofer Lind Reliability Index are widely used reliability methods. In this study the First Order Second-Moment method was used for the calculation of the reliability index. Because, it is easy to use and it doesn’t require knowledge of the distributions of random variables. However, this method also has some disadvantages. Results can be in accurate if the tails of the distribution functions cannot be approximated by normal distribution. And also, the value of the reliability index depends on the specific form of limit state function in this method (Novak 2000). According to this method the reliability index is calculated by Eq. (19)-(20).

$$\beta = \frac{g(\mu_{X_1}, \mu_{X_2}, \ldots, \mu_{X_n})}{\sqrt{\sum_{i=1}^{n} (a_i \sigma_{X\mathrm{i}})^2}} \tag{19}$$

$$a_i = \frac{\partial g}{\partial x_i} \tag{20}$$

Variation of β with P_f and vice versa based on Eq. (18) was presented in technical literature as seen in Table 2 by some technical literatures (Bayazıt 1998, Bayazıt 2006, Nowak and Collins 2000).

4. Statistical descriptions of variable parameters

Actually, numerous parameters such as design actions, geometric properties and material properties continuously show uncertainty. It is required that all statistical properties of all those parameters have to be defined accurately for accurate structural designs. In this study three different loads were taken into account to determine the loading acting of bolted connections. The first of these is Q_{bs}. Q_{bs} is the maximum load that is carried by bolts under shear forces. The second load is the maximum load carried by bolted connection without crushing at hole walls (Q_{bc}). The last load is Q_p. Q_p is defined in this study as the maximum load carried by plates. These three separate loads were calculated by formulas given in Eqs. (21)-(22)-(23) in the each reliability calculations and the smallest of them was acted on bolted connections as external load (Q_{ext}).

$$Q_p = (2e_2 + (n_r - 1)p_2 - n_r.d_h)\sigma_p \quad (21)$$

$$Q_{bs} = n_r.b_n.n_i\frac{\pi d_b^2}{4}\tau_b \quad (22)$$

$$Q_{bc} = n_r.b_n.d_h.t_{min}.\sigma_c \quad (23)$$

$$Q_{ext} = min(Q_p; Q_{bs}; Q_{bc}) \quad (24)$$

Where n_r is the number of bolt rows, and b_n is the number of bolts on a bolt row. Bolt diameter (d_b) used in Eq. (22) is obtained by Eq. (25).

$$d_b = \sqrt{5.t_{min}} - 0.2 \quad (25)$$

According to the Eq. (25), M12, M14, M16, M20, M24, M30, M33, M36 metric bolts have been chosen for the plates having t_{min}=4, 5, 7, 10, 15, 20, 25, 30 minimum plate thickness respectively.

Hole diameters (d_h) were determined as d_b+0.3 and d_b+1 mm for *SL* and *SLP* connections respectively. *St* 52 grade structural steel plates and 8.8 grade high strength bolts were used in the constitution of bolted connections in this study. In this study also e_1 and e_2, P_1 and P_2 distances, shear strength, tensile strength, yield strength of steel plates, modulus of elasticity of steel, the shear and crushing strength of bolts were taken as the variable. The parameters given above were used in calculations of compressive strength of plates. Therefore, the compressive strength of plates was not taken as the variable.

Accurately determining statistical distribution, the mean values and standard deviations or coefficient variations of variables is very important for reliability analyses. Parameters defined as variables in this study and some statistical information about them is presented in Table 3. Statistical distributions of all distances describing bolt placements and coefficiency of variations (*Cov*) of them were chosen as Gauss distribution (Normal distribution) and 0.05 respectively. Statistical distributions about material strengths were taken as Gauss distribution and value of *Cov* was taken as 0.08 in some previous studies (Basaga and Bayraktar 2006, Basaga *et al.* 2007). Therefore, Gauss distribution with 0.08 *Cov* was used in this study for both steel strengths and bolt strengths. Young Modulus was taken as statistical variables with taking of its statistical distribution as Gauss distribution with 0.08 *Cov*. Log-Normal distributions were used for hole diameter, plate thickness with 0.05 *Cov*, 0.05, *Cov*. This Study was performed according to the Allowable Stress Design method. Thus *H* and *HZ* loadings were used instead of using separate combinations of dead loads, live loads, roof loads wind loads, earthquake loads and snow loads. While Gauss distribution with 0.10 *Cov* is used for the dead loads, Log-normal distribution with 0.35, 0.35, 0.30 and 0.30 values of *Cov* is used for the live load, wind load, earthquake load and snow load respectively in literature (Basaga *et al.* 2007, Cardoso *et al.*2008. In this study, Log-normal distributions with the 0.25 *Cov* and 0.35 *Cov* were used for *H* and *HZ* loads respectively.

Table 3 Some statistical information about problem variables

Symbol	Description	Mean	Statistical distribution	Coefficent of Variation
$t_{\min}$	Plate thickness (mm)	4, 5, 7, 10, 15, 20, 25, 30	Log-Normal	0.05
d_h	Hole diameter (mm)	13, 14, 17, 21, 27, 31, 34, 37	Log-Normal	0.05
e_1	End distance (mm)	$i.d_h$ (i=1,1.1,1.2,…)	Gauss	0.05
e_2	Edge distance (mm)	$i.d_h$ (i=1,1.1,1.2,…)	Gauss	0.05
P_1	Spacing between centers of bolts in the direction of load(mm)	$i.d_h$ (i=1,1.1,1.2,…)	Gauss	0.05
P_2	Spacing between centers of fasteners in each row (mm)	$i.d_h$ (i=1,1.1,1.2,…)	Gauss	0.05
τ_p	Shear strength of plates (MPa)	122 for H loading 140.3 for HZ loading	Gauss	0.08
σ_p	Tensile strength of plates (MPa)	212 for H loading 243.8 for HZ loading	Gauss	0.08
Q_H	External load for H Loading	Calculated for each connection (Eq. (24))	Log-Normal	0.25
Q_{Hz}	External load for HZ Loading	Calculated separately for each connection (Eq. (24))	Log-Normal	0.35
σ_a	Yield strength of plates (MPa)	353 for St 52	Gauss	0.08
E	Young modulus (GPa)	210	Gauss	0.06
τ_b	Shear strength of bolts (MPa)	192 for SL type connections at the H loading 216 for SL type connections at the HZ loading 224 for SLP type connections at the H loading 256 for SLP type connections at the HZ loading	Gauss	0.08
σ_b	Crushing strength (MPa)	420 for SL type connections at the H loading 470 for SL type connections at the HZ loading 480 for SLP type connections at the H loading 540 for SLP type connections at the HZ loading	Gauss	0.08

5. Reliability computations

5.1 Constitution of limit state functions

Limit state functions expressing the limits between safe and unsafe states are used in calculations of probability of failure. Limit state functions for e_1, e_2, P_1 and P_2 distances were constituted in Eqs. (26)-(27)-(28)-(29) respectively.

$$Q_{ext} \leq Q_{e1} \leq Q_{be1} \tag{26}$$

$$Q_{ext} \leq Q_{p1} \leq Q_{bp1} \tag{27}$$

$$\mathrm{Q_{ext}} \leq \mathrm{Q_{e2}} \tag{28}$$

$$\mathrm{Q_{ext}} \leq \mathrm{Q_{p2}} \tag{29}$$

It is required that, Q_{e1} must be bigger than Q_{ext} or equivalent to Q_{ext} and must be smaller than Q_{be1} or equivalent to Q_{be1} for the safety of connections designed by chosen e_1 distances. In other words, loads carried by connection for chosen $e_{1,}$ distance must be between the external load carried safely by plates or by bolts and buckling load (Q_{be1}) carried safely by plates. This state was summarized by Eq. (26). Values of Q_{ext}, Q_{e1} and Q_{be1} in Eq. (26) were calculated by Eqs. (30)-(31)-(32) respectively.

$$Q_{ext} = min\begin{cases}(2e_2 + (n_r - 1)p_2 - n_r.d_h)\sigma_p \\ n_r.b_n.n_i\frac{\pi d_b^2}{4}\tau_b \\ n_r.b_n.d_b.t_{min}.\sigma_c\end{cases} \tag{30}$$

$$Q_{e1} = 2\left(e_1 - \frac{d_h}{2}\right).\tau_p.t_{min} \tag{31}$$

$$Q_{be1} = \sigma_{be1((2e_2+(n_r-1)p_2)t_{min})} \tag{32}$$

Where n_r is row number of bolt and b_n is bolts in a bolt row. Values of coefficiency of λ_{e1} used in the calculation of σ_{be1} were calculated by Eq. (33).

$$\lambda_{e1} = \frac{2e_1}{\sqrt{\frac{t_{min}^2}{12}}} \tag{33}$$

Limit States were constituted for P_1 distances were given by Eq. (27). Q_{ext}, Q_{p1} ve Q_{bp1} loads given in Eq. (27) can be calculated by the Eqs. (30)-(34)-(35) respectively.

$$Q_{p1} = 2\,(P_1 - d_h)\tau_p t_{min} \tag{34}$$

$$Q_{bp1} = \sigma_{bp1((2e_2+(rn-1)P_2)t_{min})} \tag{35}$$

In the Eq. (35), σ_{bp1} is allowable buckling stress for plates. Slenderness coefficient, used in the calculation of $\sigma_{bp1,}$ was calculated by Eq. (36) in this study.

$$\lambda = \frac{2P_1}{\sqrt{\frac{t_{min}^2}{12}}} \tag{36}$$

Eq. (28) was used as the limit state function for any chosen e_2 distance during reliability analyses. As seen from Eq. (28), safe state is defined as the load carried by connection designed with chosen e_2 must be equal or bigger than the load acting on connection externally. While external load Q_{ext}, given in Eq. (28), can be calculated by Eq. (30), load of Q_{e2} can be determined by Eq. (37).

$$Q_{e2} = (2e_2 - d_h)\,\sigma_p\,t_{min} \tag{37}$$

Similarly, Eq. (29) was given for the limit state of P_2. Loads of Q_{ext} and Q_{p2} used in Eq. (29) were calculated by Eq. (30) and Eq. (38) respectively.

$$Q_{p2} = (P_2 - d_h)\,\sigma_p\,t_{min} \tag{38}$$

Table 4 Numbers of solutions performed for different type connections having different plate thicknesses subjected different loadings

	e_1				P_1				e_2				e_2			
t (×d_h)	SL		SLP		SL		SLP		SL		SLP		SL		SLP	
(mm)	H	HZ	H	HZ	H	HZ	H	HZ	H	HZ	H	HZ	H	HZ	H	HZ
4	27	24	27	23	46	54	63	54	41	41	41	41	91	91	91	91
5	29	25	30	25	47	59	69	59	41	41	41	41	91	91	91	91
7	39	33	39	33	66	75	87	75	41	41	41	41	91	91	91	91
10	47	39	47	39	79	88	103	88	41	41	41	41	91	91	91	91
15	62	53	61	53	106	114	131	113	41	41	41	41	91	91	91	91
20	67	57	66	57	137	123	143	123	41	41	41	41	91	91	91	91
25	84	75	78	66	159	159	163	142	41	41	41	41	91	91	91	91
30	100	91	87	74	219	191	182	156	41	41	41	41	91	91	91	91
Total 1	455	397	435	370	859	863	941	810	328	328	328	328	728	728	728	728
Total 2	852		805		1722		1751		656		656		1456		1456	
Total	1657				3473				1312				2912			
Overall total									9354							

5.2 Computation and modelling

In this study, a computer program code in Visual Basic programming (Microsoft Visual Studio Express 2012 version) language was written for the determination of reliabilities of e_1, e_2, P_1 and P_2 distances defining bolt placements. Statistical values and descriptions of variables presented in Table 3 were given as an input data in this programming code. Then, random data related to the problem variables was generated by using input data. After problem solutions were performed by using generated random data sets, it was checked whether the limit conditions of the problem were exceeded or not.

In this study, 1×10^6 numbers of solutions were performed for each bolted connection model. After computations of mean values, standard deviations, coefficiency of variations were made for each 1×10^6 solutions of each bolted connections, failure probabilities and reliability indexes of those connections were computed. In the computation of failure probability and reliability indexes, the *MCS* method and first order second moment methods coded in a computer program were used respectively.

Different bolted connection models were constituted for the different values of e_1 distance defined as end distance in this study. The first model was constituted for value of e_1=1. The other bolted connection models for $e_1=i.d_h$ (i=1.1, 1.2,..) values were constituted and failure probabilities and reliability indexes of all of those connections were then computed. All of the modelling and computation works were performed until negative reliability index values computed. Similarly, different bolted connections were constituted for $e_2=i.d_h$ (i=1, 1.1, 1.2,..), $P_1=i.d_h$ (i=1, 1.1, 1.2,..), $P_2=i.d_h$ (i=1, 1.1, 1.2,..) values and failure probabilities and reliability indexes of all of those connections were computed until obtaining negative reliability index value. Reliability analysis for all those connections have been performed for all of the 32 combinations of two different type bolted connection type (*SL* and *SLP*), two different load types (*H* and *HZ*) and 8 different plate thicknesses ($t_{\min}$=4, 5, 7, 10, 15, 20, 25, 30 mm). 455 different models were analyzed or, in other words 455×10^6 solutions were carried out for the determination of reliabilities

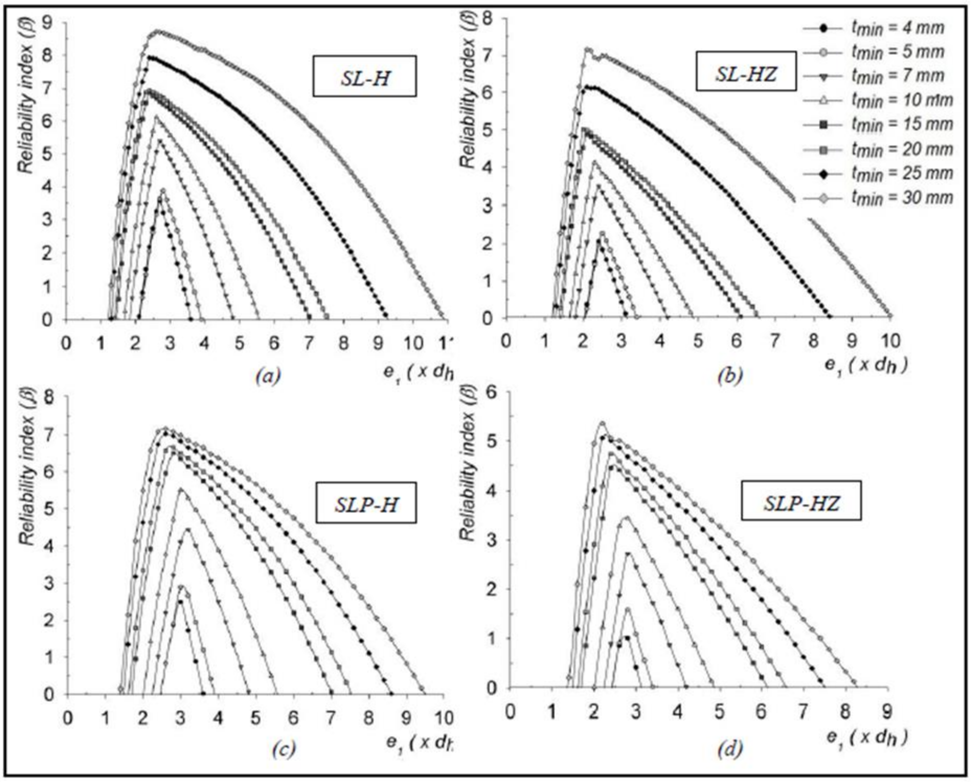

Fig. 3 Reliability indexes of e_1 distances for *SL* and *SLP* type connections under *H* and *HZ* loadings

of different e_1 distances in the *SL* type bolted connections subjected to *H* loading. Similarly, 397, 435 and 370 different models were constituted and analyzed for *SL* type connections subjected to *HZ* loading, *SLP* type connections subjected to *H* Loading and *SLP* type connections subjected to *HZ* loadings respectively. Total 1657 bolted connections were modelled and 1657×10^6 solutions have been performed for computations of reliability analysis of e_1 distances. Solution numbers and constituted models for the other distances describing bolted placements can be found in Table 4.

As seen in Table 4, 1657, 3473, 1312 and 2912 models have been constituted for e_1, P_1, e_2 and P_2 distances respectively. Finally, 9354 models have been constituted and analyzed. In other words, solutions of 9.354×10^9 bolted connections were made in this study. 1×10^6 solutions for each of the 9354 models took about 175 seconds with a computer having 2 GB RAM and Intel Core i3 processors with 2.93 GHz. 30 different computers having same properties in the computer laboratory of civil engineering department of Gumushane University were used for the solutions of 9354 bolted connection models. The total computation time took approximately 15 hours, 9 minutes and 25 seconds for 30 computers.

6. Findings and comparisons

Although both probability of failure and reliability index values computed in this study, only reliability index values were given as findings in order to avoid complexity and to ease presentation. Nevertheless, an approximate consideration can be obtained about probability of failure values corresponded to values of reliability indexes using Table 2.

Reliability index values obtained from reliability analysis for different e_1 distances are given in Fig. 3 for all combinations of "*SL* and *SLP* type bolted connections" and "*H* and *HZ* loadings". Similar graphics of P_1 are given in Fig. 4, for all loading and connection type combinations. The reliability index and e_1 distance graphics and reliability index and P_1 distance graphics consist of two parts. As seen in the first part of the graphics, the reliability of e_1 and P_1 distances increases with the increase in the value of e_1 and P_1 distances. There seems to be an inverse relationship at the second part of those graphics. After maximum values of reliability index, reliabilities of the distances of e_1 and P_1 decrease while buckling risk increases. There is nearly a linear relationship between β-e_1 and β-P_1 at the first part of graphics. Those relationships are generally nonlinear in the second part of the graphics.

Reliability index values of e_1 computed for *H* loading became greater than those values for *HZ* loading. Similarly, reliabilities of *SL* type connections were computed as bigger than those of *SLP* type connections.

It can also be understood from those figures that reliabilities of e_1 and P_1 distances increase by increased plate thickness. The lower boundaries of reliability curves got small values, and upper boundaries of reliability curves got bigger values at the bolted connections constituted by using thicker plates. In other words; in the case of using thicker plates, reliability boundaries of e_1 and P_1 distances expand.

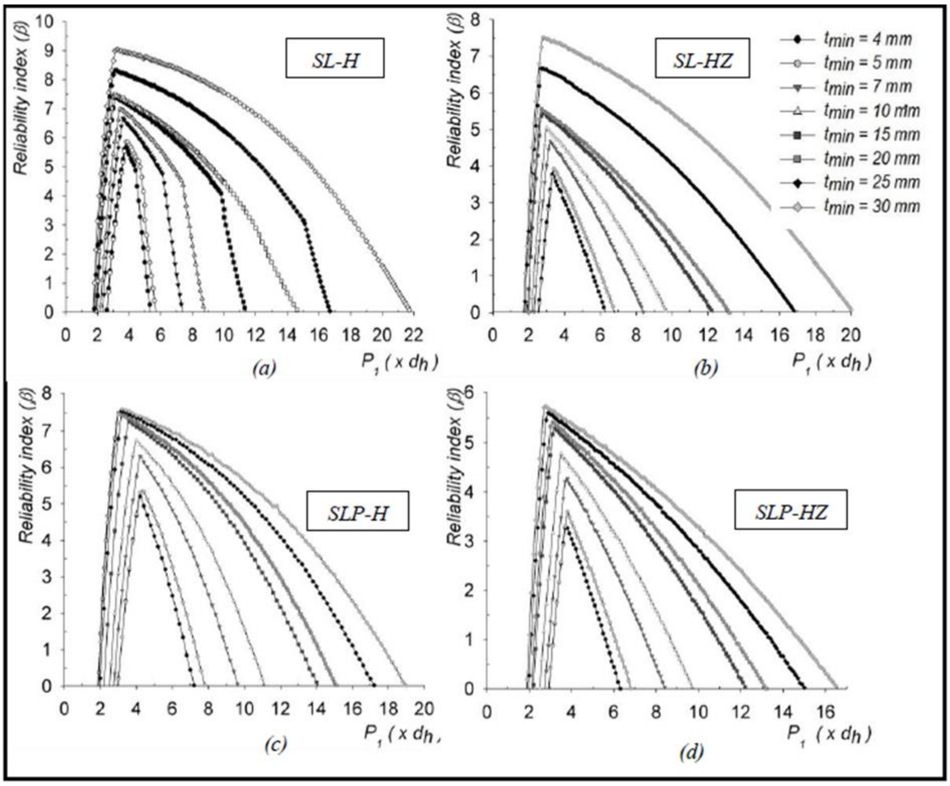

Fig. 4 Reliability indexes of P_1 distances for *SL* and *SLP* type connections under *H* and *HZ* loadings

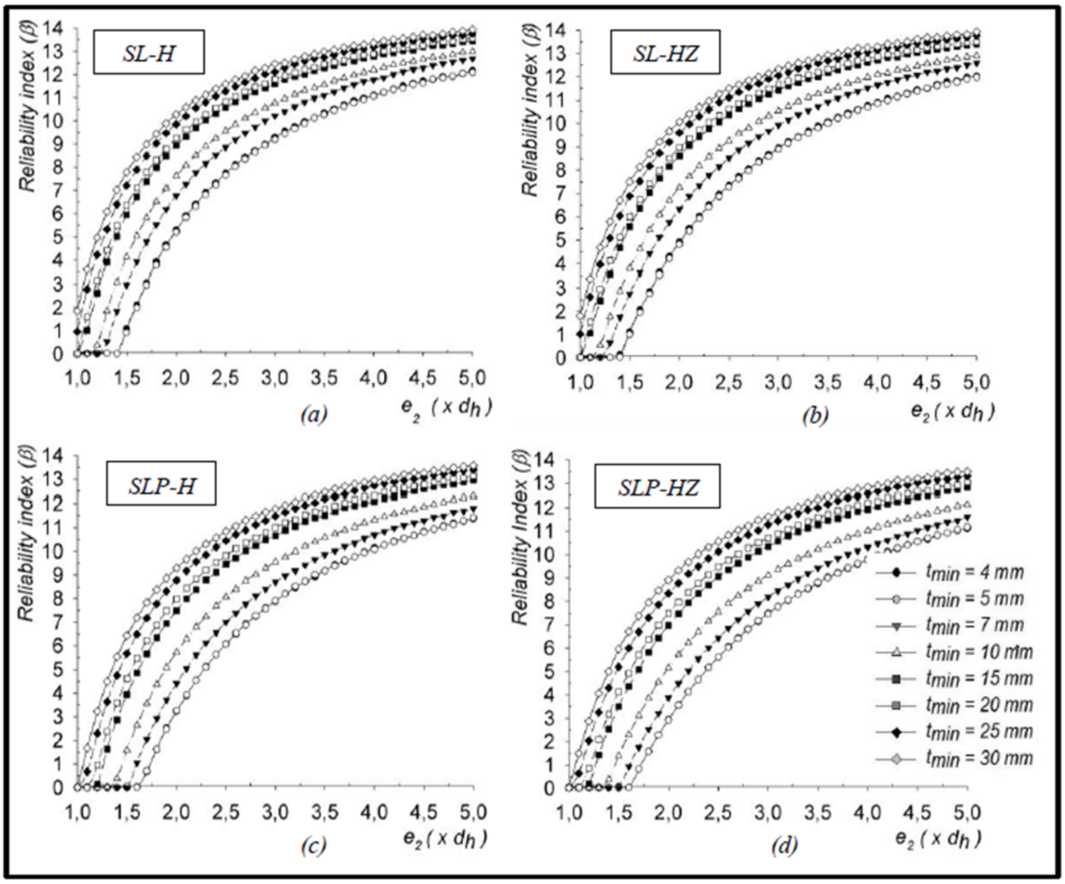

Fig. 5 Reliability indexes of e_2 distances for *SL* and *SLP* type connections under *H* and *HZ* loadings

Those figures also show us that it cannot be used in the same way as e_1 and P_1 distances for the same reliability levels of bolted connections having different plate thickness. The minimum values of e_1 and P_1 proposed by different structural codes are very risky for bolted connections having especially $t_{min} \leq 10$ mm plates. The maximum values of P_1 proposed by different structural codes except *AISC* and *CAN/CSASP16-01* are seen reliable. The maximum values of e_1 proposed by different structural codes, except for the TS648 Turkish Code, seem to be risky.

Graphics showing reliabilities of different e_2 distances are given in Fig. 5 for combinations of those "*SL* and *SLP* type Bolted connections" and "*H* and *HZ* loadings". Also, similar graphics are given for different P_2 distances in Fig. 6.

The reliability index values of e_2 and P_2 distances were computed to obtain lower reliability boundary of them. Reliability about maximum limits of e_2 and P_2 distances cannot be computed because there is no mechanical equation for the determination of maximum limits of e_2 and P_2 distances at the technical literature. For the reasons given above, β-e_2 and β-P_2 graphics consist of just a curve for each minimum plate thickness of t_{min}. Reliabilities of the distances of e_2 and P_2 are increased while the values of the distances of e_2 and P_2 are increased in the graphics.

As seen in the graphics for P_2 distances, absolutely, the same reliability index values were computed for plates having different thickness for *SL* type connections under both *H* and *HZ*

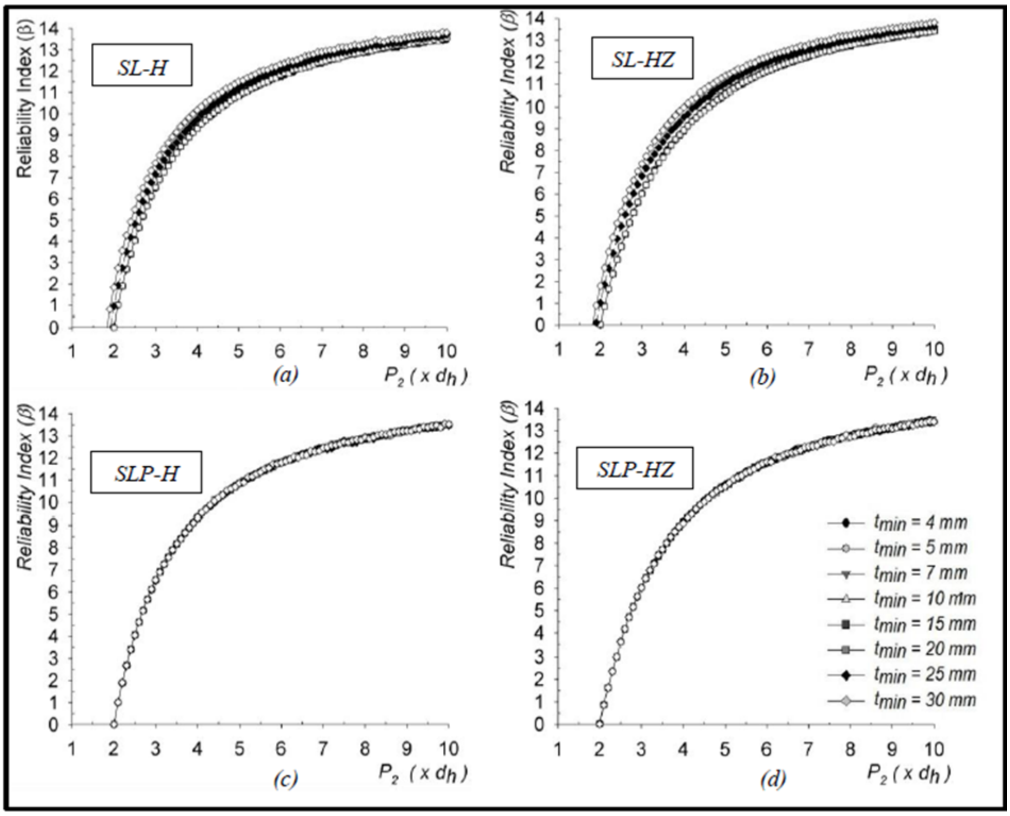

Fig. 6 Reliability indexes of P_2 distances for *SL* and *SLP* type connections under *H* and *HZ* loadings

loadings. Similar situations can be seen for *SLP* type connection from P_2 graphics.

When the values of P_2, proposed by structural codes, are compared with the graphics, it can be seen that those values can be used safely in structural design for the connections having *St* 52 steel, 8.8D grade bolted *SL* and *SLP* types connections under *H*, *HZ* loadings.

Minimum values of e_2 proposed as $1.25d_h$ by some structural codes are reliable for connections having t_{min}>10 mm plate for *SL, SLP* type connections and *H, HZ* loadings. The distance of $e_2=1.5d_h$ is not reliable for *SLP* type connections with t_{min}<=7 mm plate. Distance of $e_2=1.75d_h$ is reliable in all conditions. It can also be concluded from the β-e_2 graphics that bigger β values are computed at the plates with greater thickness.

Minimum and maximum values of e_1, P_1, e_2 and P_2 distances corresponding to β=1, β=2, β=3, β=4 and β=5 reliability index values for *SL* and *SLP* type connections and for *H* and *HZ* loading types were tabulated and given with Table 5. This table can be used at the designing of connections for β=1, β=2, β=3, β=4 and β=5 of desired reliability index values. As seen from this table, some values are not available. These unavailable values could not be obtained for the plates and bolts of whose diameters were calculated by Eq. (25) for those plates. It is possible to obtain available values using bolts having smaller diameters. In other words, values given in this table were valid for only plates having t_{min}=4, 5, 7, 10, 15, 20, 25, 30 mm thickness and the *M*12, *M*14, *M*16, *M*20, *M*24, *M*30, *M*33, *M*36 metric bolts determined by Eq. (25) for these plate thickness respectively. These values given in this table cannot be used for different plate thickness and for

Table 5 Minimum and maximum values (×t) of e_1, P_1, e_2, and P_2 distances corresponding to β=1, β=2, β=3, β=4 and β=5 reliability index values for *SL* and *SLP* type connections and for *H* and *HZ* loading types

	t (mm)	H										HZ									
		β=1		β=2		β=3		β=4		β=5		β=1		β=2		β=3		β=4		β=5	
		min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
e_1 for SL	4	2.23	3.38	2.37	3.13	2.55	2.86	-	-	-	-	2.21	2.81	2.39	2.39	-	-	-	-	-	-
	5	2.25	3.65	2.40	3.38	2.57	3.08	-	-	-	-	2.23	3.03	2.41	2.64	-	-	-	-	-	-
	7	1.94	4.52	2.07	4.18	2.22	3.82	2.39	3.39	2.59	2.92	1.94	3.76	2.09	3.27	2.27	2.71	-	-	-	-
	10	1.78	5.23	1.90	4.84	2.03	4.43	2.18	3.94	2.36	3.41	1.77	4.33	1.91	3.75	2.07	3.11	2.27	2.27	-	-
	15	1.54	6.59	1.63	6.09	1.74	5.56	1.87	4.97	2.02	4.25	1.53	5.49	1.64	4.74	1.77	3.95	1.92	3.00	-	-
	20	1.48	7.08	1.57	6.55	1.67	5.98	1.79	5.32	1.94	4.56	1.47	5.89	1.58	5.15	1.70	4.23	1.84	3.22	2.00	2.00
	25	1.37	8.75	1.45	8.21	1.55	7.62	1.65	6.96	1.78	6.20	1.36	7.70	1.46	6.90	1.57	6.05	1.69	5.12	1.83	3.92
	30	1.30	10.35	1.39	9.78	1.46	9.18	1.56	8.52	1.68	7.78	1.29	9.29	1.38	8.48	1.48	7.62	1.59	6.70	1.72	5.54
e_1 for SLP	4	2.63	3.39	2.84	2.84	-	-	-	-	-	-	2.80	2.80	-	-	-	-	-	-	-	-
	5	2.63	3.65	2.82	3.80	-	-	-	-	-	-	2.63	3.04	-	-	-	-	-	-	-	-
	7	2.40	4.52	2.57	4.18	2.76	3.82	2.98	3.40	-	-	2.42	3.78	2.63	3.25	-	-	-	-	-	-
	10	2.15	5.23	2.29	4.84	2.46	4.42	2.65	3.96	2.87	3.47	2.16	4.33	2.34	3.77	2.54	3.15	-	-	-	-
	15	1.81	6.58	1.93	6.10	2.06	5.59	2.21	4.97	2.40	4.27	1.82	5.46	1.97	4.75	2.22	3.95	2.31	3.03	-	-
	20	1.72	7.07	1.83	6.57	1.96	6.00	2.10	5.33	2.27	4.54	1.73	5.88	1.87	5.08	2.02	4.26	2.19	3.26	-	-
	25	1.57	8.07	1.67	7.48	1.78	6.82	1.91	6.09	2.06	5.20	1.58	6.70	1.70	5.81	1.84	4.82	2.00	3.71	2.19	2.45
	30	1.49	8.88	1.59	8.24	1.69	7.52	1.79	6.71	1.93	5.69	1.48	7.40	1.59	6.40	1.72	5.32	1.85	4.08	2.02	2.65
P_1 for SL	4	2.73	5.14	2.89	4.94	3.08	4.75	3.28	4.56	3.53	4.35	2.71	5.62	2.91	4.85	3.12	4.04	-	-	-	-
	5	2.75	5.45	2.92	5.24	3.10	5.00	3.31	4.93	3.56	5.16	2.73	6.09	2.93	5.25	3.14	4.40	-	-	-	-
	7	2.45	7.08	2.59	6.81	2.75	6.55	2.93	6.31	3.14	5.88	2.45	7.53	2.61	6.51	2.79	5.38	3.00	4.17	-	-
	10	2.29	8.41	2.42	8.08	2.56	7.78	2.72	7.50	2.91	6.71	2.28	8.67	2.43	7.52	2.59	6.23	2.78	4.84	2.99	2.99
	15	2.04	10.90	2.15	10.49	2.27	10.00	2.41	9.90	2.58	8.52	2.04	10.93	2.16	9.43	2.30	7.93	2.46	6.03	2.63	3.98
	20	1.99	13.66	2.09	12.75	2.21	11.95	2.34	0.69	2.50	9.14	2.05	11.74	2.10	10.15	2.23	8.46	2.38	6.51	2.55	4.22
	25	1.88	16.13	1.97	15.60	2.08	15.14	2.20	13.88	2.34	12.37	1.87	15.40	1.98	13.81	2.10	12.00	2.23	10.13	2.39	7.87
	30	1.80	20.67	1.89	19.54	1.99	18.36	2.10	17.05	2.24	15.55	1.79	18.59	1.92	16.95	2.01	15.23	2.13	13.32	2.28	11.04
P_1 for SLP	4	3.14	6.79	3.33	6.25	3.55	5.73	3.80	5.08	4.13	4.13	3.13	5.61	3.36	4.85	3.61	4.04	-	-	-	-
	5	3.14	7.31	3.34	6.76	3.55	6.17	3.80	5.53	4.10	4.72	3.13	6.07	3.36	5.25	3.62	4.36	-	-	-	-
	7	2.91	9.02	3.08	8.35	3.28	7.61	3.51	6.78	3.77	5.81	2.93	7.48	3.14	6.50	3.38	5.41	3.64	4.14	-	-
	10	2.65	10.45	2.80	9.68	2.98	8.82	3.18	7.85	3.42	6.76	2.67	8.80	2.86	7.51	3.06	6.31	3.29	4.81	-	-
	15	2.32	13.14	2.45	12.1	2.59	11.1	2.76	9.95	2.95	8.47	2.33	10.90	2.48	9.48	2.65	7.84	2.84	6.05	3.06	3.88
	20	1.96	14.13	2.06	13.2	2.17	11.9	2.30	10.64	2.46	9.09	2.24	11.74	2.38	10.19	2.54	8.49	2.72	6.54	2.93	4.36
	25	2.08	16.15	2.19	14.9	2.32	13.6	2.46	12.14	2.62	10.4	2.09	13.46	2.22	11.58	2.36	9.67	2.52	7.42	2.71	4.76
	30	1.98	17.80	2.09	16.5	2.20	15.1	2.33	13.47	2.49	11.4	1.99	14.79	2.11	12.78	2.24	10.6	2.39	8.18	2.56	5.23
e_2 for SL	4	1.49	3.38	1.59	3.13	1.69	2.86	1.81	-	1.96	-	1.72	2.81	1.86	2.39	2.01	-	2.18	-	2.37	-
	5	1.51	3.65	1.60	3.38	1.71	3.08	1.83	-	1.97	-	1.72	3.03	1.86	2.64	2.01	-	2.18	-	2.37	-
	7	1.34	4.52	1.41	4.18	1.50	3.82	1.61	3.39	1.73	2.92	1.61	3.76	1.73	3.27	1.87	2.71	2.02	-	2.20	-
	10	1.24	5.23	1.31	4.84	1.39	4.43	1.49	3.94	1.60	3.41	1.46	4.33	1.57	3.75	1.69	3.11	1.82	2.27	1.97	-
	15	1.10	6.59	1.16	6.09	1.23	5.56	1.31	4.97	1.40	4.25	1.27	5.49	1.35	4.74	1.45	3.95	1.56	3.00	1.69	-
	20	1.06	7.08	1.13	6.55	1.19	5.98	1.27	5.32	1.36	4.56	1.21	5.89	1.29	5.15	1.38	4.23	1.49	3.22	1.61	2.00
	25	1.00	8.75	1.06	8.21	1.12	7.62	1.19	6.96	1.27	6.20	1.13	7.70	1.20	6.90	1.28	6.05	1.37	5.12	1.48	3.92
	30	1.00	10.35	1.01	9.78	1.07	9.18	1.13	8.52	1.20	7.78	1.07	9.29	1.14	8.48	1.21	7.62	1.30	6.70	1.40	5.54

Table 5 Continued

e_2 for SLP	4	1.73	3.39	1.84	2.84	1.97	-	2.12	-	2.28	-	1.72	2.80	1.86	-	2.01	-	2.18	-	2.37	-
	5	1.73	3.65	1.84	3.80	1.97	-	2.11	-	2.28	-	1.72	3.04	1.86	-	2.01	-	2.18	-	2.37	-
	7	1.60	4.52	1.70	4.18	1.81	3.82	1.94	3.40	2.09	-	1.61	3.78	1.73	3.25	1.87	-	2.02	-	2.20	-
	10	1.45	5.23	1.54	4.84	1.64	4.42	1.76	3.96	1.89	3.47	1.46	4.33	1.57	3.77	1.69	3.15	1.82	-	1.97	-
	15	1.26	6.58	1.33	6.10	1.41	5.59	1.51	4.97	1.62	4.27	1.27	5.46	1.35	4.75	1.45	3.95	1.56	3.03	1.69	-
	20	1.20	7.07	1.27	6.57	1.35	6.00	1.44	5.33	1.55	4.54	1.21	5.88	1.29	5.08	1.38	4.26	1.49	3.26	1.61	-
	25	1.12	8.07	1.18	7.48	1.25	6.82	1.33	6.09	1.43	5.20	1.13	6.70	1.20	5.81	1.28	4.82	1.37	3.71	1.48	2.45
	30	1.06	8.88	1.12	8.24	1.19	7.52	1.26	6.71	1.35	5.69	1.07	7.40	1.14	6.40	1.21	5.32	1.30	4.08	1.40	2.65
P_2 for SL	4	2.10	5.14	2.21	4.94	2.34	4.75	2.49	4.56	2.67	4.35	2.12	5.62	2.25	4.85	2.40	4.04	2.57	-	2.77	-
	5	2.10	5.45	2.21	5.24	2.34	5.00	2.49	4.93	2.67	5.16	2.12	6.09	2.25	5.25	2.40	4.40	2.57	-	2.76	-
	7	2.10	7.08	2.21	6.81	2.34	6.55	2.49	6.31	2.67	5.88	2.11	7.53	2.25	6.51	2.40	5.38	2.57	4.17	2.76	-
	10	2.10	8.41	2.21	8.08	2.34	7.78	2.49	7.50	2.67	6.71	2.12	8.67	2.25	7.52	2.40	6.23	2.57	4.84	2.76	2.99
	15	2.10	10.90	2.21	10.49	2.34	10.00	2.49	9.90	2.67	8.52	2.12	10.93	2.25	9.43	2.40	7.93	2.57	6.03	2.77	3.98
	20	2.10	13.66	2.21	12.75	2.34	11.95	2.50	10.69	2.67	9.14	2.12	11.74	2.25	10.15	2.40	8.46	2.57	6.51	2.77	4.22
	25	2.00	16.13	2.11	15.60	2.23	15.14	2.37	13.88	2.53	12.37	2.00	15.40	2.12	13.81	2.26	12.00	2.41	10.13	2.59	7.87
	30	1.92	20.67	2.02	19.54	2.13	18.36	2.26	17.05	2.41	15.55	1.91	18.59	2.03	16.95	2.15	15.23	2.30	13.32	2.46	11.04
P_2 for SLP	4	2.10	6.79	2.21	6.25	2.34	5.73	2.49	5.08	2.67	4.13	2.12	5.61	2.25	4.85	2.40	4.04	2.57	-	2.76	-
	5	2.10	7.31	2.21	6.76	2.35	6.17	2.49	5.53	2.67	4.72	2.12	6.07	2.25	5.25	2.40	4.36	2.57	-	2.76	-
	7	2.10	9.02	2.21	8.35	2.34	7.61	2.49	6.78	2.66	5.81	2.12	7.48	2.25	6.50	2.40	5.41	2.57	4.14	2.76	-
	10	2.10	10.45	2.21	9.68	2.34	8.82	2.49	7.85	2.67	6.76	2.12	8.80	2.25	7.51	2.40	6.31	2.57	4.81	2.77	-
	15	2.10	13.14	2.21	12.19	2.34	11.17	2.49	9.95	2.67	8.47	2.12	10.90	2.25	9.48	2.40	7.84	2.57	6.05	2.77	3.88
	20	2.10	14.13	2.21	13.22	2.34	11.98	2.49	10.64	2.67	9.09	2.12	11.74	2.25	10.19	2.40	8.49	2.57	6.54	2.76	4.36
	25	2.10	16.15	2.22	14.93	2.35	13.63	2.49	12.14	2.67	10.42	2.12	13.46	2.25	11.58	2.40	9.67	2.57	7.42	2.77	4.76
	30	2.10	17.80	2.21	16.54	2.34	15.10	2.49	13.47	2.67	11.49	2.12	14.79	2.25	12.78	2.40	10.60	2.57	8.18	2.77	5.23

Table 6 Proposed equations for minimum and maximum values of P_1, P_2, e_1, e_2 distances at β=3

			Minimum Value	Maximum Value
H	SL	P_1	$P_1 = 4.322653t^{-0.229}$ (R^2=0.9885)	$P_1 = P_2 = 1.7845t^{0.658}$ (R^2=0.9858)
		P_2	$P_2 = -0.0007t^2 + 0.0159t + 2.2683$ (R^2=0.9676)	
		e_1	$e_1 = 3.9463t^{-0,292}$ (R^2=0.9887)	$e_1 = e_2 = 1.2853t^{0.5492}$ (R^2=0.9801)
		e_2	$e_2 = 2.4245t^{-0,242}$ (R^2=0.9882)	
	SLP	P_1	$P_1 = 5.3953t^{-0.272}$ (R^2=0.9521)	$P_1 = P_2 = 2.9266t^{0.4805}$ (R^2=0.996)
		P_2	$P_2 = 2.35$ (R^2=0.9999)	
		e_1	$e_1 = 5.3113t^{-0,339}$ (R^2=0.9933)	$e_1 = e_2 = 1.5499t^{0.4614}$ (R^2=0.9931)
		e_2	$e_2 = 2.49624t^{-0,266}$ (R^2=0.9869)	
HZ	SL	P_1	$P_1 = 4.3972t^{-0.231}$ (R^2=0.9883)	$P_1 = P_2 = 3.602e^{0.0478t}$ (R^2=0,9791)
		P_2	$P_2 = -0.0007t^2 + 0.016t + 2.2323$ (R^2=0.9538)	
		e_1	$e_1 = 4.0241t^{-0,294}$ (R^2=0.9915)	$e_1 = e_2 = 1.9738e^{0.0439t}$ (R^2=0.9781)
		e_2	$e_2 = 3.0453t^{-0,267}$ (R^2=0.9837)	
	SLP	P_1	$P_1 = 5.3577t^{-0.253}$ (R^2=0.9836)	$P_1 = P_2 = 2.0777t^{0.4792}$ (R^2=0.9965)
		P_2	$P_2 = 2.40$ (R^2=0.9999)	
		e_1	$e_1 = 5.843t^{-0,359}$ (R^2=0.9981)	$e_1 = e_2 = 1.1033t^{0.4595}$ (R^2=0.9885)
		e_2	$e_2 = 3.0453t^{-0,267}$ (R^2=0.9837)	

different bolts having different diameter. Also, interpolation may cause producing wrong results in this table. Figs. 3-6 can be used for more details and for values greater than 5 and intermediate values of e_1, P_1, e_2 and P_2.

The classic equations and values defining P_1, P_2, e_1 and e_2 distances in the normal strength bolted connections are proposed for β=3 reliability level by building-codes. In this study, new equations were developed in order to define the maximum and minimum limit values of P_1, P_2, e_1 and e_2 distances for high strength *SL* and *SLP* type bolted connections (with *St* 52 grade steel and 8.8*D* grade bolts) subjected *H* and *HZ* loadings. After, regression analyses were performed between those equations and the values given for β=3 reliability level in Table 5, correlation coefficients (R^2) were obtained. All of those equations with value of R^2 were presented in Table 6. As seen from this table, the lowest value of R^2 of the equations was obtained as 0.9521. In other words, the correlations between those equations and the values given in the Table 5 is quite good and they can be used safely for β=3 reliability level in structural designs.

7. Conclusions

In this study, reliability analyses were performed for high strength steel connections constituted by using St 52 grade steel and 8.8D grade bolts under *H* and *HZ* loadings. Analyses were performed with a written programming code. *MCS* method and analytical models were coded in this programming code. Geometrical and mechanical properties of connections are taken as variables. The conclusions obtained from this research presented herein are given below.

• Reliabilities of distances describing bolt placement in the direction of design actions and in the direction of perpendicular to design action were obtained for *SL* and *SLP* type connections under *H* and *HZ* loadings.

• Minimum and maximum values of reliabilities of e_1 and P_1 distances describing distances in the direction of design actions were obtained in this study.

• Only minimum values of reliabilities of e_2 and P_2 distances which describe distances in the perpendicular direction to design could be obtained. As similar to the applications done by structural codes, maximum values of e_1 and P_1 determined within this study can be used for the maximum values of e_2 and P_2

• Some values of bolt distances proposed by some structural codes do not have enough reliability for designing of high strength bolted connections. Those values have to be revised according to this study and similar studies.

• Reliability values given within the graphics and Table 5 in this study can be used for different structures having different desired reliability levels. Hereby designing of more economic and safer connections and steel structures became possible.

• New equations were developed for the calculation of maximum and minimum values of P_1, P_2, e_1 and e_2 distances used in the designs of high strength *SL* and *SLP* type bolted connections subjected *H* and *HZ* loadings *at* the β=3 reliability level.

• Similar studies should be conducted for different high strength steel grades or high strength bolts. Especially similar studies should be conducted for *GV* and *GVP* type bolted connections.

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