Journal of Southeast University (English Edition) Vol. 32, No. 4, pp. 445 − 450 Dec. 2016 ISSN 1003—7985

Experimental study on mechanical properties of dowel bar embedded in concrete under fatigue loads

Li Pengfei[1] An Xuehui[1] He Shiqin[2] Chen Chen[2]

([1]State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, China)
([2]School of Civil Engineering, North China University of Technology, Beijing 100144, China)

Abstract: To investigate the mechanical properties of a dowel action under fatigue loads, nine reinforced concrete specimens were fabricated, and the monotonic and fatigue loadings were performed on these specimens, respectively. All of these specimens were divided into two series. Six specimens in Series Ⅰ with different bar diameters of 12, 20 and 25 mm were subjected to monotonic loads and were used to confirm the ultimate bearing capacity. The remaining three specimens in Series Ⅱ were subjected to fatigue loads and were designed to investigate the attenuation character of dowel action and the fatigue failure modes. The test results show that the accumulated fatigue damage due to fatigue loads can reduce the ultimate bearing capacity of specimens. With the increase in fatigue loads, the failure mode can transform to fatigue rupture of the dowel bar under the serviceability loading state, i. e. 55% of the monotonic capacity. The fatigue life is determined by the fatigue properties of steel and concrete. Based on the test data, the failure process of dowel action can be divided into two stages: the accumulation of fatigue damage and the fatigue rupture of dowel bar.

Key words: dowel action; fatigue loads; fatigue failure mode; fatigue life; attenuation character

DOI: 10. 3969/j. issn. 1003 − 7985. 2016. 04. 009

Dowel action is one of the main mechanisms of load transfer along the structural joints and interfaces. Such joints are very often formed in precast concrete connections[1-4], construction joint in pavements[5-6], interfaces between old and new concrete in columns repaired or strengthened by means of reinforced concrete jackets[7-8] and so on. These interfaces and joints may turn out to be critical planes in the operation of the load-resisting mechanism and thus may govern the ultimate strength, ductility and energy absorption capacity of the entire structure[9].

As the important components of reinforced concrete structures, structural joints are directly subjected to shear loads of great magnitude and cycles. During their service life, the mechanical performances of dowel action gradually degrade due to the high cycle repetition of loads which might cause a sudden collapse of the entire structure. Therefore, the mechanical behavior of dowel action under fatigue loads should be taken into account.

In recent years, extensive experimental and analytical investigations have been carried out to study the mechanical properties of the dowel action[10-11]. Vintzeleou and Tassios[12] experimentally investigated the behavior of dowels under cyclic deformation. Test results indicate that both the bearing capacity and the stiffness of dowel action show obvious degradation, particularly in the case of full reversed deformations.

In order to investigate the mechanism of dowel action fatigue deterioration, Mattock and Hawkins[13] carried out a series of high cycles fatigue tests of push-off specimens. The relationship between the dowel shear force and the transverse shear slip for various cycle totals of specimens under different loading levels were obtained. However, it should be noted that the effect of fatigue loads on the failure mode and the residual bearing capacity of specimen were not studied. Therefore, the results of previous tests cannot be directly applied in engineering design.

In this paper, a series of block-type specimens with different bar diameters are tested to study the fatigue performance of dowel action. The attenuation character and failure mode of the specimen under fatigue loads are quantified by comparison with the monotonic test results.

1 Experimental Program

1.1 Test specimen design

To investigate the transverse displacement of a long dowel embedded in concrete, block-type specimens with the dimension of 400 mm (length) × 300 mm (width) × 250 mm (height) are designed, as shown in Fig. 1(a). In total, nine specimens are cast, with each specimen being reinforced with a single deformed bar. The yield strength of the dowel bar is 400 MPa. The mixture proportion of the concrete is shown in Tab. 1.

As summarized in Tab. 2, the specimens are divided into two series. Series Ⅰ consists of six specimens with three different bar diameters of 12, 20 and 25 mm,

Received 2016-07-12.

Biographies: Li Pengfei(1986—), male, graduate; An Xuehui (corresponding author), male, doctor, professor, anxue@tsinghua. edu. cn.

Foundation items: The Fund of the National Key Laboratory in China (No. 2015-Ky-01), the National Key Technology R& D Program of China (No. 2015BAB07B07).

Citation: Li Pengfei, An Xuehui, He Shiqin, et al. Experimental study on mechanical properties of dowel bar embedded in concrete under fatigue loads[J]. Journal of Southeast University (English Edition), 2016, 32(4): 445 − 450. DOI: 10. 3969/j. issn. 1003 − 7985. 2016. 04. 009.

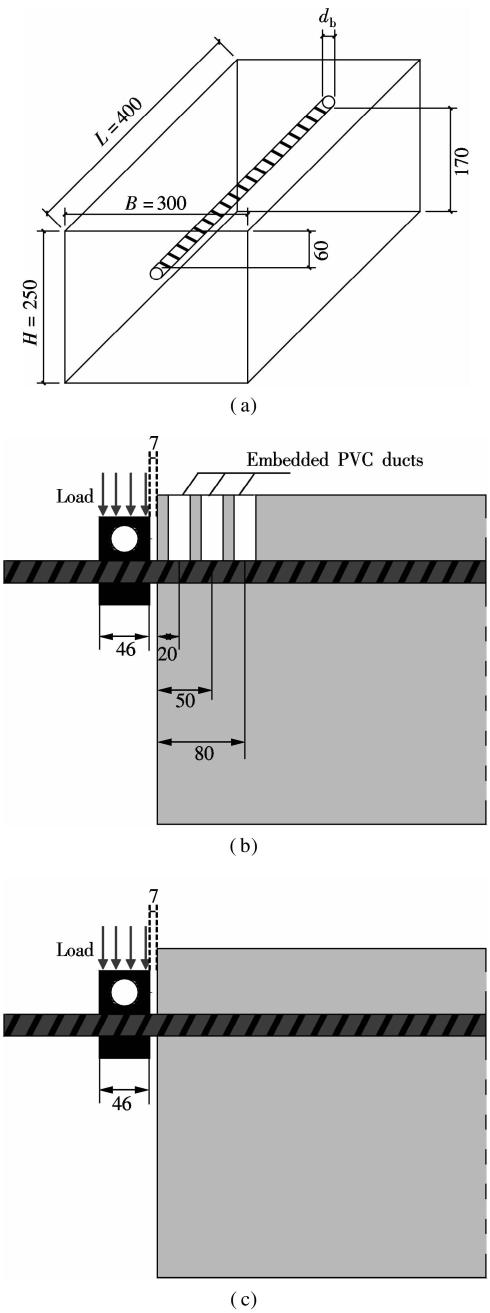


Fig. 1 Specimen design (unit: mm). (a) Specimen dimension; (b) Type-A specimen; (c) Type-B specimen

Tab. 1 Mixture proportions of concrete kg/m^3

Water-cement ratio	Superplasticizer	Cement	Water	Coarse aggregate	Fine aggregate
0.47	0.57	415	195	1 146	644

Tab. 2 Details of specimens subjected to testing

Number	Specimen	d_b/mm	f'_{cc}/(kg · m^{-3})	Loading pattern	Series
1	D12-M-A	12	50.1	Monotonic	Ⅰ
2	D12-M-B	12	49.3	Monotonic	Ⅰ
3	D20-M-A	20	49.3	Monotonic	Ⅰ
4	D20-M-B	20	50.6	Monotonic	Ⅰ
5	D25-M-A	25	50.7	Monotonic	Ⅰ
6	D25-M-B	25	49.9	Monotonic	Ⅰ
7	D12-F	12	49.6	Fatigue	Ⅱ
8	D20-F	20	50.1	Fatigue	Ⅱ
9	D20-F	25	50.8	Fatigue	Ⅱ

respectively. These specimens are subjected to monotonically increasing load and are used to confirm the monotonic capacity of dowel action. The remaining three specimens in Series Ⅱ are subjected to the fatigue loading and are designed to investigate the mechanism of dowel action fatigue deterioration and the fatigue failure modes.

For the specimens in Series Ⅰ, the displacement distribution in this test is obtained via the direct measurement of the displacements of the bar. A total of three plastic ducts are pre-cast in the concrete specimens (diameter of 20 mm, as shown in Fig. 1(b)), thereby allowing linear voltage displacement transducers (LVDTs) to touch the bar and directly measure the displacements. The influence on the dowel capacity of these pre-cast ducts will be demonstrated by comparing the response curves of specimens with ducts (Type-A) to the curves of specimens with no ducts (Type-B). For the specimens in Series Ⅱ, only Type-B specimen is used, as shown in Fig. 1(c).

1.2 Test setup

To directly obtain the transverse displacement and control the load history, a direct shear approach[14] is chosen for this study, in which the shear force is directly applied to the dowel bar. The test setup is presented schematically in Fig. 2(a). Two servo-hydraulic actuators with loading capacities of 250 and 150 kN are used in the loading frame, which allows both the shear and axial forces to be applied to the dowel bar. The monotonic tests are conducted by controlling the displacement at the loaded end

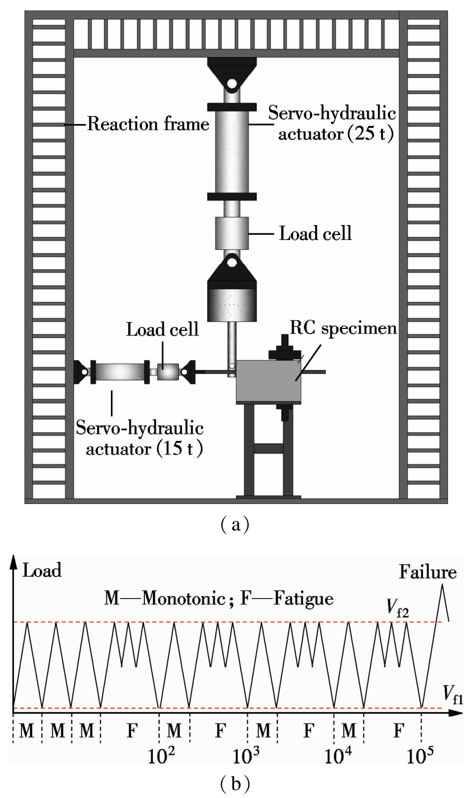


Fig. 2 Schematic of test setup. (a) Loading scheme; (b) Loading histories of fatigue tests

section, and the displacement is imposed in 40 to 60 steps. At each load step, a period of time is required for the stabilization of the displacement to be achieved, and the next step is applied after the displacements were steadied.

For the fatigue test, a repeated single-sided shear force is applied to the dowel bar. The maximum load level V_{f2} is set equal to 55% of the monotonic capacity obtained from the monotonic tests and the minimum load level is set to be 1 kN (V_{f1}) in order to keep the specimen stable. The specimens in Series Ⅱ are subjected to the following loading histories, as shown in Fig. 2(b). First, three monotonic loading cycles are performed to eliminate the influence of the deformation of the support device. Then a numbers of fatigue cycles ($N = 1\times10^2$, 1×10^3, 1×10^4, 2×10^4, 4×10^4, 6×10^4, 8×10^4, 1×10^5) are carried out. A force controlling mode is adopted for fatigue loading and the loading frequency is set to be 2 Hz. After 1×10^5 times fatigue cycles, the specimen is tested up to failure to measure the residual carrying capacity.

1.3 Measurement scheme

Fig. 3 schematically shows the measurement scheme. In all tests, the shear displacements and shear forces are continuously recorded during loading with a data acquisition frequency of 1 Hz. For Type-A specimens, the displacements at different points along the bar are recorded by 4 LVDTs. Furthermore, several LVDTs are used to monitor the concrete block at different positions, and to measure possible rigid body displacements of the specimen with respect to the loading frame.

Fig. 3 Measurement scheme

2 Experimental Results and Discussion

2.1 Monotonic loading

Load-displacement curves for specimens with different bar diameters (12, 20 and 25 mm) are shown in Fig. 4 and the displacement distribution measurements under different load levels collected from Type-A specimens are shown in Fig. 5. The ducts containing the stems of the LVDTs are found not to influence the dowel action based on the closeness of the response curves between these specimens. The differences may be due to the scattering of the experiment, and all these results can, therefore, be combined together for analysis.

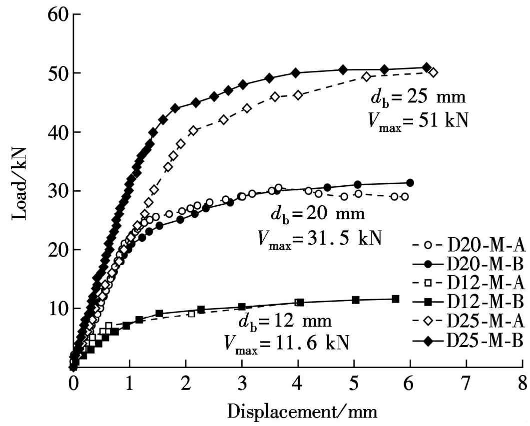


Fig. 4 Load-displacement curves for specimens in Series Ⅰ

The dowel behavior demonstrates a better ductility and similar elastic-plastic trends are presented. The demarcation point of the elastic stage and the plastic stage may be caused by either the yielding of the bar or the crushing of the concrete and can be defined as approximately 2/3 of the maximum load. Both the dowel stiffness and strength increase with the increase in bar diameter, which are in agreement with previous published results[14]. In the elastic stage, the bars do not exhibit obvious plasticization and the displacement along the bars is approximately linearly distributed. When the shear loads approach or exceed the demarcation point, the behavior exhibits obvious nonlinear characteristics, and a turning point is formed in the displacement distribution curves. As shown in Fig. 5, the

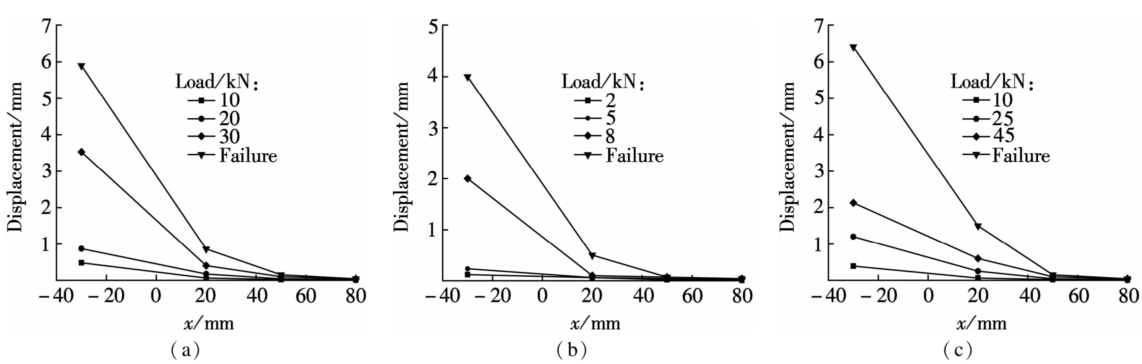
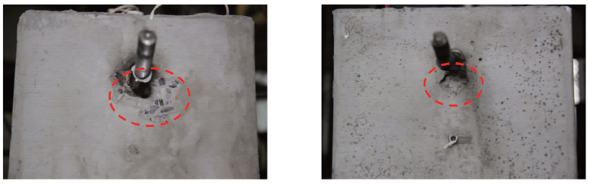


Fig. 5 Displacement distribution for specimen. (a) D20-M-A; (b) D12-M-A; (c) D25-M-A

displacement along the dowel bar continues to increase until the destruction of the specimen. With reference to the phenomenon, both the concrete and steel nonlinearities have to be considered, as well as the localized damage of the subgrade concrete.

Based on these results, it can be speculated that a plastic hinge is formed in the dowel bar which is located about 20 to 25 cm away from the surface of the specimen. All the specimens failed due to bar yielding and localized crushing of concrete, as shown in Fig. 6. At a load level equal to approximately the maximum load, the concrete under the dowel bar close to the shear plane began to deteriorate, leading to flaking as also reported by other researchers[14].



(a) (b)

Fig. 6 Typical failure mode for specimen. (a) D20-M-A; (b) D12-M-B

2.2 Fatigue loading

Based on the experimental data obtained from the monotonic test, the maximum load level V_{f2} for each specimen in Series Ⅱ is determined, as shown in Tab. 3. For specimen D12-F, the maximum load level is set to be 7.0 kN (60% of the monotonic capacity) to ensure the accuracy of the servo-hydraulic actuator.

Tab. 3 Details of specimens subjected to fatigue loads

Specimen	d_b/mm	f'_{cc}/(kg · m^{-3})	V_{f1}/kN	V_{f2}/kN
D12-F	12	49.6	1.0	7.0
D20-F	20	50.1	1.0	18.0
D20-F	25	50.8	1.0	28.0

2.3 Attenuation character of dowel action under fatigue loads

The typical dowel force-dowel displacement curves of specimen D12-F is given in Fig. 7. The residual carrying capacity after 1×10^5 times fatigue cycle is 9.2 kN, less than the monotonic capacity (11.6 kN for specimen D12-M-B).

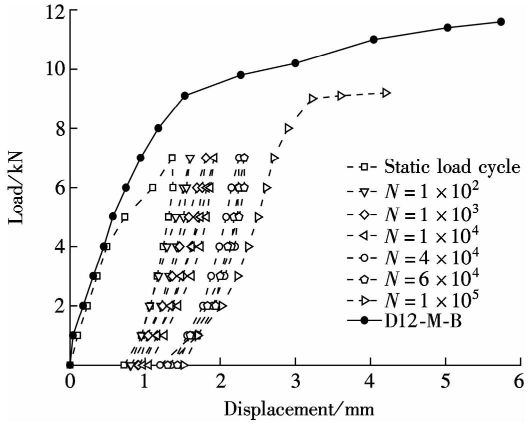


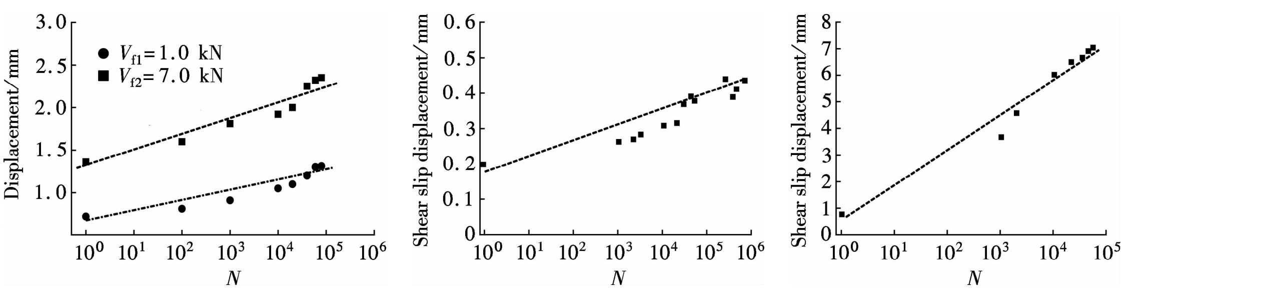
Fig. 7 Load-displacement curves for specimen D12-F

It can be concluded that the accumulated fatigue damage due to fatigue loads will reduce the ultimate bearing capacity of the dowel action. This experimental phenomenon is of great significance to practical engineering design. For the construction joints subjected to fatigue loads, the bearing capacity of dowel action cannot be designed according to the monotonic tests. The dowel action fatigue deterioration should be considered and quantified based on the analysis of the actual load history.

Both the displacement of the dowel bar at the maximum load level (7.0 kN) and at the minimum load level (1.0 kN) increase as the number of cycles increases. Fig. 8(a) shows the incremental displacement against the number of fatigue cycles. There is a linear relationship between the incremental shear displacement and the logarithm of the number of fatigue cycles. This is similar to the *S-N* diagram for the fatigue life of materials, which is in agreement with previous published results, as shown in Figs. 8(b) and (c)[13].

2.4 Fatigue failure modes

Dowel bars of specimen D20-F and D25-F are ruptured at the 68 720th and 72 485th fatigue cycles. The positions of fractures are located about 20 to 25 cm away from the



(a) (b) (c)

Fig. 8 Incremental displacement against the number of fatigue cycles. (a) D20-F; (b) Low amplitude (9.6 kN) of published results[13]; (c) High amplitude (22.5 kN) of published results[13] surface of the specimen which is close to the position of the plastic hinge formed in the bar in monotonic test. Fig. 9 shows the typical failure mode of these specimens. It can be concluded that the fatigue failure mode of dowel action is the fatigue rupture of the dowel bar and the fatigue life is determined by the fatigue properties of steel and concrete.

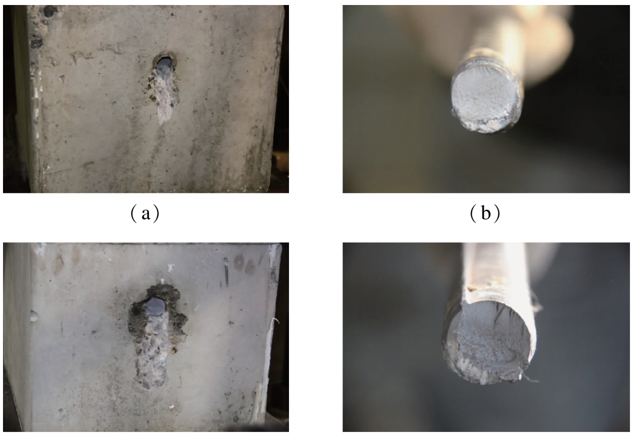

(a) (b)
(c) (d)

Fig. 9 Typical failure mode of specimen. (a) D20-F; (b) Steel bar of D20-F; (c) D25-F; (d) Steel bar of D25-F

The load-displacement curves and the incremental evolution of shear displacement for both specimens are shown in Fig. 10 and Fig. 11, respectively. When the number of cycles is less than 4×10^4, similar trends are presented to the specimen D12-F, and a linear relationship between the incremental shear displacement and the logarithm of the number of fatigue cycles is obtained. When the number of fatigue cycles is equal to 6×10^4, there is a sudden increase in the shear displacement of the dowel bar and the stiffness degradation can be clearly observed.

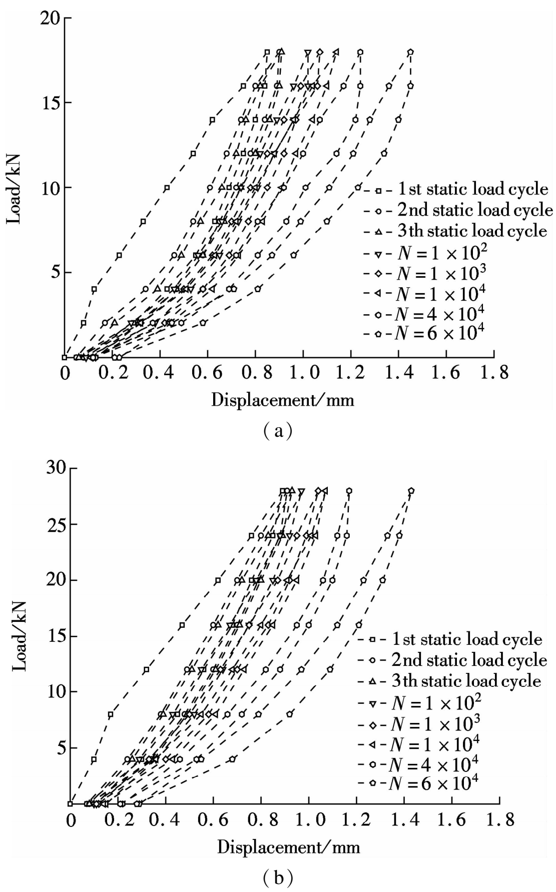


Fig. 10 Load-displacement curves for specimen. (a) D20-F; (b) D25-F

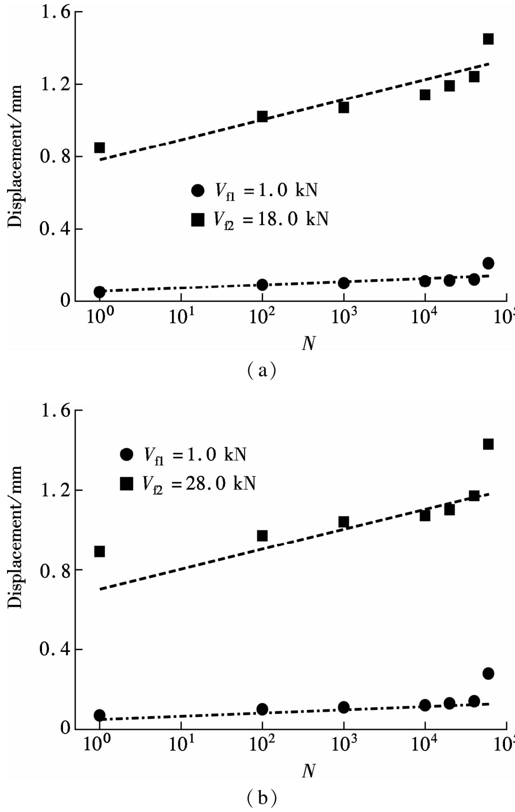


Fig. 11 Incremental displacement against the number of fatigue cycles. (a) D20-F; (b) D25-F

The observation on the macroscopic feature and microscopic feature of these specimens is shown in Fig. 9. The fracture characteristics are similar to the fatigue rupture of the steel bar. Based on the test data, the fatigue failure process of dowel action can be divided into two stages: the accumulation of fatigue damage and the fatigue rupture of dowel bar. In the former stage, the fatigue damage of materials gradually accumulates under the fatigue loads. In the latter stage, the bearing section of the dowel bar is fractured due to the growth and propagation of the micro cracks in steel.

3 Conclusions

1) The load-displacement curves are mostly elastic-plastic in the case of monotonic loading. The behavior of a long dowel is mostly elastic for a shear load not exceeding 60% of the ultimate capacity. When the shear loads approach or exceed the demarcation point, the behaviour exhibits obvious nonlinear characteristics, and a plastic hinge is formed in the dowel bar which is located about 20 to 25 cm away from the surface of the specimen.

2) The accumulated fatigue damage due to the fatigue

loads can significantly reduce the ultimate bearing capacity of dowel action. The fatigue deterioration of dowel action should be considered in engineering design to ensure the safety of the structures.

3) The failure mode of dowel action can transform to fatigue rupture of the dowel bar under serviceability loading state (55% of the monotonic capacity). The fatigue life is determined by the fatigue properties of steel and concrete.

4) The fatigue failure process of dowel action can be divided into two stages: the accumulation of fatigue damage and the fatigue rupture of dowel bar. In the former stage, there is a linear relationship between the incremental shear displacement and the logarithm of the number of fatigue cycles. In the latter stage, the bearing section of dowel bar will suddenly fracture due to the growth and propagation of the micro cracks in steel.

References

[1] Chen Zikang, Zhou Yun, Zhang Jichao, et al. Retroversion and forecast of present research and application of precast concrete structure[J]. *Earthquake Resistant Engineering and Retrofitting*, 2012, **34**(4): 1 − 11. (in Chinese)

[2] Song Guohua, Huo Da, Wang Dongwei, et al. Shear capacity of vertical-grooved connection in PBP structures [J]. *China Civil Engineering Journal*, 2003, **36**(11): 61 − 64. (in Chinese)

[3] Huang Yuan, Xu Ming, Zhang Rui. Experimental study of the shear behavior of total precast concrete structures with steel cable connections[J]. *Journal of Hunan University (Natural Sciences)*, 2014, **41**(6): 22 − 27. (in Chinese)

[4] Li Yingmin, Yu Jing, Xia Hongliu. Experimental research on seismic behavior of frame columns with construction joint [J]. *China Civil Engineering Journal*, 2011(S1): 81 − 86. (in Chinese)

[5] Li Luoke. Research on the load transfer failure mechanism for dowel bar in concrete pavement[D]. Harbin: School of Transportation Science and Engineering of Harbin Institute of Technology, 2012. (in Chinese)

[6] Tan Yiqiu, Li Luoke, Cao Peng, et al. Analysis of corrosion mechanism and deterioration process for dowel under de-icing salt environment[J]. *Engineering Mechanics*, 2013(12): 199 − 205. (in Chinese)

[7] Zhang Yinling. The behavior research of new-to-old concrete composite components[D]. Xi'an: Xi'an Technological University, 2015. (in Chinese)

[8] Austin S, Robins P, Pan Y. Tensile bond testing of concrete repairs [J]. *Materials and Structures*, 1995, **28**(5): 249 − 259. DOI: 10.1007/bf02473259.

[9] Soltani M, Maekawa K. Path-dependent mechanical model for deformed reinforcing bars at RC interface under coupled cyclic shear and pullout tension[J]. *Engineering Structures*, 2008, **30**(4): 1079 − 1091. DOI: 10.1016/j.engstruct.2007.06.013.

[10] Soroushian P, Obaseki K, Rojas M C. Bearing strength and stiffness of concrete under reinforcing bars[J]. *ACI Materials Journal*, 1987, **84**(3): 179 − 184.

[11] Moradi A R, Soltani M, Tasnimi A A. A simplified constitutive model for dowel action across RC cracks[J]. *Journal of Advanced Concrete Technology*, 2012, **10**(8): 264 − 277. DOI: 10.3151/jact.10.264.

[12] Vintzeleou E N, Tassios T P. Behavior of dowels under cyclic deformations[J]. *ACI Structural Journal*, 1987, **84**(1): 18 − 30.

[13] Mattock A H, Hawkins N M. Shear transfer in reinforced concrete-recent research[J]. *Journal of PCI*, 1972, **17**(2): 55 − 75. DOI: 10.15554/pcij.03011972.55.75.

[14] Dei Poli S, Di Prisco M, Gambarova P G. Shear response, deformations, and subgrade stiffness of a dowel bar embedded in concrete[J]. *Structural Journal*, 1992, **89**(6): 665 − 675.

钢筋混凝土销栓作用的疲劳承载性能试验研究

李鹏飞[1] 安雪晖[1] 何世钦[2] 陈 宸[2]

([1] 清华大学水沙科学与水利水电工程国家重点实验室, 北京 100084)

([2] 北方工业大学土木工程学院, 北京 100144)

摘要: 为研究钢筋销栓作用的疲劳承载性能,制作了9个钢筋混凝土试件分别进行静载试验和疲劳加载试验.试件共分为2组,首先通过6个试件的静载试验确定销栓作用的极限承载力,其钢筋直径分别为12,20和25 mm;然后通过3个试件的疲劳加载试验来研究疲劳荷载作用下销栓作用承载性能的衰减特征及疲劳破坏形态.试验结果表明,在疲劳加载的过程中,疲劳损伤的积累会降低销栓作用的承载能力.在正常使用状态下,即极限承载力的55%,随着疲劳循环次数的增加,销栓作用的破坏模式会发生转化.疲劳破坏形态表现为钢筋的瞬时断裂,其疲劳寿命由钢筋和混凝土的材料性能所决定.基于试验结果,可以将钢筋销栓作用的疲劳破坏过程分为2个阶段,分别为损伤积累阶段和瞬时断裂阶段.

关键词: 销栓作用;疲劳荷载;疲劳破坏形态;疲劳寿命;衰减特征

中图分类号: TU312