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Experimental Study on Shear Strength of Friction-Type High-Tension Bolted Joints at Elevated Temperature

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ABSTRACT

Fire engineering design based on numerical analysis of actual fire behavior of building structures was proposed in Japan as early as 1989. The second author and his colleagues performed a numerical study on fire resistance of steel structures of 48 high-rise buildings exposed to compartment fire, and their results indicate that steel structures that are designed against seismic load exhibit fire resistance up to nearly 600℃. Further, they report when a fire occurs in a building of steel structure, steel structural members exposed to fire exhibit large deformations at their ends, derived from thermal elongation, in combination with severe restraint by adjacent structural members. Analysis of thermal stresses and deformation is based on the assumption that beam-column connections do not lead to failure. For proper fire engineering design of steel structure, the bearing strength of joints at elevated temperature must be clarified.

It is known that bearing strength of high-tension bolted joints reduce over 350℃ and reach to zero over 600℃. Therefore, it is necessary for fire engineering design of steel structures to clarify the shear strength of high-tension bolts at elevated temperature. In this study, tension tests of friction type high-tension bolted joints are conducted at constant temperatures ranging from room temperature to 650℃.

KEYWORDS
Friction-Type High-Tension Bolted Joint, Elevated Temperature, Experiments, Shear Strength, Tensile Strength, Slip Load

INTRODUCTION

In Japan, building elements are usually selected by comparison between the required fire endurance time[1] and the time to failure as determined by standard fire-resistance tests[2]. Meanwhile, fire engineering design based on numerical analysis of actual fire behavior of building structures was proposed in Japan as early as 1989[3]. The second author and his colleagues performed a numerical study on fire resistance of steel structures of 48 high-rise buildings exposed to compartment fire, and their results indicate that steel structures that are designed against seismic load exhibit fire resistance up to nearly 600℃[4]. Further, they report that when a fire occurs in a building of steel structure, steel structural members exposed to fire exhibit large deformations at their ends, derived from thermal elongation, in combination with severe restraint by adjacent structural members. Analysis of thermal stresses and deformation is based on the assumption that beam-column connections do not lead to failure. For proper fire engineering design of steel structure, the bearing strength of joints at elevated temperature must be clarified. The object of the present study is to determine the bearing strength of a friction-type high-tension bolted joint at elevated temperature.

Slip load of a friction-type high-tension bolted joint exposed to fire heating is reduced by the relaxation of bolts and steel plate. Experimental studies on slip load show that slip of high-tension bolted joints occurs at approximately 350℃[5),6]. These studies were conducted under the conditions that the allowable temperature for steel structural members is limited to below av. 350℃ and max. 450℃. Therefore, these experiments were carried out within the range of about 500℃. Meanwhile, design of steel structures within the range of about 600℃ has been possible[7]. At this high temperature, a friction-type bolted joints become a bearing –type joints. The shear strength of a joint consisting of fire-resistant bolts is clarified by experiments up to 800℃[8], but few data are available on shear strength of a conventional high-tension bolted joint. The purpose of this experimental study is to obtain fundamental data on ultimate shear strength of friction-type high-tension bolted joints at constant temperatures ranging from room temperature to 650℃.

TENSILE TESTS OF BOLT MATERIALS

The bolts employed in the present study are S10T-type torque-control bolts prepared in accordance with the JSS II-09-1996[9]. In the S10T-bolts, proof stress≥900 N/mm^2, tensile strength=1000～1200 N/mm^2, elongation≥14%, and reduction in area≥40%[9]. Specimens for tensile testing are cut out from S10T-bolts of 22 mm diameter. Figure 1 shows the shape and dimensions of a specimen. Tensile tests are carried out up to 700℃ in accordance with JIS G

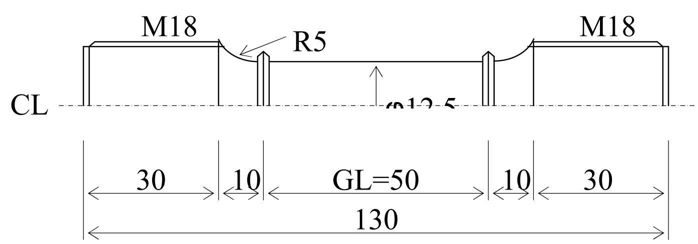


Figure 1. Shape and Dimensions of Specimen: Tensile Tests of Bolt Materials

0567-1993[10]. A cylindrical electric furnace serves as the heating means, and has an inside diameter of 150 mm and a height of 400 mm. Temperatures of bolts are measured by R-type thermocouples. The temperatures at the midpoints of specimens are within ±3℃ of the target temperatures. Tensile tests of bolt materials are carried out with a loading machine in which velocity of displacement is controlled. Specimen deformation is measured with a displacement meter and amplifiers. The rate of strain in the elastic range is 0.3%/minute, and that in the plastic range is 7.5%/minute.

Table 1 and Figure 2 show the results of high-temperature tensile tests. As shown in Fig. 2, proof stress decreases relatively slowly with temperature up to 400℃, and decreased rapidly thereafter. Tensile strength decreases rapidly with temperature over 300℃. The proof stress at 600℃ is about 0.15 times the proof stress at room temperature, and the tensile strength at 600℃ is about 0.25 times the tensile strength at room temperature. Elongation increases rapidly with temperature over 550℃. Photograph 1 shows the specimens subjected to tensile tests of bolt materials at room-temperature and at 600℃. Figure 3 shows the stress-strain curves of bolts. As the rate of strain is increased from 0.3%/minute to 7.5%/minute, stresses increase. This phenomenon is especially apparent at high temperature.

Table 1. Conditions and Results of High-Temperature Tensile Tests of Bolt Materials

	Test Series	Test Temperatures [℃]								
		20	200	300	400	500	550	600	650	700
0.1% Proof Stress [N/mm^2]	No.1	957	868	813	803	333	231	145	75	44
	No.2	1009	815	799	681	331	197	127	80	48
0.2% Proof Stress [N/mm^2]	No.1	959	919	867	817	413	256	164	90	52
	No.2	1011	867	853	735	385	236	149	95	55
Tensile Strength [N/mm^2]	No.1	1025	1063	1037	887	554	404	285	192	127
	No.2	1077	1013	1027	855	568	404	279	193	129
Elongation [%]	No.1	20	19	27	20	32	46	58	74	99
	No.2	19	20	26	23	29	46	62	68	75
Reduction of Area [%]	No.1	70	71	80	81	92	95	97	98	99
	No.2	70	71	80	82	92	95	97	98	98

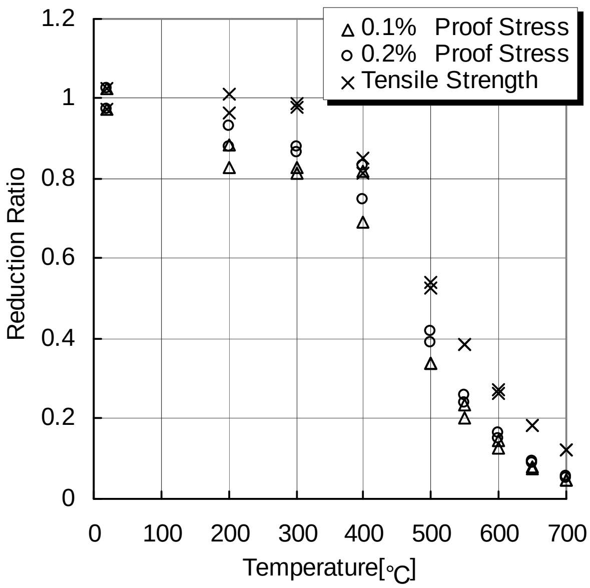


Figure 2. Reduction Ratio of Proof Stress and Tensile strength of Bolts

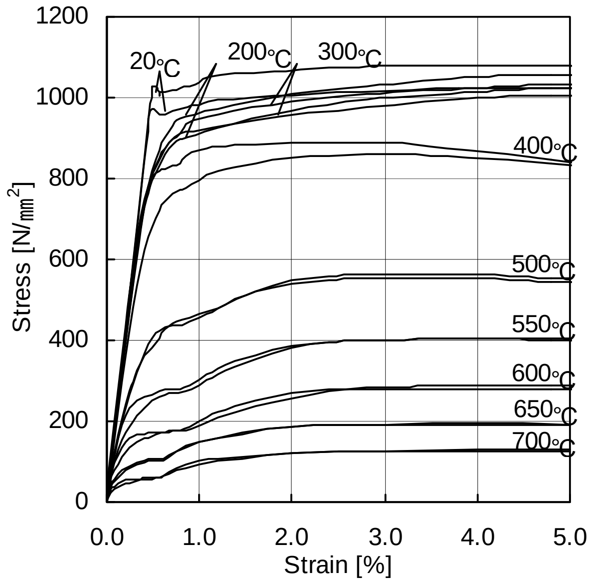
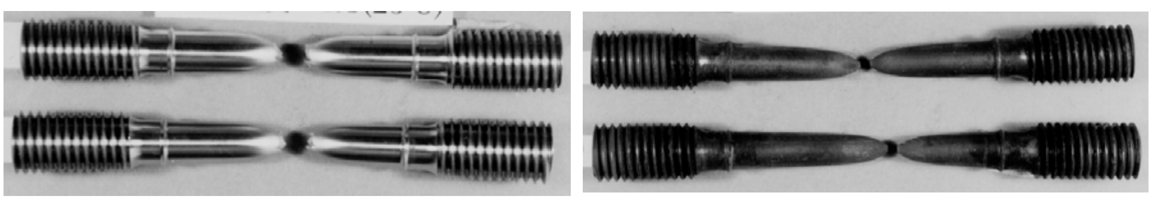


Figure 3. Stress-Strain Curves of Bolts at Elevated Temperature



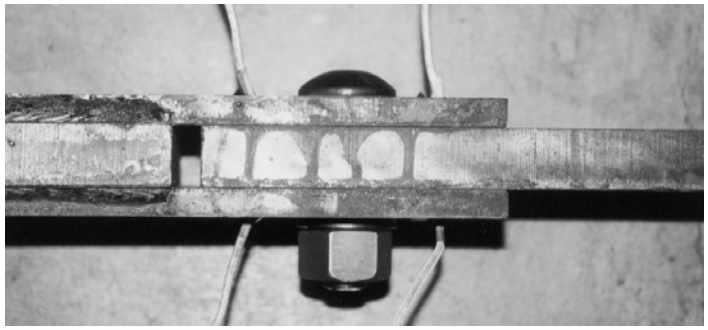
(a) Room Temperature **(b) 600℃**

Photograph 1. Fracture of Bolts Subjected to Tensile Tests of Bolt Materials

TENSILE TESTS OF FRICTION-TYPE HIGH-TENSION BOLTED JOINTS

SPECIMENS AND TESTING APPARATUS

Photograph 2 shows a friction-type high-tension bolted joint used in this experiment. Bolts are of the same type (S10T-M22) produced by the same maker as those used in tensile testing. This joint has two friction surfaces. One surface has a thread of a bolt, and the other surface has a shank of a bolt. Figure 4 shows the shape and dimensions of a specimen. Specimen length is 1400 mm, base plate thickness is 25 mm, and splice plate thickness is 12 mm. The material of these plates is SM490A (yield point≥325N/mm^2, tensile strength=490-610N/mm^2). One joint is a fillet-welded joint, and the other joint is the high-tension bolted joint. Steel friction surfaces are subjected to shot blasting, and painted with a rust accelerant.



Photograph 2. Friction-Type High-Tension Bolted Joint

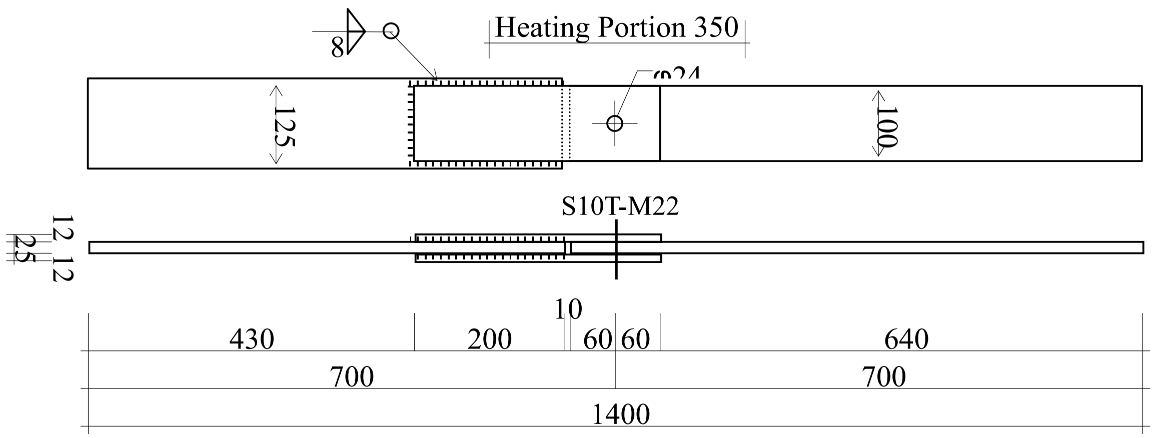
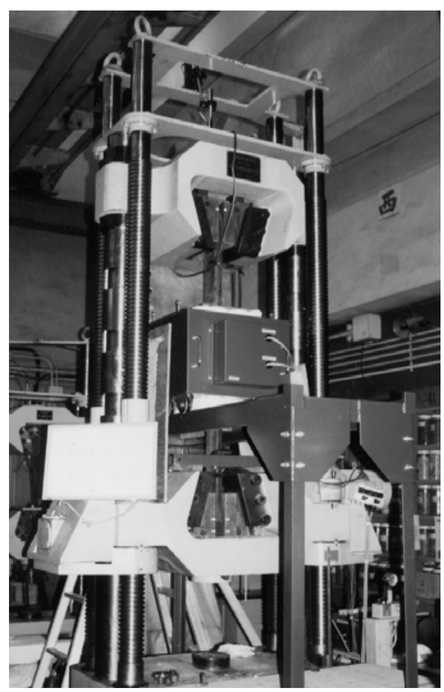


Figure 4. Shape and dimensions of a Specimen of Joint Tests

TEST CONDITIONS

Photograph 3 shows the employed testing machine and furnace. Specimens are tensilely loaded by a 200tf universal testing machine. The relative displacement between the plate of the upper crosshead and the plate of the lower crosshead is measured by a displacement meter (Capacity 50 mm, sensitivity 200μ/mm). This displacement represents total specimen elongation, and includes a slight slip movement in the chucks.

The specimen is heated by a box-shaped electric furnace having a length of about 350 mm and an inside diameter of about 200 mm. Specimen temperature is measured with Cromel-Almel thermocouples which are arranged at 4 points on the

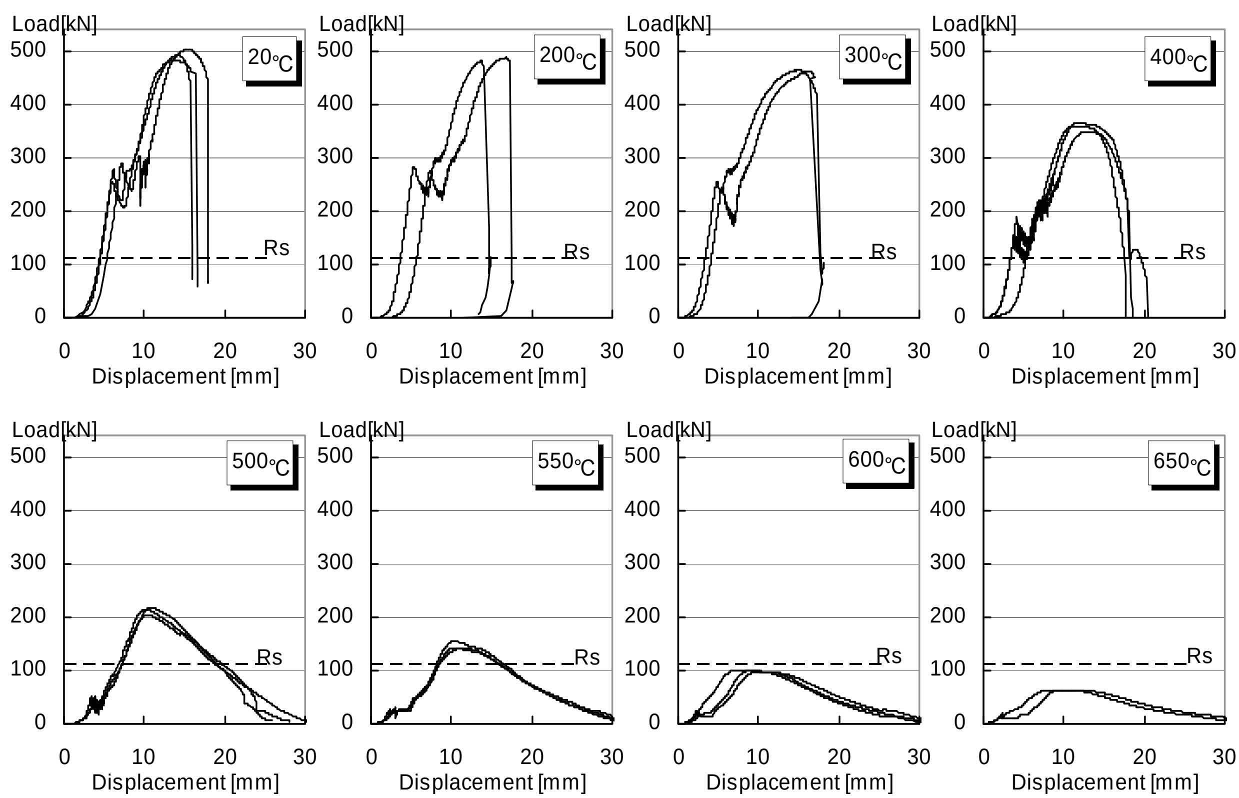


Photograph 3. Testing Machine

specimen surface and whose hot junction are covered with stainless steel foil for protection from radiant heat from the heating panels. The temperatures at the midpoints of specimens are within about ±5℃ of the target temperatures. Joint is protected by stainless net, in order to prevent bolt fracture from breaking the furnace.

RESULTS

Figure 5 shows the tests results of loading and displacement. Before loads reach slip load, load increases in proportion to displacement. After friction joints slip, load increases again and reaches maximum load. In Fig. 5, “Rs” denotes the allowable shear load for sustained load as recommended by AIJ (Architecture Institute of Japan)[11]. In tests conducted within the range of room temperature to 300℃, slip loads are about 2 times Rs and maximum loads are about 4 times Rs. In the test conducted at 400℃, slip loads are about 1.5 times Rs and maximum loads are about 3 times Rs. In tests conducted above 500℃, slip loads are less than Rs. Maximum load decreases with increasing temperature. However, ductility of bolted joints



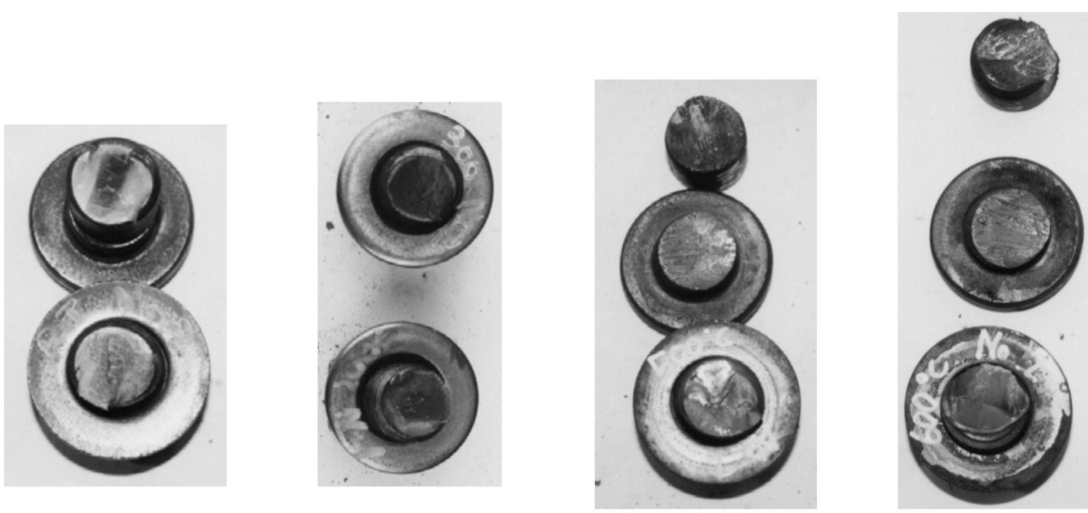
increases with increasing temperature. In tests conducted above 500℃, a crashing sound accompanying bolt fracture was not heard. Table 2 shows the values of slip load and maximum load.

Figure 5. Load-Displacement Curves of Friction-Type High-Tension Bolted Joints

Table 2. Results of Tension Tests of Friction-Type High-Tension Bolted Joints

	Tests Series	Test Temperatures [℃]							
		20	200	300	400	500	550	600	650
Slip Load [kN]	No.1	279	282	255	157	53	28	20	21
	No.2	290	273	245	184	50	21	24	13
	No.3	255			187	51	31	22	-
	Mean	275	278	250	176	51	27	22	17
	Reduction Ratio	1	1.01	0.91	0.64	0.19	0.10	0.08	0.06
Maximum Load [kN]	No.1	480	482	464	359	214	155	97	64
	No.2	502	486	461	348	218	143	101	64
	No.3	490			365	204	141	99	
	Mean	491	484	463	357	212	146	99	64
	Reduction Ratio	1	0.99	0.94	0.73	0.43	0.30	0.20	0.13

Photograph 4 shows fractured sections of bolts subjected to joint tests. The bolts tested within the range of room temperature to 300℃ are fractured only in the thread. The bolts tested above 400℃ are fractured in both the thread and the shank. In tests conducted above 500℃, lines against shear direction appear on the fractured section.



(a) Room Temperature **(b) 300℃** **(c) 500℃** **(d) 600℃**

Photograph 4. Fractured Sections of Bolts Subjected to Joint Tests

Figure 6 shows the bearing strength of friction-type high-tension bolted joints at elevated temperatures. Shear strength denotes the maximum load divided by the two sectional areas of the shear planes, and slip strength denotes the slip load divided by the two sectional areas of the shear planes. The solid line denotes the shear strength, which is obtained by dividing the tensile strength of a bolt material by √3 . The broken line denotes the allowable shear stress for sustained load as recommended by AIJ[11). Slip strength of high-tension bolted joints at 500 ℃ decreases to less than half the allowable shear stress for sustained load. This indicates that beyond 500 ℃ the friction-type joint becomes a bearing member. Near 600℃, the shear strength of the high-tension bolt becomes lower than the allowable shear stress for sustained load. In all probability, bolts are fractured by sustained load beyond 600 ℃. Shear strength approximately corresponds with tensile strength divided by √3.

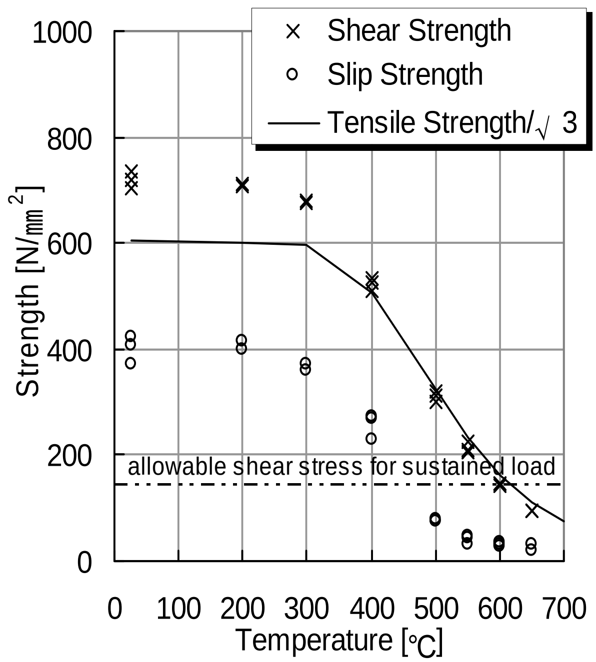


Figure 6. Bearing Strength of Friction-Type high-tension bolted joints

CONCLUSION

In this study, tension tests of friction type high-tension bolted joints are conducted at constant temperatures ranging from room temperature to 650℃. The results are summarized as follows:

1) Beyond 500℃, friction-type high-tension bolted joints become bearing-type joints, because slip load decreases to less than one-half allowable shear stress for sustained load.

2) Near 600℃, the shear strength of a high-tension bolt drops below the allowable shear stress for sustained load.
3) The shear strength of friction-type high-tension bolted joints can be approximated from the tensile strength of the bolt material.

ACNOWLEGMENT

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