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Study on applicability of high durability friction grip joints with high strength countersunk head bolts for steel bridge structures

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Synopsis

The authors focused on the high strength bolted friction grip joints with countersunk head bolts which can finish the surface of the connection plate flat smoothly and prevent from functional depression due to corrosion. Firstly we carried out Finite Element Analysis in order to evaluate the contact pressure of double shear connected friction joints with countersunk heads varying the angle of countersunk head. Secondly, we have compared the slip strength of the joints which has the optimum countersunk head angle with that of the joint with the normal high strength bolt through the standard slippage test considering variation of plate thickness and the yield strength of the base and splice plates. As a result, it has concluded that the slip strength of the joints with countersunk heads exceeds the required design slip strength which has specified in JSHB and that its slip coefficients is about 10% lower than that with normal head bolts.

KEYWORDS: Countersunk head bolt; contact pressure; slippage test; slip coefficient; slip to yield resistance ratio

1. Introduction

High strength bolted friction grip joints have been generally applied to connections of the steel structures from the viewpoint of economical rationality and reliability. The paint on the connection tends to deteriorate due to rust or shortage of the thickness of the paint at the corner edge. Because corrosion is accelerated at a place where drainage is poor and water is readily stagnant (See Pic.1). Moreover, asphalt pavement on the steel deck tends to be damaged by the existence of the bolt heads in it.

Therefore, the authors focused on the high strength bolted friction grip joints with countersunk head (See Pic.2) which can finish the surface of the splice plate flat smoothly and prevent from functional decline due to corrosion.

However joints with high strength countersunk head bolt has been already applied to the bearing type of the connection, there is almost no research paying attention to the friction grip joints with countersunk head bolts. When employing a friction grip joints with countersunk head bolts, it is necessary to verify the performance of the joint which can satisfy the required functions as a connection.

In this study, firstly we carried out FEA (Finite Element Analysis) varying the angle of countersunk head in order to evaluate the contact pressure of double shear connected friction joints with countersunk heads. Also, we have investigated the influence on load transferring mechanism by using countersunk head bolt for frictional joints. Secondly, we have compared the slip strength of the joints which has the optimum countersunk head angle with the normal high strength bolts through the standard slippage test focusing on variation of the plate thickness, the yield strength of the base and the splice plates.

Pic.1 Corrosion damage of joint of steel pier

Pic.2 High strength countersunk head bolt

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2. Mechanical Behavior from FEA

2.1 Outline of FEA and FE models

The axisymmetric FEA was conducted by ABAQUS Standard 6.9[1]. Double shear connected joint are dealt with in the analysis. .

The countersunk head bolt for FEA is shown in Fig.1. In order to evaluate the slip strength with countersunk head bolts, the angle of countersunk head is changed as 60, 70, 80, 90, and 110 degrees. For a comparison, the joint with the hexagon head bolt shown in Fig.2 is also dealt with. All of analytical cases in this analysis are tabulated in Fig.1 and 2.

An example of the FEA model, CD-90 is shown in Fig.3. The thickness of the splice plate and the base plate is 16mm and 32mm respectively, and the length of the splice plate and the main plate is 50 and 70 mm respectively referring to the minimum spacing distance between bolts specified in Ref. [2] .Diameter of the bolt hole is 24.5 mm, which is the standard value also specified in Ref. [2].

A contact boundary which can consider contact, friction, and separation is installed into the analytical surface between the splice and the base plate.

In order to clarify distribution of the contact pressure on the contact surface, the area where two surfaces are expected to be contact has fine mesh division. Friction coefficient for the contact surface is both 0.5 between the splice and the base plate, and also between the splice and countersunk bolt head surface. Design bolt axial force 205kN for F10T (M22) is installed into the bolt. The steel material is SS400($\sigma_y=235\text{MPa}$), elastic modulus E is $2 \times 10^5 \text{MPa}$, and poisson's ration is 0.3. The FE model of the joint with hexagon head bolt (HD model) is also shown in Fig.4. Dimensions of the splice plate and the base plate are the same of CD series.

case name	Angle of countersunk head θ (degree)	Diameter of bolt neck d (mm)	Diameter of bolt head D (mm)	Curvature of bolt head and bolt neck R (mm)	Thickness of bolt head H (mm)
CD-60	60	22.0	34.7	3.0	11.0
CD-70	70	22.0	37.5	3.0	11.0
CD-80	80	22.0	40.5	3.0	11.0
CD-90	90	22.0	44.0	3.0	11.0
CD-110	110	22.0	53.5	3.0	11.0

Fig.1: Countersunk head bolt

case name	Diameter of bolt neck d ₁ (mm)	Diameter of bolt head B (mm)	Diameter of bolt head C (mm)	Diameter of bolt head D (mm)	Curvature R (mm)	Thickness of bolt head H (mm)
HD	22.0	36.0	41.6	34.0	3.0	14.0

Fig. 2: Hexagon head bolt

2.2 Analytical results and discussions

2.2.1 Contact pressure distribution

Distribution of contact pressure at the contact surface between the splice and the base plate obtained from the FEA is shown in Fig.5. The vertical axis is contact pressure (MPa) and horizontal axis is the distance from the hole edge. As shown in Fig.5, it is found that high contact pressure over yield strength occurs around the hole edge in CD series comparing with that of HD. Its maximum value is that of CD-110. As the angle of countersunk head increase, contact pressure tends to become higher around the hole edge. On the other hands, the existence area of contact pressure of CD series is smaller than that of HD. The minimum case of the existence area of contact pressure is CD-110. Therefore, the FEA results indicate that contact pressure of CD series is higher than that of HD and is distributed in smaller area.

2.2.2 Shear stress distribution

Fig.6 shows the shear stress distribution on the contact surface. Arrow diagram of nodal force at the contact surface and the deformation are also shown in Fig.7. To understand deformation characteristics with ease, each displacement is multiplied by 100. It is understood from these two Figures that high shear stress occurs

near the bolt hole edge .due to the friction force by the local deformation of the splice plate.

2.2.3 Maximum stress

An example of stress contours of Von-Mises of CD-90 is depicted in Fig.8. High stress concentration over the yielding stress between the countersunk head and the shank is observed when the design bolt axial force, 205kN is applied. Maximum stresses of all cases when the design bolt axial force is applied are tabulated in Table 1. It is found that the maximum stress of CD series is higher than that of HD, and that the case that the angle of countersunk head is 90 degrees shows lowest maximum stress. The reason is considered that the stress at the corner part between bolt shank and bolt head depends on the magnitude of the contact force along the perpendicular direction to the countersunk head and the distance from here to the applied point. It has concluded that the most suitable angle of the countersunk head is 90 degrees.

Fig.3: FEA model for CD-90

Fig.4: FEA model for HD

Fig.5: Contact pressure distribution on the contact surface

Fig.6: Shear stress distribution on the contact surface

Fig.8: Stress contours of Mises(CD-90)

Table 1: Maximum stress

case name	Maximum stress ($\times 10^3$, MPa)
CD-60	1.593
CD-70	1.416
CD-80	1.227
CD-90	1.196
CD-110	1.364
HD	1.056

3. Slippage test

3.1.Outline of the slippage test and specimens

In order to clarify the behaviour of friction joints with high strength countersunk head bolts for steel bridge structures, we have carried out the standard slippage test taking into account for steel material grade, slip to yield resistance ratio β , and the number of contact surface(double or single shear). Geometrical configurations of the specimens for the slippage test are shown in Fig.9. The structural parameters of the specimens are listed in Table 2. The angle of the countersunk head is fixed 90 degrees based of the analytical results described in chapter 2 and in Ref. [3]. Contact surface of the plates are painted by inorganic zinc-rich paint with more than 75 μ m thickness. Pic.3 shows the specimen with the countersunk head bolts. Structural parameters in this experiment are explained in detail as follows;

- Steel material grade (SS400, SM490) : Investigated is influence of local yielding around the bolt holes on the slip resistance.
- Slip to yield resistance ratio β : This is for clarification of the difference of mechanical behaviour between slipping type($\beta < 1.0$) and yielding type($\beta > 1.0$). β_d (See Table2) is the ratio calculated by the friction coefficient(0.5) and the nominal yield resistance. β_e is the ratio calculated by the slip coefficient obtained from the experiment for the specimen of slipping type and yield stress obtained from the material test (See Table 3).
- Number of the contact surface (double or single shear): Difference of behaviour caused by different number of the contact surface and eccentricity between the base and splice plate is investigated.

In the experiment, bolt axial force for the hexagon head bolt is measured by the strain gauge which glued on the bolt shank as shown in Pic.4. Bolt axial force for the countersunk head bolt is also measured from the strain gauges glued on the bolt head in consideration of preventing from stiffness decrease by the holes for the strain gauge wires as shown in Pic.4. The slippage test is executed by using universal testing machine (1,000kN) of Osaka City University. To clarify the slip behaviour with ease, fixed and slipped sides are set in advance by changing the bolt axial force. The bolts at fixed side are tightened with 10% higher of the design bolt axial force. Tensile load is applied until the major slip at the slipped side is observed. As shown in Fig.10, measured are relative displacements between the base plate and the splice plate, applied tensile load and bolt axial forces. In this experiment, the definition of slip occurrence is when the relative displacement at δ_3 becomes 0.2 mm in accordance with the specification of Architectural Institute of Japan [4].

Fig.9: Geometrical configurations of the Specimen for slippage test (mm)

Table 2: List of specimens and experimental parameters

	Base plate		Splice plate		Number of the contact surface	Slip to yield resistance ratio β_d	Slip to yield resistance ratio β_e	Number of the specimen	Yield strength of base plate Py (kN)
	grade	mm	grade	mm					
Countersunk head bolt									
CD-12M12S	SM490	12	SS400	12	double	1.39	1.72	3	346
CD-12M12M	SM490	12	SM490	12		1.39	1.72	3	346
CD-16M12M	SM490	16	SM490	12		1.04	1.28	3	466
CD-32M16M	SM490	32	SM490	16		0.52	0.66	3	899
CS-12S16M	SS400	12	SM490	16	single	1.08	1.21	3	230
CS-12M16M	SM490	12	SM490	16		0.78	0.96	3	309
CS-16M22M	SM490	16	SM490	22		0.57	0.69	3	429
Hexagon head bolt									
HD-12M12S	SM490	12	SS400	12	double	1.39	1.93	3	346
HD-12S12M	SM490	12	SM490	12		1.39	1.93	3	346
HD-16M12M	SM490	16	SM490	12		1.04	1.43	3	466
HD-32M16M	SM490	32	SM490	16		0.52	0.74	3	899
HS-12S16M	SS400	12	SM490	16	single	0.96	1.21	3	257
HS-12M16M	SM490	12	SM490	16		0.70	0.96	3	346
HS-16M22M	SM490	16	SM490	22		0.52	0.73	3	466

(a) surface of countersunk hole

(b) After tightened of bolts

Pic.3: Overview of the Specimen

(a) Hexagon head

(b) Countersunk head

Pic.4: Strain gauges for bolt axial force measurement

Table 3: Results of the material test

Material	Thickness	Yield strength	Tensile strength	Elastic modulus	Poisson's ratio
	mm	N/mm ²	N/mm ²	N/mm ²	
SM490	32	338.2	500.5	2.07×10^5	0.28
SM490	22	344.0	533.6	2.11×10^5	0.29
SM490	16	350.5	526.2	2.10×10^5	0.29
SM490	12	347.0	516.5	2.09×10^5	0.29
SS400	12	275.8	434.5	2.09×10^5	0.29

(a) Countersunk head bolt

(b) Hexagon head bolt

Fig.10: Dimensions of the specimen and measured location of relative displacements

3.2.Experimental Results and discussions

3.2.1.Definition of the slip coefficient

Experimental results are summarized in Table.4. Each obtained slipping resistance force and slip coefficient are tabulated. The slip coefficient μ_1 is the ratio of the slipping resistance force divided by the total bolt axial

force before slippage test as shown in the equation (1),

$$\mu_1 = \frac{P}{m * n * N_1} \quad (1)$$

μ_1 : slip coefficient

P : slipping resistance force at $\delta = 0.2\text{mm}$ (kN)

m : number of the splice plate

n : number of the bolt

N_1 : average of two bolts axial force before slippage test(kN)

The slip coefficient μ_0 is the ratio of the slipping resistance force divided by design bolt axial force as shown in the equation (2),

$$\mu_0 = \frac{P}{m * n * N_0} \quad (2)$$

N_0 : design bolt axial force (205kN)

The slip coefficient μ_2 is the ratio of the slipping resistance force divided by total bolts axial force when slipping occurs as shown in the equation (3),

$$\mu_2 = \frac{P}{m * n * N_2} \quad (3)$$

N_2 : average bolt axial force at slip (kN)

3.2.2. Effectiveness of the steel material grade

In order to clarify the slip resistance under various steel grades (SS400, and SM490), it is compared with the slip coefficient of CD-12M12M and CD-12M12S as yielding type. Also CS-12M16M and CS-12S16M as slipping type are investigated.

As shown in Table.4, slip coefficient of CD-12M12M ($\mu_1=0.46$) is approximately 2% higher than that of CD-12M12S ($\mu_1=0.45$). In addition, CS-12M16M ($\mu_1=0.51$) is also approximately 11% higher than that of CS12S16M ($\mu_1=0.46$).

These results indicate that slip coefficients becomes higher by using high strength steel SM490 for the splice plate with countersunk bolt holes. The improvement of the slip coefficient for the slipping type by using higher strength steel is more effective than that of the yielding type.

3.2.3. Slip to yield resistance ratio β and number of the contact surface

Fig.11 shows the relationship between slip coefficient μ_1 and slip to yield resistance ratio β_e . It is observed that slip coefficient μ_1 has a tendency to get lower by increase of β_e regardless of bolt type, steel material grade, and number of the contact surface.

Maximum slip coefficient μ_1 is 0.66(CD-32M16M)/0.74(HD-32M16M) for CD/HD series respectively. These are both slipping type. Minimum slip coefficient μ_1 is 0.45(CD-12M12S) /0.48(HD-12M12S) for CD/HD series respectively. These are both yielding type. It is summarized that slip coefficients μ_1 for the countersunk head specimens are approximately 10% lower than those for hexagon head specimens in spite of number of the contact surface.

The reason is considered that the contact pressure of the joints with countersunk head reduce due to progress

Fig.11: Relationship between μ_1 and β_e

Fig.12: Relationship between μ_2 and β_e

Table 4: Summary of experimental results

Specimen	Slip Resistance P	Axial force before test N1	Axial force at slipping N2	Slip coefficient (P/N1)		Slip coefficient (P/205kN)		Slip coefficient (P/N2)		decreasing rate of axial force	
	kN	kN	kN	μ_1	Ave.	μ_0	Ave.	μ_2	Ave.	Ratio	Ave.
Double shear series											
CD-12M12S	364.79	208.97	186.96	0.44	0.45	0.44	0.45	0.49	0.50	0.89	11.2%
	366.05	207.69	186.89	0.44		0.45		0.49		0.90	
	386.07	209.30	182.08	0.46		0.47		0.53		0.87	
HD-12M12S	363.91	192.37	178.15	0.47	0.48	0.44	0.46	0.51	0.54	0.93	9.9%
	387.99	195.99	168.83	0.49		0.47		0.57		0.86	
	379.76	197.95	181.39	0.48		0.46		0.52		0.92	
decreasing rate of slip coefficient (C/H)					6.2%		2.2%		7.4%		
CD-12M12M	384.51	209.20	189.91	0.46	0.46	0.47	0.46	0.51	0.50	0.91	9.8%
	385.99	208.05	183.75	0.46		0.47		0.53		0.88	
	368.44	208.08	190.50	0.44		0.45		0.48		0.92	
HD-12M12M	389.26	201.03	183.66	0.48	0.48	0.47	0.47	0.53	0.52	0.91	8.2%
	378.49	202.23	186.43	0.47		0.46		0.51		0.92	
	invalid										
decreasing rate of slip coefficient (C/H)					4.2%		2.1%		2.7%		
CD-16M12M	422.93	210.67	191.31	0.50	0.53	0.52	0.55	0.55	0.59	0.91	10.2%
	460.29	214.18	192.07	0.54		0.56		0.60		0.90	
	474.37	211.39	187.74	0.56		0.58		0.63		0.89	
HD-16M12M	469.89	198.80	181.42	0.59	0.60	0.57	0.58	0.65	0.66	0.91	9.6%
	484.38	201.61	182.43	0.60		0.59		0.66		0.90	
	473.05	198.95	178.15	0.59		0.58		0.66		0.90	
decreasing rate of slip coefficient (C/H)					11.7%		5.2%		9.7%		
CD-32M16M	579.87	218.96	200.45	0.66	0.66	0.71	0.72	0.72	0.72	0.92	8.4%
	593.38	220.53	202.19	0.67		0.72		0.73		0.92	
	588.19	228.85	209.69	0.64		0.72		0.70		0.92	
HD-32M16M	594.56	202.13	187.59	0.74	0.74	0.73	0.73	0.79	0.79	0.93	7.1%
	invalid										
	602.19	203.97	189.85	0.74		0.73		0.79		0.93	
decreasing rate of slip coefficient (C/H)					10.8%		1.4%		9.2%		
Single shear series											
CS-12S16M	invalid				0.46		0.48		0.58		20.6%
	195.20	216.53	171.96	0.45		0.48		0.57		0.79	
	198.72	211.42	167.76	0.47		0.48		0.59		0.79	
HS-12S16M	invalid				0.52		0.51		0.62		17.2%
	202.30	202.11	171.21	0.50		0.49		0.59		0.85	
	213.53	200.34	162.20	0.53		0.52		0.66		0.81	
decreasing rate of slip coefficient (C/H)					11.5%		5.9%		7.1%		
CS-12M16M	237.48	213.85	174.41	0.54	0.51	0.58	0.56	0.66	0.62	0.82	17.6%
	224.49	228.46	188.73	0.49		0.55		0.59		0.83	
	223.31	218.53	181.55	0.51		0.54		0.61		0.83	
HS-12M16M	234.17	214.29	181.69	0.55	0.54	0.57	0.55	0.64	0.63	0.85	13.7%
	219.89	203.11	178.30	0.54		0.54		0.62		0.88	
	invalid										
decreasing rate of slip coefficient (C/H)					5.6%		-1.8%		1.3%		
CS-16M22M	264.10	215.49	182.37	0.61	0.57	0.64	0.62	0.72	0.65	0.85	12.9%
	252.40	236.12	209.00	0.53		0.62		0.60		0.89	
	247.25	222.14	196.00	0.56		0.60		0.63		0.88	
HS-16M22M	257.65	212.71	189.32	0.61	0.61	0.63	0.63	0.68	0.68	0.89	11.0%
	invalid										
	invalid										
decreasing rate of slip coefficient (C/H)					6.6%		1.6%		4.1%		

of local yielding around the countersunk bolt holes by increasing applied tensile load.

Slip coefficients of the double shear series are higher than those of the single shear series regardless of type of the bolt head. This is caused by that the contact pressure of the single shear joints is lower than that of the double shear joints because of eccentric bending between the base plate and the splice plate.

Fig.12 shows the relationship between slip coefficient μ_2 and slip to yield resistance ratio β_e . It can be confirmed that the slip coefficients μ_2 of all specimens are higher than the slip coefficients μ_1 .

It is also found that the variation of the slip coefficients μ_2 under the same slip to yield resistance ratio β is

smaller compared with the variation of the slip coefficients μ_1 . Because the slip coefficients μ_2 are evaluated by the slipping resistance force and total of bolt axial forces at slip occurrence, these values become higher and the variation becomes smaller by elimination of the bolt axial force decreasing during load transfer. It is concluded from the experimental results that the slip strength of the joints with countersunk head bolts exceeds the design required slip strength which has specified in JSHB by the slip coefficient 0.45.

4. Conclusions

This paper deals with the applicability of high strength bolted friction grip joints with countersunk head bolts for steel bridge structures which can finish the surface of the connection plate flat smoothly and prevent from functional depression due to corrosion. The main conclusions obtained are as follows,

- (1) In order to clarify distribution of the contact pressure on the contact surface of the joints with countersunk heads, the FEA was carried out varying the angle of countersunk head. It has concluded that the most desirable angle of the countersunk head is 90 degrees from the viewpoint of distribution of the contact pressure and stress concentration of the bolt.
- (2) In the cases of CD series, the FEA results indicate that high contact pressure over yield strength occurs around the countersunk edge of the bolt hole and the distributing area is small comparing with HD series.
- (3) In order to clarify the behavior of friction joints with countersunk head bolts, the standard slippage test were executed considering variation of plate thickness and the yielding strength of the base and splice plates.
- (4) It has concluded from the experimental results that the slip strength of the joints with countersunk head bolts exceeds the design slip strength specified in JSHB calculated by the slip coefficient 0.45 and that its slip strength is about only 10% lower than that with normal head bolts. It is caused by that the contact pressure of the joints with countersunk head reduce due to progress of local yielding around the bolt holes as increasing applied tensile load.
- (5) In order to apply such joints to practical joints of bridge members, further researches on applicability of the over-sized holes and multiple arrangements of countersunk bolts and so on are should be required.

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