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Fatigue Life of Extended Hollobolt Connection in Concrete Filled Tube

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Abstract: Studies on the performance of blind bolt connections have been carried out by many researchers. A number of recent studies of new blind bolted connection system have been proposed. The system uses the so called Extended Hollobolt fastener to connect the concrete filled tubular columns. The strength performance of this system has been investigated under both monotonic and cyclic loading. However, the performance of such connections under fatigue loading is still unknown. Therefore, a study to investigate the fatigue performance of Extended Hollobolt was proposed. The main objective of this study is to provide a better understanding of the fatigue life of the proposed blind bolt, consequently provides the design guidance for Extended Hollobolt connection in concrete filled tube. A number of tests were conducted to determine the effect of the frequency and the level of stress range loading on the behaviour of the Extended Hollobolt. The tests were used grade 8.8 bolts subjected to tension. Results show that the frequencies between 0.2 Hz to 5 Hz does affect fatigue life and the stress-range versus fatigue life behaviour of Extended Hollobolt follows the expected pattern of behaviour of standard bolts. The test results of Extended Hollobolt under different stress range then further compared to the normative regulation Eurocode 3. The fatigue life or behaviour of Extended Hollobolt is found to be higher than the theoretical curve of Eurocode 3. Meanwhile, the failure mode of Extended Hollobolt is similar to the standard bolt which is a very positive outcome for blind bolt. However, fatigue life for standard bolt appears to be higher.

Keywords: Blind Bolt, Connection, Fatigue, Frequency, Stress

1. Introduction

The use of structural hollow section (SHS) as columns in multi story construction is attractive due to aesthetic and high strength to weight ratio. The use, however, in allowable capacity is inhibited by problems in providing connections to other members. Early development in overcoming the connection problem is by using the fully welding system, which in some countries is not an attractive site option. Meanwhile, the use of standard dowel, the principal alternative to welding for open section is often impossible in the case of SHS as it requires access to the inside of the tube to facilitate tightening [1]. The use of additional components such as gusset plates and brackets can overcome this problem, but is not generally considered an acceptable solution for aesthetic reasons. Thus, the need for one-sided mechanical connection has arisen in engineering fields and has resulted in the development of several types of so-called blind fasteners. In the context of structural engineering, commercially available blint bolts include the Flowdrill, the Huck high strength blind bolt and the Lindapter Hollobolt (see Fig. 1).

Most of the recent studies have described the behaviour of the blind bolt subjected to monotonic increasing load or cyclic loading. This is because engineers specifying fasteners often based on the requirement on strength (tensile strength, yield strength, proof strength or threaded stripping strength) without taking into account the fatigue and stress concentration [2]. The lack of concern for this issue may cause an unfortunate event as these types of connection are used with a service loading that varies with time. According to Barsom and Stanley [3], most of the structural components are subjected to repeated fluctuating loads whose magnitude is well below the fracture load under monotonic loading.

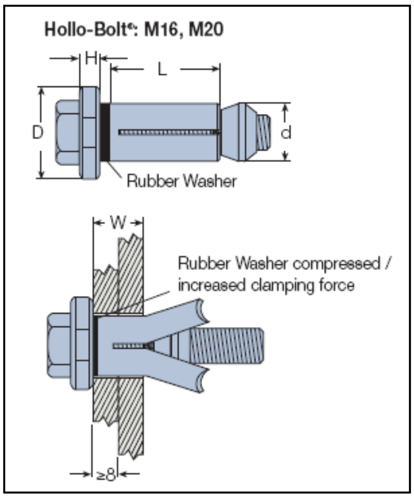

Fig. 1 Lindaptor Hollobolt

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For many years, fatigue has become significant and difficult problem for engineers, especially for those involved in structural designs such as aircraft, bridges, pressure vessel, cranes etc [4]. Therefore, further research of blind bolt under fatigue load need to be carried out to investigate the behaviour of fasteners so-called Extended Hollobolt under fatigue loading.

2. Methodology

The objectives of the fatigue tensile tests are to determine:

i. the effect of frequency
ii. the effect of stress range and the fatigue life of the Extended Hollobolt connection in concrete filled tube.
iii. carry out statistical analysis of S-N curve to classify the category of Extended Hollobolt.

2.1 Extended Hollobolt

Extended Hollobolt as can be seen in Fig. 2 is one of the types of blind bolt, which can be tightened form one side only. Extended Hollobolt is a variation of the Lindapter Hollobolt that has been developed at the University of Nottingham. Series of monotonic test have been conducted in order to investigate the behaviour of the blind bolt connection [1][5][6]. Table 1 indicates the measurements properties and standard properties for 8.8 bolts used in the test.

Fig. 2 Extended Hollobolt.

Table 1 Mechanical properties of 8.8 bolts.

Properties	Tensile Test	Nominal
Ultimate load (kN)	136	125
Yield strength (N/mm^2)	662	640
Tensile strength (N/mm^2)	866	800

2.2 Concrete filled tube

Filling tubular steel column sections with concrete significantly increases axial load capacity and also improves resistance to fire. The design and practical use of concrete-filled (composite) columns has been well documented by Bergmann et al. [7]. Concrete filled columns have been investigated by many researchers using blind bolts and the result shows that the concrete filled tube can prevent the excessive localised deformation [1][8][9]. There are significant increases in ductility and strength as concrete filled tube allows the full development of tensile capacity of the bolts. Also, the concrete seems to grip onto the bolt and prevent it to being pulled out.

The concrete used for the test was mixed in the department laboratory. The design compressive cube strength was 40N/mm^2. The compressive strength of 100mm concrete cubes was determined after 7 days and the day of testing. Table 2 provides the compressive strength of the concrete.

Table 2 Concrete compressive strength.

No.	Concrete Strength at 7 Days (N/mm^2)	Concrete Strength at Test Day (N/mm^2)
1	35.8	35.8
2	39.5	42.5
3	40.3	40.3
4	40.3	40.3
5	38.8	38.85
6	41.0	41.0
7	41.0	41.0
8	38.9	40.9
9	38.7	38.7
10	40.0	40.0
11	38.25	38.25
12	41.2	41.2
13	37.4	37.4
14	40.9	40.9

2.3 Square hollow section

Square hollow sections (SHS) with a dimension 200 x 200 x12.5 were cut to 500mm long. Then, one hole with diameter of 28mm was drilled in the middle of tube face of SHS. Table 3 shows the properties of SHS.

Table 3: Mechanical properties of Square hollow section.

Section (mm)	Steel Grade	Yield Strength (N/mm^2)	Young Modulus (kN/mm^2)	Ultimate Load (kN)
200 x 200 x 12.5	355	393.404	205.174	125.28

3. Test Set-Up

To evaluate the performance of Extended Hollobolt under fatigue loading, tensile tests were carried out. The tensile test consists of a 30 mm thick plate, an Extended Hollobolt grade 8.8, hollow section 200 x 200 x 12.5 filled with concrete as can be referred in Fig. 3.

Thicker hollow section was used to eliminate the effect of the tube face bending. The test was conducted using a 100kN capacity Servocon Hydraulic system as shown in Fig. 4.

Under controlled load, a constant tensile force was applied to the specimen as can be seen in Fig. 5. The constant applied load is simple loading-history and easy to define compared with the variable applied load which is more complex with fluctuating-history. In addition, the different load/stress ranges were applied to the specimens. The ranges are based on design yield stress of the bolt, which is according to Eurocode 3 (BS EN 2005) has value approximately 640N/mm^2. Four different load ranges were used: 90kN, 70kN, 60kN and 50kN equating to nominal stress ranges of 584N/mm^2, 455N/mm^2, 390N/mm^2 and 325N/mm^2 respectively.

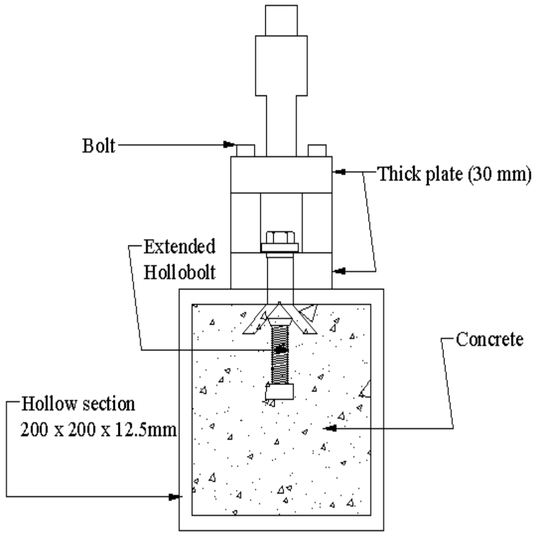

Fig. 3 Extended Hollobolt in concrete filled connection.

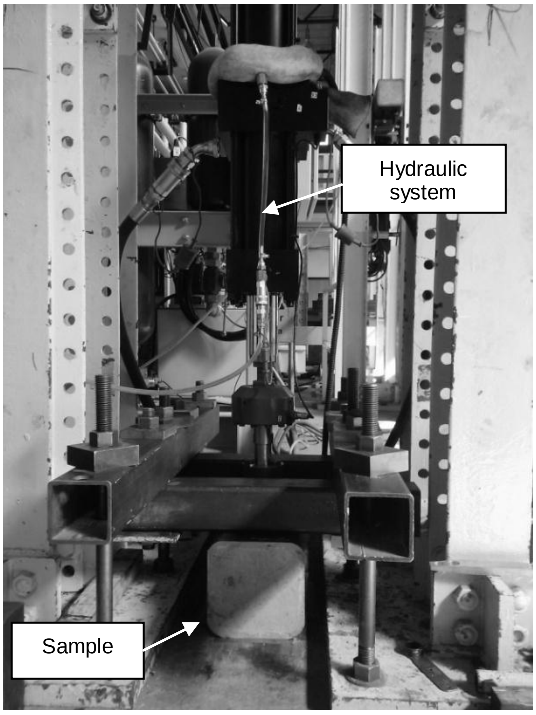

Fig. 4 Experiment set-up.

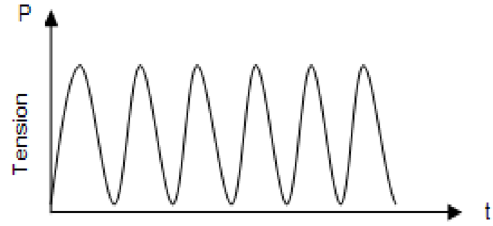

Fig. 5 Loading hysteresis.

As the test is to determine the behaviour of the Extended Hollobolt in concrete filled, concrete strength is a paramount parameter. In this study, the concrete strength parameter is controlled by keeping it constant. The adopted design cube strength of 40 N/mm^2 (C40) at the time of testing was used. Testing was performed after the concrete achieved the concrete strength at 7 days. The actual cube strength at the time of testing is given in Table 2.

4. Results

All stress values in this test are calculated using equation (1):

$$\sigma = \frac{P_e}{A_t} \tag{1}$$

where,

P_e = actual load during the test, and
A_t = tensile area of the bolt according to EN20898-1 and can be determined using Equation (1.1) below.

$$A_t = \pi / 4 \left(\frac{d - \left(\frac{3}{8}\right) H + d_o - \left(\frac{H}{6}\right)}{2} \right)^2 \tag{2}$$

where,

A_t = 154.13 mm^2,
H = height of fundamental triangle
= 8/5(d-d_o)/2,
d = thread outer diameter, and
d_o = thread root diameter

4.1 Effect of frequency (f)

Due to the long required time for some fatigue test, there is a desire to shorten the testing time. To determine whether frequencies will affect the fatigue life of the specimen, frequency between 0.25 Hz to 5 Hz were applied. The results of various frequency tests are shown in Table 4. The results indicate that the frequency does affect the fatigue life from 0.25 Hz to 3 Hz which is increase more than 50% but only 16% of increment for frequency from 0.25Hz to 1Hz.

At the load around 70kN, the number of cycles decreases by about 37% at 3 Hz and further decreases by about 20% at 5 Hz. Under the higher frequency of 5 Hz, it was noticed that the actual applied stress range was actually higher than the nominal input. This was attributed to the controlling software.

Final failure of the bolt can be considered as a fracture failure. The bolts do not show a consistent failure location because of the effect of frequency. This is proven by different types of failure mode, where fracture failure occurs at all bolts especially at 3 Hz. The differences in fracture failure are because of the flexibility inconsistency of the samples during the test. Fig. 6 to Fig. 9 show the fatigue failure of Extended Hollobolt due to tensile which is comparable to the standard bolt.

Table 4: Experimental result.

No.	Actual load range (Pe) kN	Actual Stress range ($\Delta\sigma_e$) N/mm^2	Number of cycles N_f	f (Hz)	Fracture failure
1	89.67	581.78	8,025	0.25	*Shank*
2	89.93	583.48	9,314	1	*Shank*
3	89.89	583.24	10,489	3	*Shank*
4	90.20	585.26	12,063	3	*Head*
5	69.90	453.51	20,608	0.25-1	*Shank*
6	71.94	466.81	28,331	3	*Shank*
7	73.80	478.82	28,632	3	*Shank*
8	76.10	493.75	20,649	5	*Head*
9	76.44	495.94	21,441	5	*Head*
10	60.60	393.17	55,822	1 - 2	*Shank*
11	60.93	395.34	58,142	3	*Head*
12	49.93	323.95	78,803	2	*Shank*
13	51.13	331.73	89,300	3	*Shank*
14	50.88	330.11	91,878	3	*Head*

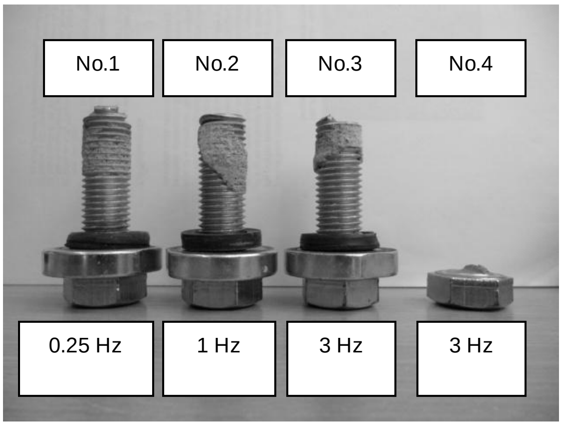

Fig. 6 Tensile fracture at $\Delta\sigma$ 584N/mm^2.

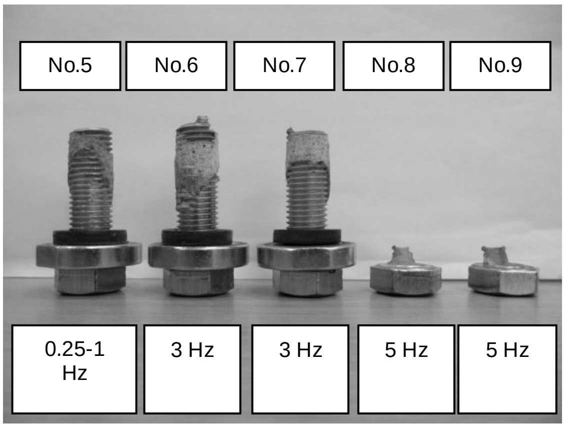

Fig. 7 Tensile fracture at $\Delta\sigma$ 455N/mm^2.

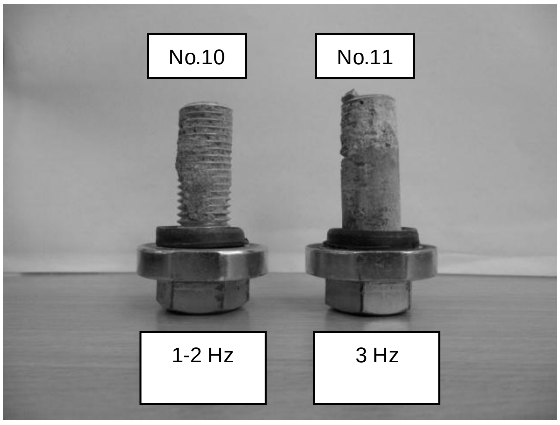

Fig. 8 Tensile fracture at $\Delta\sigma$ 390N/mm^2.

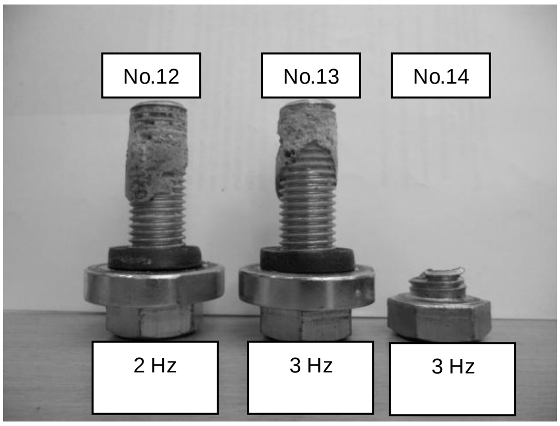

Fig. 9 Tensile fracture at $\Delta\sigma$ 325N/mm^2.

4.2 Effect of stress range (Δσ)

Bouwman has suggested [10] that increasing the mean stress level will leads to decreasing fatigue life. As expected, by applying different load ranges to the specimen, the results showed that higher amplitudes give a small number of cycles to failure compared to lower amplitudes. In order to understand the effect of load range or stress range on the specimens, the results at 3 Hz frequency is taken for the comparison as depicted in Table 5. Overall observation, as expected, the fatigue life of Extended Hollobolt connection is increased under a higher constant load range or stress range.

Table 5 Stress range result at 3 Hz.

No.	Concrete Strength at Test Day (N/mm^2)	Actual Load Range (P_e) kN	Actual Stress Range ($\Delta\sigma_e$) N/mm^2	Number of Cycles N_f
3	40.3	89.89	583.24	10,489
4	40.3	90.21	585.26	12,063
6	41.0	71.95	466.81	28,331
7	41.0	73.80	478.82	28,632
11	38.4	60.93	395.34	58,142
13	37.4	51.13	331.73	89,300
14	40.9	50.88	330.11	91,878

4.3 S-N curve

Fatigue assessment of bolt can be carried out according to Eurocode 3 (BS EN 2006) Part 1-9 that describes the classification of the welded connection under fatigue loading. From the fatigue assessment, the Extended Hollobolt can be classified in category 50. A comparison between test results under fatigue tensile load and relevant S-N curve is presented in Fig. 10. Results from the fatigue test of Extended Hollobolt lies above detail category 50 of Eurocode 3. Furthermore, it was found that the experimental fatigue life of the Extended Hollobolt within the tested stress range $584N/mm^2$ to $325N/mm^2$ has a higher fatigue life compared to that obtained from the nominal standard bolt.

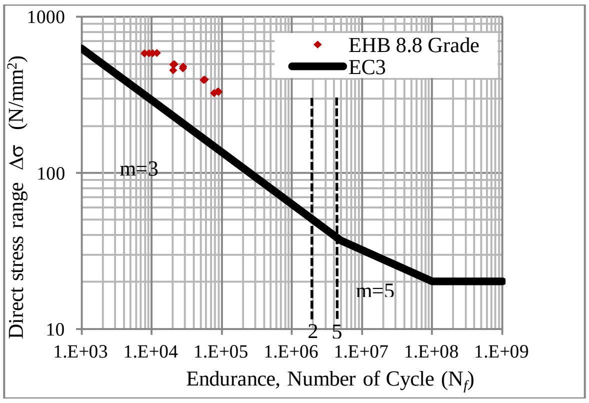

Figure 10: Comparison between scatter of tests result and Eurocode 3 S-N curve.

As the current results only cover the range of load where the number of cycles is below than two million cycles, testing at lower range is necessary in order to complete the S-N curve for these types of bolts.

Since the test specimens and testing conditions are never identical between test, the resulting data are invariably scattered and uncertainties exist in the fatigue process even though every care have been exercised to ensure that the testing conditions are as identical as possible. Therefore, in order to analyse these scatter data, statistical methods are available and were applied in the analysis. There is underlying liner relationship between log Δσ and log N in the form:

$$\log N = \log A - m \log \Delta\sigma \tag{3}$$

with the form of :

$$y = a + bx \tag{4}$$

where, *y=log N, x =logΔσ, a= log A, and b=-m with m* is slope and *A* is the intercept. This can be re-written in a form that is commonly used to describe S-N curves in the design rules as:

$$\Delta\sigma^m N = A \tag{5}$$

The best application for the comparison with the classification as adopted in Eurocode 3 is using the characteristic strength at two million cycles. It can be written that x_c=log $\Delta\sigma_c$ and let consider that y_c=log N_c corresponding to given value x_c. The sample distribution can be obtained from the following estimation as suggested by Ronald et al. [11].

$$\bar{y}_c = \bar{a} + \bar{b}.x_c \tag{6}$$

and

$$Var(y_c / x_c) = \sigma^2 y_c x_c \tag{7}$$

or can be written as:

$$Var(y_c / x_c) = s_y{}^2 \left(1 + \frac{1}{n} + \frac{x_c - \bar{x}}{s_{xx}}\right) \tag{8}$$

where Var(y_c/x_c) is the variance of y_c given that x is equal to x_c, and

$$s_y{}^2 = \frac{s_{yy} - b.s_{xy}}{n-2} \tag{9}$$

where S_{yy} and S_{xy} can be calculated using the following equations:

$$s_{yy} = \sum y_1^2 - \frac{(\sum y_i)^2}{n} \qquad (10)$$

$$s_{xy} = \sum x_i y_i - \frac{\sum x_i \sum y_i}{n} \qquad (11)$$

With the 95% confidence interval given by BS EN 2006, the estimation of y_{ck} is based upon:

$$y_{ck} = y_c - t_{95}(\sigma_{yc/xc}) \qquad (12)$$

The characteristic S-N curve, therefore, is given by following equation:

$$\log N_k = (\log A - t_{95}\sigma_{yc/xc} - m.\log \Delta\sigma_k) \qquad (13)$$

Using the equation provided above, the characteristic strength at two million cycles for the test data has a standard deviation ($\sigma_{yc/xc}$) equal to 0.143. Therefore, by using the standard deviation value with 95% confidence interval, the characteristic strength at two million then can be classified under category 127 as shown in Fig. 11.

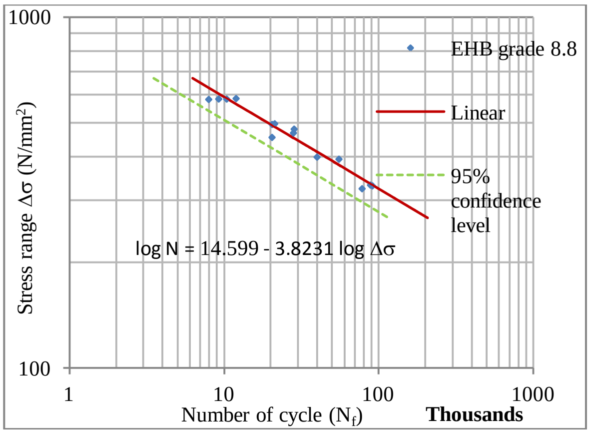

Fig. 11 Statistical evaluation of the S-N curve.

The standard deviations are varying from test to test, and from the type of detail studied. In general, higher stress concentration factor will contributes to the lower standard deviation of the fatigue tests result. Table 6 shows the comparison between fatigue tests of Extended Hollobolt with other various types of category which is obtained when performing the statistical analysis. These values of the standard deviation are somewhat different to the values appearing in Appendix C of ECCS [12] due to the fact that more complete sources of fatigue data were analysed when reviewing the classification for Eurocode 3.

Table 6 Standard deviation of various types of detail category.

Type of detail	**Range of standard deviation**
Rolled beam	0.125-0.315
Welded beam	0.150-0.230
Vertical stiffener	0.115-0.190
Longitudinal attachment	0.115-0.140
Cover plate on flange	0.070-0.140
Extended Hollobolt	0.143

5. Conclusion

The tensile fatigue test of Extended Hollobolt shows that the frequency does affect the fatigue life of the connection from 0.25Hz to 3Hz with more than 50% increment. The test which is carried out using a stress range between 584N/mm^2 to 325N/mm^2 follows the expected pattern of the S-N curve of stress range versus fatigue life. The failure mode of the connection is considered as a fatigue fracture which is comparable with that of the standard bolt.

Comparing the fatigue test of Extended Hollobolts with the current basic design S-N curve, fatigue of Extended Hollobolt under statistical evaluation can be classified under category/class 127 which is far above the class 50 for the bolt in tension as proposed by Eurocode 3. To establish more accurate S-N curve for Extended Hollobolt, a series of test with a lower stress range should be conducted with different types of bolt as described in Table 7. Different concrete strengths can also be used to investigate the effect of the concrete on the fatigue life of Extended Hollobolt.

Table 7 Type of bolt for future test.

Type of Bolt	Bolt Grade	Concrete Strength (N/mm^2)
Standard Bolt	8.8	40
Standard Hollobolt	8.8	40
Extended Hollobolt	10.9	40
Extended Hollobolt	8.8	60

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