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Comparative Study on Design and Calculating Theories of High-Strength Bolted Connections with Non-Standard Holes between China and Indian

Zaihua Zhang [1], Yihong Liu [2]

Doctor, Civil Engineering College of Hunan City University, Yiyang, Hunan, China[1]

Associate Professor, Civil Engineering College of Hunan City University, Yiyang, Hunan, China[2]

ABSTRACT: With the development of modular, assembly steel structural engineering, engineers pay more and more attention to the high-strength bolted connections with non-standard holes, in virtue of its facilitation installation. For the design and calculation theories of such a kind of connection, the work introduces the provisions of relevant specifications between China and Indian. A detail comparison and analysis of the configuration and mechanical behaviour of the connections are presented, which can provide the readers a quick and clear idea about the design and application of this kind of connections.

KEYWORDS: High-strength bolted connection, Non-standard hole, Design and calculation theory, Design code

I. INTRODUCTION

As a kind of effective connection type, high-strength bolted connection has been widely used in assembly steel structural engineering, and the specifications of design, erection and inspection for such a type of connections are comprehensive in various countries and regions. In many cases, the standard hole is required and the application of non-standard hole is cautious for the design of connections. The non-standard hole includes oversize hole, short slot hole and long slot hole. In the practical engineering application, non-standard hole can supply greater erection tolerance and can facilitate both fabrication and erection of steel structures, so it is more popular for fabricators/erectors. This paper focuses on the design and calculation theories for high-strength bolted connection with non-standard hole considering the provisions of relevant specifications between China and Indian. A detail comparison and analysis of the configuration and mechanical behaviour of the connections are presented, which can provide reference for application of practical engineering.

II. COMPARISON ABOUT THE SERVICEABLE RANGE AND RELATIVE CONFIGURATION

According to the difference of load transfer mechanism, high-strength bolted connections can be classified into the following two kinds: (a)Bearing type—bolts bears against the holes to transfer the load from one member to another. Eg. Slip type.(b)Friction type—when the force is transferred by friction between the plates due to tensioning of bolts. Eg. Slip-critical connections. The type of bolt hole include standard hole and non-standard holes(oversize hole, short slot hole and long slot hole).In China, it is the situation of recent years that non-standard hole is taken into account during the design of high-strength bolted connections. Relevant specifications for such kind of connections mainly include: Code for design of steel structure(GB50017-201x)(exposure draft)[1], Technical specification for high strength bolted connections of steel structures(JGJ82-2011)[2]. Among these specifications, only some design clauses for the friction type connections are put forward considering the application of non-standard. That is to say, high-strength bolted connection with non-standard only can be adopted the type of friction type connection. The situation is somewhat different in Indian, the high-strength bolted connections with non-standard hole can be used as friction type

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or bearing type connections. Indian Code of Practice for Construction in Steel(IS 800:2007) provide detailed rules for design of both kinds of connections[3].

As for the concrete meaning of bolt hole, there are some differences between the design codes of the two countries. Table 1and Table 2 show the clearances for the bolt holes in the codes of China and Indian respectively. It can be seen that, the rules for the dimension of oversize hole is similar, while for the slot hole, there is no concepts of short slot hole and long slot hole in China, both of them are called slot hole and the differences of the dimension provisions are obvious between the design codes of two countries.

Table 1 Clearances for the bolt holes (GB50017-201x and JGJ82-2011)

Nominal diameter of bolt d			M12	M16	M20	M22	M24	M27	M30
Hole type	Standard hole	Diameter d_0	13.5	17.5	22	24	26	30	33
	Oversize hole	Diameter d_0	16	20	24	28	30	35	38
	Slot hole	Length of slot	22	30	37	40	45	50	55

Note: the width of slot hole is equal to the diameter of standard hole

Table 2 Clearances for the bolt holes (IS 800:2007)

Nominal diameter of bolt d			M12	M14	M16	M20	M22	M24	Large than M30
Hole type	Standard hole	Diameter d_0	13	15	18	22	24	26	33
	Oversize hole	Diameter d_0	15	17	20	24	26	30	38
	Short slot hole	Length of slot	16	18	22	26	28	32	40
	Long slot hole	Length of slot	2.5d						

Note: the width of slot hole is equal to the diameter of standard hole

The arrangement of bolts has great influence on the behaviour of connections. It is necessary to meet the requirements of force-transfer and construction. Table 3 shows the comparison of design rules for bolts arrangement between the codes of China and Indian. It is clear that the bolt layout in Indian code is more compact than that in Chinese code.

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Table 3. Comparison of the Maximum and Minimum Allowed Distances of High-strength Bolts between the design codes of China and Indian

Name	Position and Direction			The Maximum Allowed Distances		The Minimum Allowed Distances	
				GB 50017 (JGJ82-2011)	IS 800:2007	GB 50017 (JGJ82-2011)	IS 800:2007
Pitch	Outside lines（Direction perpendicular or parallel to the line of stress）(p_1)			$8d_0$ or 12t	100mm+4t or 200mm	$3d_0$	2.5d
	Central lines	Direction perpendicular to the line of stress（p_2）		$16d_0$ or 24t	——		
		Direction parallel to the line of Stress（p_3）	Compression member	$12d_0$ or 18t	12t or 200mm		
			Tension member	$16d_0$ or 24t	16t or 200mm		
	Direction of cater-corner			——	——		
Edge Distance(e_1)	Sheared or Hand-cut edges			$4d_0$ or 8t	12t ε	$1.5d_0$	1.7 d_0
	Rolled, Automatic gas cutting or Sawed Edges						1.5 d_0
End Distance(e_2)	Sheared or Hand-cut edges					$2d_0$	1.7 d_0
	Rolled, Automatic gas cutting or Sawed Edges						1.5 d_0

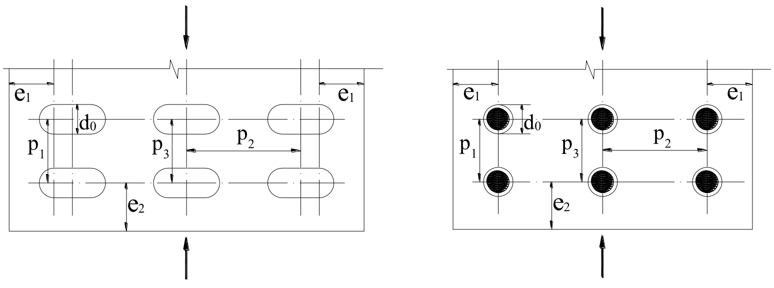
Note: 1. ε = (250/fy)1/2, and fy is the yield stress of connected plate

2. d_0 is the diameter of oversize hole or the width of slot hole

3. d is the nominal diameter of bolt

4. t is the thickness of thinner outside plate

5. the parameters p_1, p_2, p_2 and e_1, e_2 , refer to Figure 1.



(a) slot hole arrangement (b) oversize hole arrangement

Fig.1 Symbols for end distance, edge distance and pitch of high-strength bolts with non-standard bolt hole

III. COMPARISON ABOUT THE DESIGN AND CALCULATION METHODS

Connection design according to Indian code(IS 800:2007)

In Indian, both the friction type and bearing type connections can adopt non-standard hole. For each type of connection, the calculation methods of design resistance for a single bolt are listed in Table 4 according to the different loading modes(carrying load in shear, tension and combined tension and shear). Analysing these calculation methods, we can

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see that, the type of bolt hole is only affects the shear resistance of connection, and has no influence on the tension capacity. The parameter K_{h1}, K_{h2} show the influence of hole type on the shear capacity of friction type connection, and bearing type connection, respectively.

According to the provision of Indian code(IS 800:2007), the non-standard hole in the outer ply should be covered with a cover-plate which has a sufficiently large size and thickness, and has a standard hole to correspond to the non-standard hole. Meanwhile, for the connection of friction type, a harden washer should be adopted under the nut of bolt. If the hole diameter is large the bolt diameter by 3mm at more, the thickness of plate washer should be not less than 4mm.

Table 4. Design resistance of a single bolt subjected to different loading modes according to IS 800:2007

	Friction type connection	Bearing type connection
Shear resistance of connection	$V_{dsf}=[(\mu_f n_e K_{h1} F_0) / \gamma_{mf}]\beta_{lj}$ (1) Where, μ_f=slip factor as in Table 5 ($\mu f < 0.55$) n_e= number of effective interfaces offering frictional resistance to slip K_{h1} =1.0 for fasteners in clearance holes = 0.85 for fasteners in oversized and short slotted holes = 0.7 for fasteners in long slotted holes loaded parallel to the slot. γ_{mf} =1.10 (if slip resistance is designed at service load) γ_{mf} =1.25 (if slip resistance is designed at ultimate load) F_0= minimum bolt tension (proof load) at installation ($A_{nb}f_0$) A_{nb}= net area of the bolt at threads, and f_0= proof stress (=$0.70f_{ub}$) Note: V_{dsf} may be evaluated at a service load or ultimate load using appropriate partial safety factors, depending upon whether slip resistance is required at service load or ultimate load.	$V_{db}=\min(V_{dsb}, V_{dpb})$ (2) Where, $V_{dsb}=[\frac{f_u}{\sqrt{3}}(n_n A_{nb} + n_s A_{sb})/\gamma_{mf}]\beta_{lj}\beta_{lg}\beta_{pk}$ (2a) $V_{dpb}=(2.5\ K_{h2}k_b d t f_u)/\ \gamma_{mb}$ (2b) F_u=ultimate shear capacity of a bolt n_n=number of shear planes with threads intercepting the shear plane n_s=number of shear planes without threads intercepting the shear plane A_{nb}=nominal plain shank area of bolt A_{sb}=net shear area of the bolt at threads $k_b=\min(\frac{e}{3d_0}, \frac{p}{3d_0} - 0.25, \frac{f_{ub}}{f_u}, 1)$ K_{h2} =1.0 for standard holes; = 0.7 for oversize hole and short slot holes; = 0.5 for long slot holes *e*,*p*=end and pitch distance of the fastener along bearing direction(see Figure 1); d,d_0=nominal diameter of the bolt and diameter of the holes, respectively; t= summation of the thickness of the connected plates experiencing bearing stress in the same direction f_{ub}, f_u=ultimate tensile stress of the bolt and the ultimate tensile stress of the plate, respectively
	Note: 1. Shear connection should check for block shear as follows: $T_{db}=\min([\frac{A_{vg} f_y}{\sqrt{3}\gamma_{m0}}+\frac{0.9A_{tn} f_u}{\gamma_{ml}}], [\frac{0.9A_{vn} f_u}{\sqrt{3}\gamma_{ml}}+\frac{A_{tg} f_y}{\gamma_{m0}}])$ (3) where, A_{vg} and A_{vn} = minimum gross and net area in shear along a line of transmitted force, respectively, and A_{tg} and A_{tn} = minimum gross and net area in tension from the hole to the toe of the angle, perpendicular to the line of force, respectively(as in shown in Figure 2. 2. $B_{lj}, \beta_{lg}, \beta_{pk}$ is the influence coefficient of connection length, the total thickness of fastening plates, and the filler plate for the shear resistance of connection, respectively. $B_{lj} = 1.075 - 0.005(l_j/d)$, and $0.75 \leq \beta_{lj} \leq 1.0$ $\beta_{lg} = 8/(3 + l_g/d)$, and $l_g/d \geq 5.0$ $\beta_{pk} = (1 - 0.0125t_{pk})$ ($t_{pk} \geq 6mm$)	

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	l_j is the length of connection, l_g is the total thickness fo fastening plates,and t_{pk} is the thickness of filler plate, as is shown in Figure 3.	
Tension resistance of connection	$T_{df} = 0.9 f_{ub} A_n / \gamma_{mf} < f_{ub} A_{sb} \left(\gamma_{ml} / \gamma_m\right) / \gamma_{mf}$ (4)	$T_{df} = 0.9 f_{ub} A_n / \gamma_{mb} < f_{ub} A_{sb} \left(\gamma_{mb} / \gamma_{m0}\right) / \gamma_{mb}$ (5)
	Note: 1. f_{ub} is the ultimate tensile stress of the bolt 2. A_n is the effective area(the area at bottom of the threads) 3. A_{sb} is the shank area of the bolt.	
Combined shear and tension for connection	$\left(\frac{V_{sf}}{V_{dsf}}\right)^2 + \left(\frac{T_f}{T_{df}}\right)^2 \leq 1.0$ (6)	$\left(\frac{V_{sb}}{V_{db}}\right)^2 + \left(\frac{T_b}{T_{db}}\right)^2 \leq 1.0$ (7)
	Note: V_{sf}, T_f , V_{sb}, T_b are shear and tension design values of a high-strength bolt; V_{dsf}, T_{df} V_{dsb}, T_{db} are the shear and tensile bearing capacity design values of the corresponding type of bolt.	
Note: partial safety factor for materials should be taken as follows: 1. resistance, governed by yielding, γ_{m0}=1.1 2. resistance, governed by ultimate stress, γ_{ml}=1.25 3. resistance of friction type bolted connection, γ_{mf}=1.25 4. resistance of bearing type bolted connection, γ_{mb}=1.25		

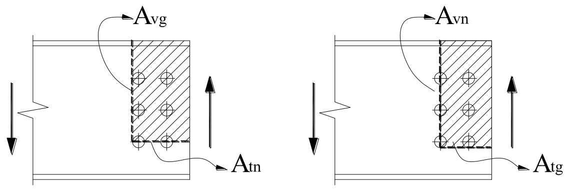

Fig.2 Symbols for controlling section for check of block shear

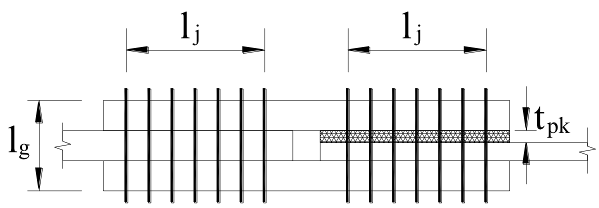

Fig. 3 Symbols for parameter of connection configuration

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Table 5 typical average values for coefficient of friction (µf)

S1 No.	Treatment of Surface	Coefficient of Friction, μ_f
1	Surfaces not treated	0.20
2	Surfaces blasted with short or grit with any loose rust removed, not pitting	0.50
3	Surfaces blasted with shot or grit and hot-dip galvanized	0.10
4	Surfaces blasted with shot or grit and Spray metalized with zinc (thickness 50-70 μm)	0.25
5	Surfaces blasted with shot or grit and Painted with ethylzinc silicate coat (thickness30-60 μm)	0.30
6	Sand blasted surface, after light rusting	0.52
7	Surfaces blasted with shot or grit and painted with ethylzinc silicate coat (thickness60-80 μm)	0.30
8	Surfaces blasted with shot or grit and painted with alcalizinc silicate coat (thickness60-80 μm)	0.30
9	Surface blasted with shot or grit and spray metalized with aluminium (thickness>50 μm)	0.50
10	Clean mill scale	0.33
11	Sand blasted surface	0.48
12	Red lead painted surface	0.1

Friction type connection design according to Chinese code(JGJ82-2011)

In China, the design and calculation method of friction type connections with non-stand hole are basically the same between the two codes of GB50017-201x (exposure draft) and JGJ82-2011. The code GB50018-201x mainly targets the connection design of hot rolled steel plate, while JGJ82-2011 is suitable for the connection design of both hot rolled steel plate and cold-formed thin-walled steel plate. Table 6 shows the calculation methods of design resistance for a single bolt subjected to different loading modes(carrying load in shear, tension and combined tension and shear) according to JGJ82-2011.

According to the provision of JGJ82-2011,a thicker washer or a continuous cover plate with standard hole should be adopted for the design of bolted connection with non-standard hole. Meanwhile, the washer or cover plate should meet the requirements as follows:

1. The thickness of washer or cover plate should be not less than 8mm for a bolt with nominal diameter not more than 24.
2. The thickness of washer or cover plate should be not less than 10mm for a bolt with nominal diameter large than 24.
3. The thickness of washer or cover plate should be not less than the thickness of connected plate(inner plate) for the connection of cold-formed thin-walled steel plate.

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Table 6. Design resistance of a single bolt subjected to different loading modes according to JGJ82-2011

	Friction type connection
Shear resistance of connection	$N_v^b = (K_1 K_2 n_f \mu P)\beta$ (8) Where: k_1=0.8 for the cold-formed steel structure plate(thickness less than 6mm), =0.9 for other cases. K_2=1.0 for standard size holes, =0.85 for oversized holes, =0.70 for slotted holes perpendicular to the direction of the load =0.60 for slotted holes parallel to the direction of the load, n_f =number of slip planes for load transference μ_f=slip factor as in Table 7 ,8
	Note: β is the influence coefficient of connection length. $\beta = 1.1 - (l_1/150d_0)$, l_1 is the length of connection, (with the same meaning of l_j as is shown in Figure 3) d_0 is the diameter of bolt hole
Tension resistance of connection	T_{df} = 0.8P=0.8(0.608$f_u A_e$)=0.486 $f_u A_e$ (9) where, f_u is the ultimate tensile stress of the bolt A_e is the effective area(the area at bottom of the threads)
Combined shear and tension for connection	$\frac{N_v}{N_v^b} + \frac{N_t}{N_t^b} \leq 1.0$ (10)
	Note: V_{sf}, T_f , V_{sb}, T_b are shear and tension design values of a high-strength bolt; V_{dsf}, T_{df} V_{dsb}, T_{db} are the shear and tensile bearing capacity design values of the corresponding type of bolt.

Table 7 Slip Coefficient μ for steel friction surface（JGJ82-2011）

Processing Methods on Surface		steel grade			
		Q235	Q345	Q390	Q420
Common Steel Structure	Sand blast(Shot blast)	0.45	0.50	0.50	0.50
	Red rust after sand blast(Shot blast)	0.45	0.50	0.50	0.50
	Rust removal by wire brush or clean rolled surface untreated	0.30	0.35	0.35	0.40
Cold-formed Thin-walled Steel structure	Sand blast(Shot blast)	0.40	0.45	-	-
	Rust removal for rolling surface of hot rolled steel	0.30	0.35	-	-
	Rust removal for rolling surface of cold-formed Steel	0.25	-	-	-

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Table 8 Slip Coefficient μ for coat friction surface（JGJ82-2011）

Type of coat	The requirement of surface treatment	The thickness of coat(mm)	Slip Coefficient μ
Inorganic Zinc -rich paint	Sa2 1/2	60-80	0.40
ZINGA paint			0.45
Anti-skid and anti-rust Zinc silicate paint		80-120	0.45
Polyurethane zinc-rich paint or Alkyd zinc primer of iron	Min Sa2	60-80	0.15

IV. CONCLUSION

Through the comparison and analysis of the design and calculation theories for high-strength bolted connection with non-standard hole between the two countries, Following observations are made in this study.

1. There are some difference for the concrete meaning of non-standard hole between the design specifications of China and Indian. The configuration of bolt arrangement is more compact in Indian code.

2. Under the case of properly using of washer, the impact of hole type to the tension resistance of bolted connection is ignored in both the specifications of China and Indian.(as is shown in Equation of 4,5 and Equation 9)

3. In the process of confirming the shear resistance of high-strength bolted connections, the coefficient of hole type is taken into account in both the specifications of two countries. The parameters of K_{h1}, K_{h2} (as is shown in Equation 1 and Equation 2a) and K_2(as is shown in Equation 8) show the influence of hole type on the shear resistance of bolted connections. Considering the difference of the configuration for the bolt hole in two countries, there are some variances for the specific value of the parameters.

4. As for the combined stress of shear and tension, the interaction between shear and tension is taken into account in both the codes of two countries, but the interrelated relation is different. 1/4 circle correlation is adopted in Indian code(IS 800:2007), while, in Chinese specification (JGJ82-2011), it is linear correlation.(as is shown in Equation 6, 7 and 10, respectively)

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