FATIGUE DEBONDING at the INTERFACE of REINFORCED CONCRETE

Chen Yanhua[1], Zhu Qingjie[2], Jia Limei[3], Feng Leilei[3]

[1]*Associate professor, College of Civil and Architectural Engineering, Hebei Polytechnic University, Tangshan,China*

[2]*Professor, College of Civil and Architectural Engineering, Hebei Polytechnic University, Tangshan,China*

[3]*Postgraduate student, College of Civil and Architectural Engineering, Hebei Polytechnic University, Tangshan,China*

ABSTRACT:

Reinforcing steel bar and concrete have different mechanical properties. Reinforced concrete (RC) can work normally in actual engineering, which depends on well interfacial bond strength between reinforcing steel bar and concrete. It is the bond strength that makes the stress and strain accommodated between reinforcing steel bar and concrete. Relative sliding or interfacial debonding may occur under external loading, especially cyclic loading. Cyclic loading can be seen in many engineerings, for example, ocean platform and crane girder. Interfacial debonding is one of the main damage forms for RC and its structure. The friction between reinforcing steel bar and concrete decreases under cyclic loading, which accelerates interfacial debonding.

A test about interfacial debonding of RC under cyclic loading is designed. Cyclic loading can be carried by MTS equipment. Through the test, stress and strain of the reinforcing steel bar and concrete are measured respectively, also the relative slippage between steel bar and concrete. At the same time, by the aid of the finite element method-ADINA, bond stress-slippage relationship between concrete and reinforcing steel bar is established, and numerical solutions are obtained. Numerical results are compared with experimental results. The effects of reinforcing steel bar type and anchor depth on interfacial fatigue are analyzed. It can provide effective numerical ideal and method for investigation of RC lasting quality.

KEYWORDS: reinforced concrete (RC), interfacial debonding, fatigue, slippage, finite element method (FEM), ADINA

1. INTRODUCTION

Good interfacial bond strength is one necessary condition for RC working, though physical and mechanical characteristics are different between reinforcing steel bar and concrete. Interfacial debonding and relative sliding between reinforcing steel bar and concrete will happen under external loading (Guo and Shi 2003, Gao and Li 2001). Especially for RC components under cyclic loading, its properties are different from static and monotonic loading. For example, interfacial bond strength and ductibility are affected, and the stability of the whole structure is changed. So the investigation on the interfacial properties of RC during the whole cyclic loading is more important.

There are many researches on bond properties of RC under monotonic loading, including experimental researches (Zheng et al 2002, Li and Zhao 2002, Li et al. 2004, Zhao et al. 2002, Liu et al. 2001), theoretical researches (Jin et al. 2002, Karin and Kent 2000, Lu et al. 2005a, Lu et al 2005b), and numerical analysis (Gao and Li 2005, Lu et al. 2004). Many researchers start with experiments, then experiential and half theoretical relationships about bond slippage of RC are established (Zheng et al. 2002, Li et al. 2004, Karin and Kent 2000, Gao and Li 2005).

Now, with the progress of computer and its abroad applications in engineering areas, FEM on interfacial bond of RC develops rapidly. Especially for cyclic loading which is difficult to carry out in experiments, numerical simulation is signality.

By the combination of experimental research and FEM, experimental scheme on interfacial debonding of RC under cyclic loading is designed, and 3-D finite element model about interfacial debonding of RC is established by ADINA. Main influencing factors of interfacial debonding under cyclic loading are analyzed. Some available conclusions are obtained for engineering design and structure protection.

2. EXPERIMENT DESIGN AND LOADING SCHEME

2.1 Experiment Design

Taking the tension member in RC as an object, columnar tension test specimen is designed as figure 1. The section dimension of the anchor part of test specimen is 400×400mm. Reinforcing steel bar is laid in the middle of the test specimen, and the anchor length is 500mm. Ⅰ and Ⅱ level reinforcing steel bar is adopted, whose diameter is 22mm. And C30 concrete is adopted. The exterior strain of reinforcing steel bar and concrete can be measured by sticking strain slice on outer surface. Furthermore, slippage can be measured by setting micrometer on the loading end and free end, which can be seen as figure 2.

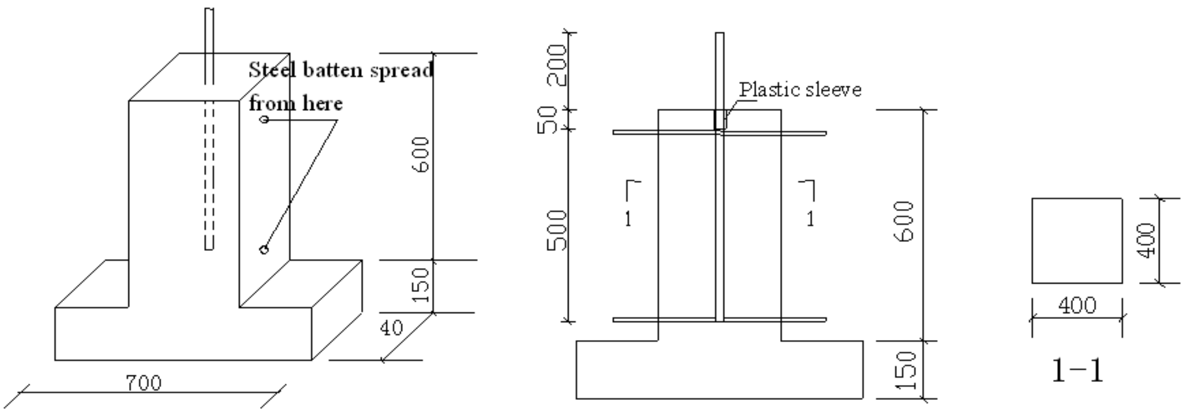


Figure 1 Plan of the specimens

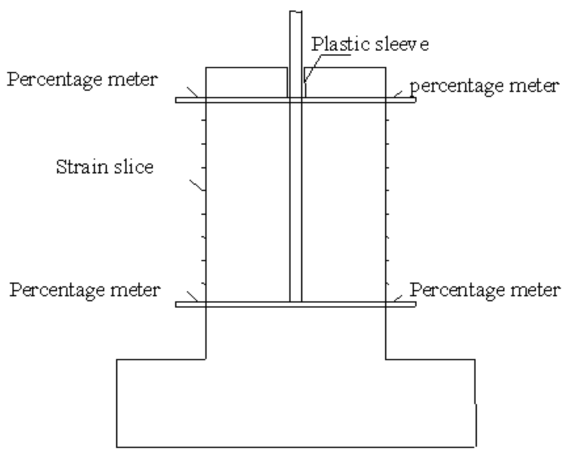


Figure 2 Location of slippage measure

2.2 Loading Scheme

A triangle wave loading is applied on the specimen by MTS dynamic loading equipments, which is seen as figure 3. Experimental equipments and specimen fixing are seen as figure 4.

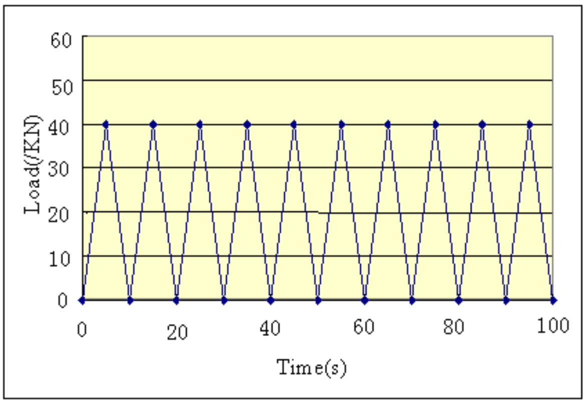


Figure 3 Loading scheme

Figure 4 Experimental equipments and specimen

3. 3-D FINITE ELEMENT MODEL ESTABLISHMENT

3.1 Geometric Model

According to shear-lag model, reinforcing steel bar and concrete can be simplified as a lag whose size is equivalent to RC prism. By the aid of ADINA, Parasolid modeling method is used in concrete body and native modeling method is used directly in reinforcing steel bar. Then 3-D geometric model is established as firgure 5. Load shown as figure 3 is applied on the model.

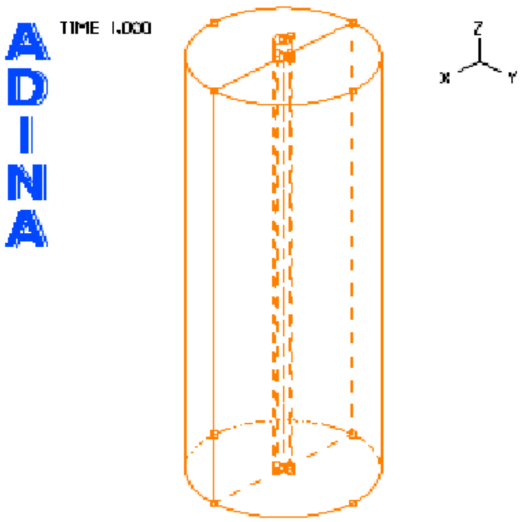


Figure 5 Geometric model of RC component

3.2 Model Parameters

Geometric parameters of RC are shown as table 1. The bottom of concrete is fixed completely, and reinforcing steel bar is free. 8-nodes and 3-D entity elements are adopted in reinforcing steel bar and concrete. Also, geometric model is simulated by the definition of physical conditions under cyclic loading.

Table 1 Geometric parameters of RC model

Title	Values
Diameter of reinforcing steel bar *d*（/mm）	12，18，20，22，25
Diameter of concrete *D*（/mm）	150,200,250,300
Anchor depth *l*（/mm）	200,300,400,500,600

4. NUMERICAL SIMULATION RESULTS and COMPARISON with Experimental Results

4.1 the Effects of Diameter

Figure 6 shows the relationship among bond stress, anchor depth and diameter of reinforcing steel bar. From figure 6, it can be seen that with the increase of diameter, the curve of bonding stress becomes smooth and the max of bond stress decreases. The bigger diameter is selected in actual engineering, which is good to distribute the bonding stress uniformly, but the reinforcing steel bar would be pulled out suddenly. The smaller diameter reinforcing steel bar is selected, which is good at the peak value larger. But the concentration of stress distribution is a disadvantage, and the ability of tension resistance of reinforcing steel bar is less, which is damaged easily. So proper diameter of reinforcing steel bar should be selected, the reasonable range is 18-22mm seen from figure 6.

Figure 7 shows the relationship among debond time, debond length and diameter of reinforcing steel bar. From figure 7, it can be seen that debond time is long during initial period, then with the increase of diameter, the time in the same debond length is descending, and debond rate becomes quick. Because with the increase of cyclic numbers, bond action is weakened continually and initial bond energy is released continually, interfacial debond rate increases. The diameter of reinforcing concrete should be selected properly, which is not the bigger the diameter, the higher the safety. The reasonable range of diameter is 18-20mm seen from figure 7.

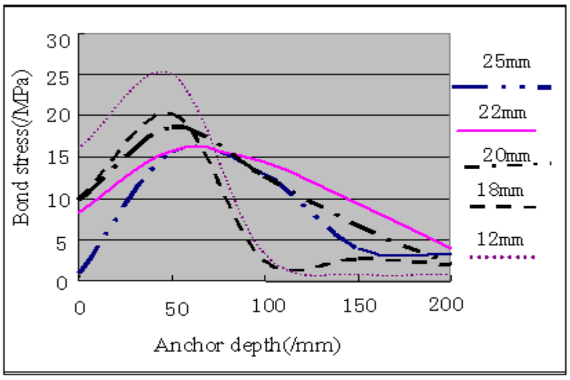


Figure 6 Bond stress versus anchor depth under diameter of reinforcing steel bar

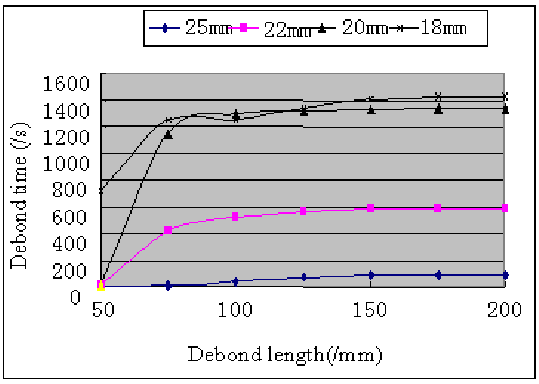
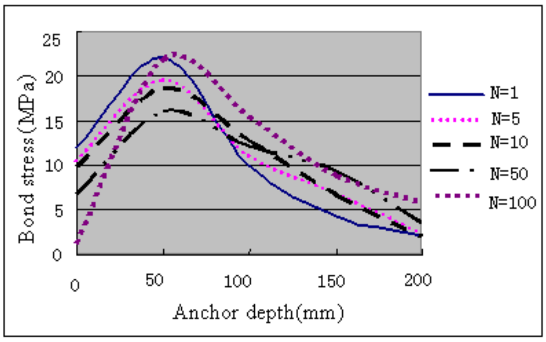


Figure 7 Debond length versus debond time different under different diameter of reinforcing steel bar

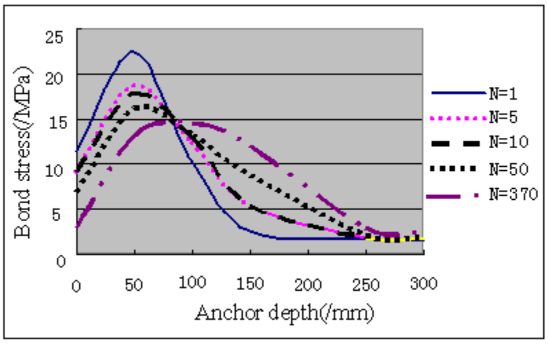
4.2 the Effects of Anchor Length

Figure 8 shows relationship among bond stress, anchor depth and cycle number under different anchor length. From figure 8, the less the anchor length, the more uniform the distribution of bond stress, and the maximum of bond stress appears at loading end mostly. Furthermore, with the increase of cycle number, the maximum of bond stress decreases early, then moves to free end. The tendency is obvious with the increase of anchor length.

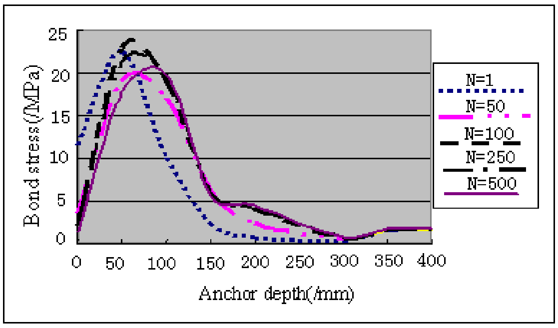
Because the relative slippage arrives to the maximum, bond stress arrives the maximum. Going on loading, debonding happens at the interface of RC, which depends on bond stress to prevent reinforcing steel bar from slipping. It can be seen from figure 8(c) and (d) that distribution tendency of bond stress are consistent when anchor length increases to a certain value. Also it can be seen from figure 8 that bond stress is distributed in 0-400mm anchor depth, bond stress is very low when anchor depth exceeds 400mm. So, it is safety for structure if anchor length was selected in 500-600mm. Anchor length is too long to be economic and to be reinforce.



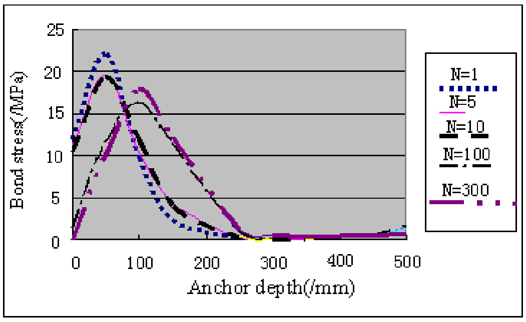
(a) Anchor length 200mm



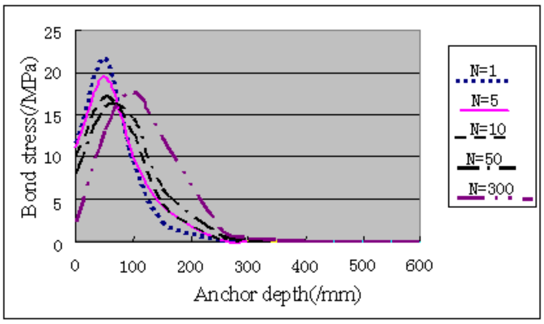
(b) Anchor length 300mm



(c) Anchor length 400mm



(d) Anchor length 500mm



(e) Anchor length 600mm

Figure 8 Bond stress versus anchor depth under different anchor length

Table 2 lists debonding finite element results of RC. For longer anchor length, damaged limit of concrete has been exceeded when reinforcing steel bar is not pulled out, program stops computing. At the same time, rupture or cleave will be happened in concrete. Therefore, anchor depth can't be improved without limit, it should be defined in a suitable range. It is reasonable that anchor length is selected in 400-500mm.

It is sum up that anchor length should be 400-600mm. That is the reasonable ratio of anchor length to diameter of reinforcing steel bar to be 20-30.

Table 2 Debond length by finite element method

Anchor length(mm)	Compute time(/s)	Debond length(/mm)
200	1445	200
300	3365	300
400	4205	275
500	4630	250
600	7685	200

4.3 Comparison Between Finite Elemment Results and Experimental Results

Seen from table 3, model results of nodes dealing with is very close to measure results. The maximum error is 8%. When loading in figure 3 is applied, reading of micrometer on the loading end is 0.08mm after 400 cycles, and reading of micrometer on the free end is 0.01mm. The comparison between experimental results and finite element results can be seen as table 4. It can be seen from table 4 that computing results at the loading end are bigger than experimental results, whose errors keep in 13%. So it can be thought that the computing results are consistent with experimental results. At free end, the errors are very small when low frequency loading is applied. Computing results are much smaller than experimental results when high frequency loading is applied. Because simulating method with communion nodes will make the restriction larger than the value of actual engineering between reinforcing steel bar and concrete, slippage of reinforcing steel bar at free end decreases much more.

Table 3 Results comparison between FEM and experiments

	Load on free end during early slipping(/KN)	Slipping at loading end during breakage(/mm)	Slipping at free end during breakage(/mm)
Experimental results	80	0.157	0.058
Computing results （nodes dealing with）	85	0.169	0.055
errors	6%	8%	5%
Computing results（no nodes dealing with）	85	0.148	0.012
errors	6%	6%	79%

Table 4 The comparison between experimental results and computing results

	Slippage at loading end (/mm)			Slippage at free end (/mm)		
	Experimental results	Computing results	Error	Experimental results	Computing results	Error
beginning of loading	0.06	0.066	10%	0.002	0.001	50%
end of loading	0.08	0.07	13%	0.01	0.002	80%

5. CONCLUSIONS

According to the design of debonding experiment of RC, the establishment and analysis of finite element model, main influencing factors on interfacial debonding of RC are discussed. Some conclusions are obtained,

1）when concrete size and anchor length are definite, the less the diameter of reinforcing steel bar, the stronger the bond intensity which distributes asymmetry; the larger the diameter, the weaker the bond strength which distributes uniformity. So relative less diameter of reinforcing steel bar should be selected under criterion content and its intensity guarantee. The ratio of perfect protective layer thickness of concrete to diameter of reinforcing steel bar is 4.5-5.05.

2）when the diameter '*d*' and debond length '*l'* of reinforcing steel bar are changeless, the longer the anchor length, the slower the debond rate. Longer anchor length should be selected under concrete intensity guarantee. But excessive anchor length will be no use. It will not only waste material, but also its effects little. The perfect *l/d* is 20-30.

3）according to experimental results, the strain of reinforcing steel bar will diminish from loading end to free end, and the strain of concrete at the outside of loading end is less than the stain at the free end. The slippage at loading end is consistent with the result of FEM.

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