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Preload retention performance of bolted connections locked with adhesive

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ABSTRACT

Purpose: The cyclic performance of bolted assemblies locked with adhesive are affected by various parameters, such as pitch type, diameter, surface finish, coating type, pre-torque, and loading type. The purpose of this study is to find out the influence of bolt diameter, coating type and pitch type on the preload retention performance of threaded components under cyclic loading conditions.

Design/methodology/approach: In this experimental research, the effects of various bolt diameters, coating materials (base material, zinc and zinc phosphate) and pitch type on the preload retention performance of bolted joints were tested. The tests were carried out under cyclic loading conditions.

Findings: The highest load cycle was measured at bolts coated with zinc phosphate and the lowest cycle number was measured at zinc coated joints. The fine pitch bolts showed higher retention performance than the coarse pitch ones. To obtain high retention performance, zinc phosphate coated and fine pitch bolts should be used. They offer important economic and technical advantages in cyclic loading conditions. They are resistant to self-loosening under vibration and impact loading.

Research limitations/implications: A pneumatic vibration test machine was designed. This machine can be operated only at 25 Hz. Also, this study contains only experimental results. So, the numerical methods can be used in the future research processes.

Practical implications: The findings of the experimental study are valid for the specific case of the bolted joint designing. The study helps designers to understand the behaviour of bolted joints with locked adhesive.

Originality/value: The main contribution of the study is mostly on the practical side. To the authors' best knowledge, this paper is one of few studies investigating the design of adhesively bonded threaded joint.

Keywords: Anaerobic adhesive; Bonding strength; Thread locking; Cyclic loading

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PROPERTIES

1. Introduction

The joining methods are extremely important in the engineering design. One of the joining methods is a bolted connection. The best known threaded fasteners are bolts, nuts, screws, lag screws, and set screws. Bolts are tightened by turning the nut or the bolt-head. When the torque is applied, the preload and tension occur in the bolt. The tension in the bolt joint should be high enough to prevent it from self-loosening when exposed to impact loading, vibration or thermal cycles [1]. To prevent unwanted loosening of bolts and nuts, there are different mechanical locking methods, such as castle nuts, spring washers, and wire retainer.

Thermal extension and contraction, the stresses due to vibration, impact loading and friction of the joined elements decrease the preload and lead to joint failure [2]. Nowadays, a lot of thread-locking methods are used. The American National Standards Subcommittee B18:20 established three basic locking fastener categories. These are chemical locking, friction locking, and free spinning.

Friction can be increased by influencing surface finish and structure on interfacing surfaces of bolts and nuts [2]. The application of liquid thread lockers on thread increases the friction force as a result of interfacial connections between the bolt and the nut surface [3]. Microscopic gaps are completely filled with adhesive which provides various advantages, such as higher friction coefficient in locking threads, prevention of micro movement and protection of joints from corrosion [4].

Anaerobic adhesives are used to lock threaded joints. They cure to tough solid state when they contact with metal surface. Liquid adhesives fill the gaps of bolt-nuts and cure as thermoset plastics when they contact with metal ions in the absence of oxygen [5]. Generally, anaerobic adhesives are easily applied as liquid on screws-bolts and they are quite effective in maintaining the preload and eliminating self-loosening tendencies [6].

George et al. [7] investigated various materials which are bonded with anaerobic adhesive. The physical properties of the joints and curing process were investigated and it was determined that the curing period changed according to the adherends. The curing periods of aluminium adherends were found to be longer than those of the copper and stainless steel. They emphasized that the composition of the adherend is a substantial parameter for curing since the process is started by metal ions. Also, the curing process has to be controlled with care to obtain the maximum joint strength.

Sekercioglu [8] emphasized that the free surface energy of the adherend is very important and directly influences the adhesive strength. Generally, adherends which have high surface energy provide high bonding strength [9].

In another study [10], the effects of pitch size, bolt diameter and coatings type on bolted joints locked with adhesive were tested. It was found that the bonded area of the joint, type of coating and pitch size significantly affect the joint torque strengths. The highest torque value was measured for a zinc phosphate coated joint. The coarse pitch bolts showed higher torque values than the fine pitch bolts.

Martinez et al. [11] investigated various screw threads and measured theoretical and actual thread length to obtain the stress undergone by the thread when locked with adhesive. The interference line between bolt and nut threads increases with the torque. They reported easier loosening torque and lower friction effects than expected. Break-loose torque can be considered as a criterion for wetting, adhesion and curing in comparative tests. The break-loose torque is a primary torque needed for decreasing or eliminating the axial load in preloaded bolted joints. Generally, there is no direct relationship between self-loosening resistance and break-loose torque. Some firms have produced adhesive products which have different break-loose torques. The break-loose strength is affected by different factors such as bolt diameter, surface finish, length of thread, material and pre-torque [12].

The purpose of this study is to find out the influence of bolt diameter, coating type and pitch type on the preload retention performance of threaded components under cyclic loading conditions.

2. Materials and method

A pneumatic vibration test machine has been designed for this experimental study (Fig. 1). The test machine is capable of transverse shock and vibration by right-left pneumatic cylinders.

It has four main sections which are called as pneumatic cylinder (hammer), guideway, control unit and fitting section of test specimen. The control unit is composed of sub-units such as photocell, load cycle and time counter. The frequency of the machine is about 25 Hz. The loading of test specimen is given in Fig. 2. The bolts and nuts were tightened and preloaded by a dial indicating torque wrench. A complete description of the joint design and testing procedures can be found in [13].

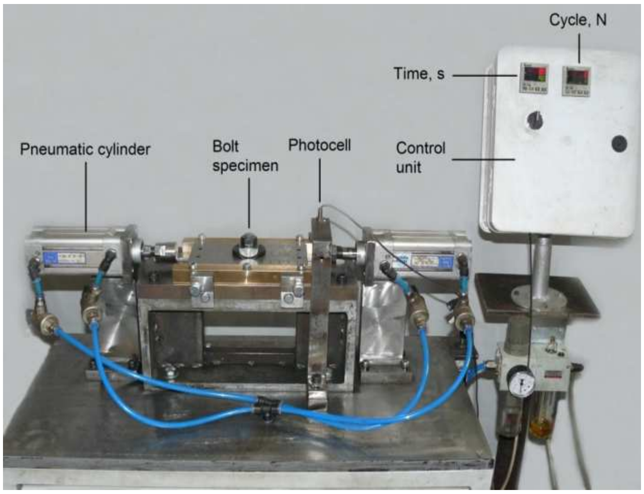

Fig. 1. Pneumatic test machine

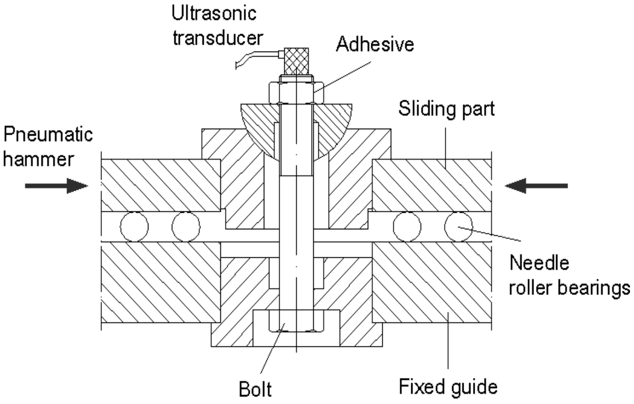

Fig. 2. Loading of the test specimen

The unloaded and loaded lengths on bolted joint were measured by ultrasonic bolt tension meter, which measures the actual elongation produced by tightening a threaded fastener. Displacement-controlled tests were applied. The bolt tension meter can measure the elongation of bolts made of any material from 12.70 mm to 1200 mm in length. The accuracy of the bolt tension meter is 0.001 mm [14].

In order to examine the effect of bolt diameter, three different bolt diameters (M10, M12 and M16) are tested in this experimental study. The bolt material is C21B and the bolt grade is 8.8. Chemical analysis of the base bolt materials is given in Table 1.

The coating material effect on preload retention performance was examined. The base steel, coated with zinc and zinc phosphate bolts-nuts were tested. The immersion technique was applied in zinc phosphate coating and the electrolysis was applied in zinc coating. The iron phosphating and zinc phosphating are different from each other due to the structure of the coating layer. Phosphating is a chemical process that occurs between the metal surface and liquid phosphate. These coatings are used in very different applications, such as increasing corrosion resistance and providing better adhesion conditions. Improving adhesion degree of material surface provides higher torque strength in bolted connections locked with adhesive.

The fine and coarse pitch effects were also tested using M10x1.25 and M10x1.5 bolt joints. Loctite 7063^{TM} was used as a cleaner. The coated and cleaned test specimens were bonded with Loctite 243^{TM} anaerobic adhesive. The nut was tightened onto the bolt by a torque wrench. According to the bonding area, pre-torques of 37, 44 and 56 Nm were applied on seated bolt joints (M10, M12, M16) respectively. The pre-torque values were selected to generate the same preload in each assembly. These tightened and bonded joints were cured at room temperature for 24 h (Fig. 2).

The cured bolt joints were loosened using the pneumatic test stand which can load about 1500 cycles per minute. The elongation changes were measured every 30 seconds via a bolt tension meter. The test conditions are given in Table 2.

Three test specimens were used for each measured cycle. The measured average elongation changes and cycle values are given in Tables 3-5. The preload loss factor (e) is defined in the tables for the comparison of each bolted joint. The formula for (e) is simply:

$$e = \frac{L_i - L_1}{L_2 - L_1} \cdot 100 \qquad (1)$$

where, L_1= unloaded length, L_2= loaded length, L_i= length at load cycle.

Table 1.
Chemical Analysis of the base bolt materials

Element (%)								
C	S	Mn	P	Si	Cr	Mo	Cu	B
0.1900	0.0050	0.7300	0.0090	0.0900	0.1000	0.0200	0.0600	0.0024

Table 2.
Test conditions

Adhesive	Loctite 243 ™
Surface cleaner	Loctite 7063™
Ambient temperature (°C)	20±2
Coated materials	Steel (base), zinc, zincphosphate
Bolt diameter	M10, M12, M16
Pitch type	M10x1.25, M10x1.5
Number of specimen	3[a]
Curing time (h)	24
Input torque (Nm)	M10 M12 M16 37 44 56

[a] Used for each measured value.

3. Results and discussion

3.1. Bonded area

The effect of the bolt diameter on the torque strength was examined. The bonding area was determined by multiplying nut height with the perimeter of the bolt's mean diameter. The variation of the cycle number with bolt diameter for steel, zinc and zinc phosphate coated coarse pitch assemblies is shown in Figs. 3-5.

Although the adhesively bonded area increased about five times, cycle numbers did not show the same increase. The cycle numbers for M10 joints varied slightly but the cycle numbers which were obtained for M16 joints increased, some of which even doubled. The strength of the joint may be unfavourably affected if the bonded area is not fully covered by the liquid adhesive in the bonding process. The adhesive should diffuse onto the adherend surface and cover the bonding area [15].

3.2. Coating type

The number of cycle as a function of the coating type is given in Figs. 6-8. The cycle numbers for M10 coarse pitch connections were slightly affected by the coating type (Fig. 6). As for M12 and M16 coarse pitch connections (Fig. 7-8), lower elongation changes were measured for the same cycle number. The coating type affects the elongation change excessively. The highest elongation changes were measured for the zinc coated specimens. Also, the minimum decrease in preload retention was obtained in zinc phosphate coated specimens.

The free surface energy of liquid adhesive must be lower than that of the adherend's for wetting a surface. An imminent contact is obtained by fully wetting which is provided by molecular attraction forces. Therefore, the type of coating improves adhesion forces and wetting of the adherend quite a lot [15]. The highest preload retention ability was measured for zinc phosphate-coated bolts. The porous structure of zinc phosphate provided higher adhesive strength owing to the improved key effect on adherend surfaces.

3.3. Pitch type

The number of cycle as a function of the pitch type is given in Figs. 9-11. The fine pitch tests were done only for M10 because of the long test time. The cycle numbers of coarse pitch bolts were lower than that of the fine-pitch bolts. The fine pitch threaded bolts showed slightly higher preload retention performances than coarse pitch bolted joints.

Usually, when the bolt perimeter and thread pitch increase, more liquid adhesive is used. The coarse pitch can be wetted more easily than the fine pitch. However, cyclic tests showed that the fine pitch thread locked with adhesive is more usable than the coarse pitch thread. Although cohesive failure was found in almost all fine pitch specimens, some of the coarse pitch specimens showed adhesive failure.

Table 3.
Measured average values for M10 connections

M10x1.5 (coarse)								
Steel (base)			Zinc			Zincphosphate		
L_1*		70.8188	L_1		75.1813	L_1		70.9597
L_2		71.0523	L_2		75.4359	L_2		71.2086
Cycle**	L_i	e	Cycle	L_i	e	Cycle	L_i	e
0	71.0523	100.0	0	75.4359	100.0	0	71.2086	100.0
708	71.0276	89.4	671	75.4174	92.7	712	71.1848	90.4
1387	71.0169	84.8	1354	75.4054	88.0	1421	71.1765	87.1
2076	71.0117	82.6	2008	75.3933	83.3	2131	71.1718	85.2
2770	71.0088	81.4	2669	75.3846	79.9	2833	71.1689	84.0
3444	71.0075	80.8	3327	75.3765	76.7	3545	71.1660	82.9
			4022	75.371	74.6	4256	71.1646	82.3
			4712	75.3676	73.3			
			5379	75.3656	72.5			

M10x1.25 (fine)								
L_1		71.1669	L_1		75.7885	L_1		70.9976
L_2		71.4478	L_2		76.0494	L_2		71.3368
0	71.4478	100.0	0	76.0494	100.0	0	71.3368	100.0
483	71.4332	94.8	708	76.0262	91.1	703	71.3095	92.0
967	71.4256	92.1	1419	76.0178	87.9	1401	71.2999	89.1
1452	71.4150	88.3	2124	76.0101	84.9	2105	71.2961	88.0
2178	71.4091	86.2	2831	76.0042	82.7	2809	71.2930	87.1
2903	71.4077	85.7	3545	76.0014	81.6	3512	71.2910	86.5
3628	71.4064	85.2	4255	75.9990	80.7	4216	71.2891	85.9
4355	71.4056	85.0	4963	75.9976	80.1	4926	71.2884	85.7
5080	71.4047	84.6	5675	75.9961	79.5			
5806	71.4042	84.4						

* L_1, L_2, L_i (mm) ; ** Cycle (N)

Table 4.
Measured average values for M12 connections

M12 (coarse)								
Steel (base)			Zinc			Zincphosphate		
L_1		67.1782	L_1		76.0566	L_1		67.1057
L_2		67.3273	L_2		76.2080	L_2		67.2634
Cycle	L_i	e	Cycle	L_i	e	Cycle	L_i	e
0	67.3273	100.0	0	76.2080	100.0	0	67.2634	100.0
460	67.3097	88.2	426	76.1743	77.8	464	67.2498	91.4
907	67.3017	82.8	886	76.1517	62.8	929	67.2432	87.2
1374	67.2989	80.9	1301	76.1356	52.2	1390	67.2392	84.6
2103	67.2946	78.1	1993	76.1204	42.1	2087	67.2368	83.1
2820	67.2919	76.3	2686	76.1127	37.0	2784	67.2341	81.4
3511	67.2904	75.3	3361	76.1101	35.3	3481	67.2330	80.7
4221	67.2896	74.7	4068	76.1079	33.8	4177	67.2312	79.6
4933	67.2894	74.6	4744	76.1065	32.9	4873	67.2303	79.0
5644	67.2890	74.3	5413	76.1061	32.6	5570	67.2302	78.9

Table 5.
Measured average values for M16 connections

M16 (coarse)								
Steel (base)			Zinc			Zincphosphate		
L_1		89.1706	L_1		88.9465	L_1		87.9192
L_2		89.2784	L_2		89.0580	L_2		88.0433
Cycle	L_i	e	Cycle	L_i	e	Cycle	L_i	e
0	89.2784	100.0	0	89.0580	100.0	0	88.0433	100.0
446	89.2571	80.0	359	89.0225	68.2	450	88.0213	82.2
898	89.2491	72.4	723	89.0099	56.9	904	88.0120	74.8
1354	89.2434	67.2	1084	89.0025	50.3	1354	88.0071	70.9
2019	89.2389	62.8	1438	88.9975	45.8	2032	88.0035	67.9
2692	89.2344	58.3	1794	88.9931	41.8	2712	88.0022	66.9
3352	89.2323	56.2	2157	88.9893	38.5	3393	88.0010	66.0
4022	89.2299	54.0	2876	88.9840	33.8	4076	88.0003	65.4
4679	89.2282	52.4	3579	88.9800	30.2	4758	87.9995	64.8
5332	89.2268	51.1	4289	88.9779	28.3	5440	87.9990	64.3
			5005	88.9773	27.8			
			5724	88.9772	27.7			

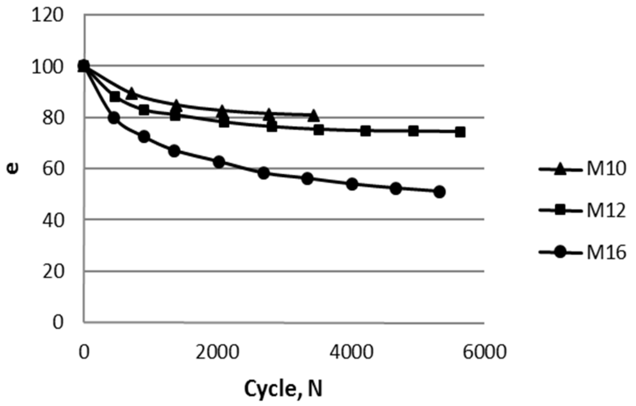

Fig. 3. Number of cycles as a function of bolt diameter for steel (base)

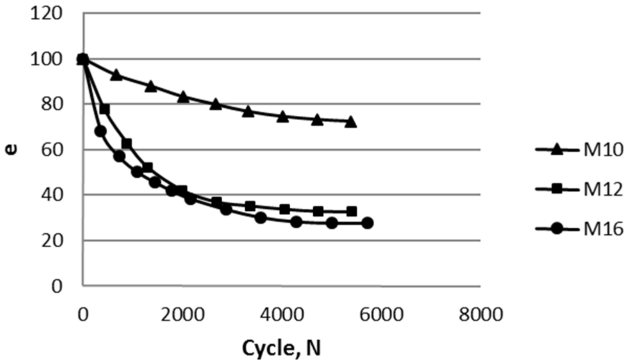

Fig. 4. Number of cycles as a function of bolt diameter for zinc

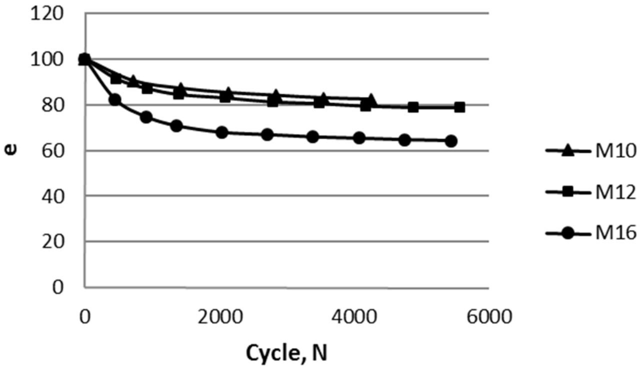

Fig. 5. Number of cycles as a function of bolt diameter for zinc phosphate

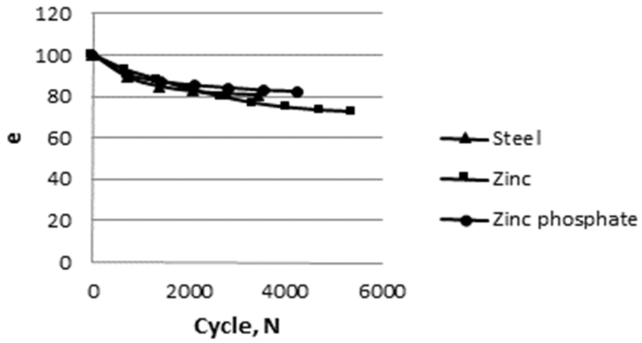

Fig. 6. Number of cycles as a function of coating type for M10

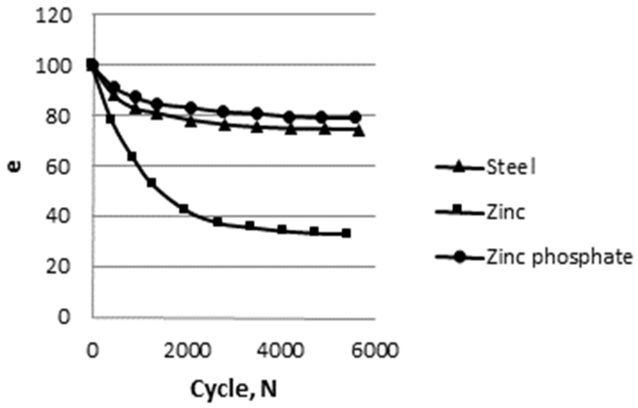

Fig. 7. Number of cycles as a function of coating type for M12

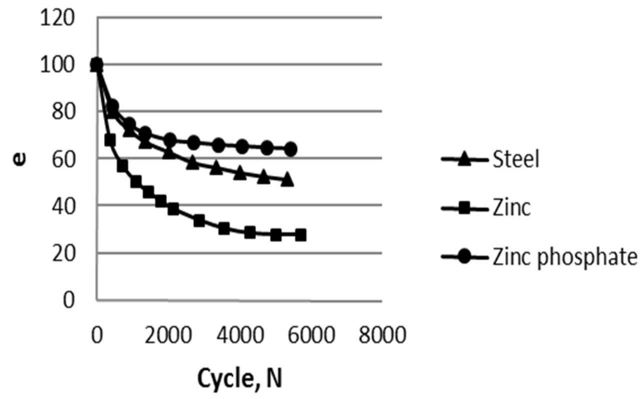

Fig. 8. Number of cycles as a function of coating type for M16

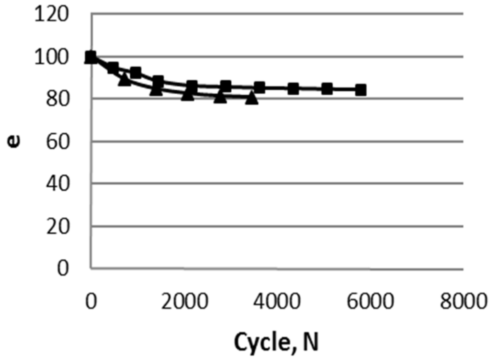

Fig. 9. Number of cycles as a function of pitch type for steel M10

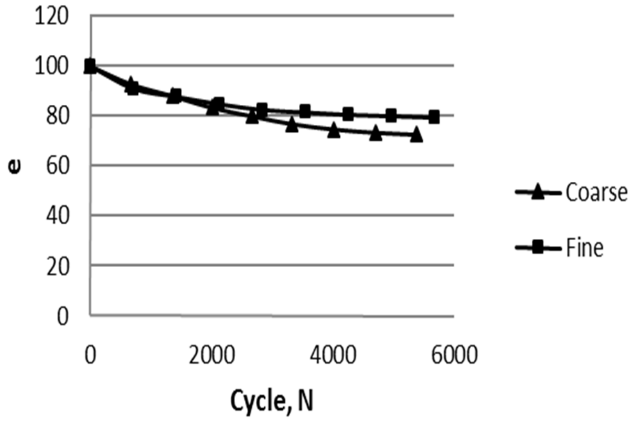

Fig. 10. Number of cycles as a function of pitch type for zinc coated M10

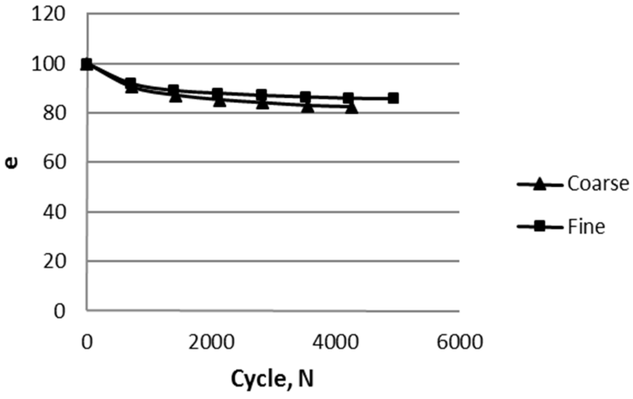

Fig. 11. Number of cycles as a function of pitch type for zinc phosphate coated M10

4. Conclusions

Adhesive bonding is an increasingly attractive alternative locking method of bolted joints. The bonding parameters such as bonded area, chemical compositions of adherend, surface roughness, required strength properties, and environment must be taken into consideration for the optimum design of bolt connections locked with adhesive. In this experimental research, the effects of bolt diameter, coatings and pitch type were examined. As a result, it was found that:

When the bolt size increases, the bolt retention performance decreases a little.

Coating type significantly affects the retention performance. The bolts coated with Zn phosphate showed the maximum cycle numbers.

The fine pitch threaded connections exhibit higher preload retention performance than the coarse-pitch threaded ones.

To obtain high retention performance, zinc phosphate coated and fine pitch bolts should be used. They offer important economic and technical advantages in cyclic loading conditions. They are resistant to self-loosening under vibration and impact loading.

Acknowledgements

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