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Study on the Mechanical Characteristics of Steel Fiber Reinforced Concrete Crack using Strain Gauges for Structure Health Monitoring

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Abstract: The study aims to investigate the mechanical characteristics of steel fiber reinforced concrete crack for structure health monitoring. Due to the nature of harsh working environment, the steel fiber reinforced concrete is prone to crack. A tiny crack on a steel fiber reinforced concrete beam may result in severe damages. Hence, it is crucial to investigate the mechanical characteristics of steel fiber reinforced concrete crack to detect early crack semiotics. In this study, the mechanical properties of steel fiber reinforced concrete crack have been inspected by experiment tests on four specimens. The influence of the loading position has been considered in the tests. The relationship between the fracture damaged zone deformation and load have been revealed. The experiment results demonstrate that the crack opening displacement is proportional to the load in its early developing stage and there is a critical value for the crack opening displacement under fixed load. Hence, the mechanical characteristics of steel fiber reinforced concrete crack can be used to detect the crack development in practice.

Keywords: Crack, mechanical characteristics, steel fiber reinforced concrete, strain gauges

INTRODUCTION

Steel fiber reinforced concrete is a new type concrete by adding appropriate amount of discontinuity and disorderly steel fiber in ordinary concrete. These short steel fibers can depress the crack development in the inner side of the concrete and hence significantly enhance the stiffness, toughness and ability of deformation energy absorption, etc. As a result, the steel fiber reinforced concrete has satisfactory mechanical properties, such as good strength of extension, etc. Taking the advantages of good mechanical properties, the steel fiber reinforced concrete has been widely used in civil engineering and related industry.

Up to date, many experimental investigations have been done to address the mechanical properties of the steel fiber reinforced concrete under abnormal condition and a lot of attentions have been given to the concrete cracks. Literature review indicates that the major research interest include the size effect of the steel fiber concrete fracture parameters, the mechanical model of steel fiber concrete, influence of crack width on the tensile strength and the suppression and anti-permeability of the steel fiber concrete crack, etc (Guo *et al*., 2007; Harajli and Gharzeddine, 2007; Kazemi *et al*., 2007; Rios and Rier, 2004; Yi *et al*., 2004). Zhang *et al*. (2000) conducted the uniaxial tensile fatigue experimental analysis to investigate the bridge effect across the fiber crack. Xu *et al*. (2007) used the compact tension specimen to analyze the energy to failure of the steel fiber reinforced concrete. Gao *et al*. (2005) researched the splitting properties specimen of the steel fiber reinforced concrete. Han *et al*. (2006) carried out experimental research to study the tensile property of the fiber reinforced concrete. The investigation on the mechanical properties of the fiber reinforced concrete can be also found in the study reported by Abdul (2007), Banh and Sappakit (2007), Jiang *et al*. (2010), Sivakum and Sant (2007), Yang *et al*. (2010) and Zhang *et al*. (2007). The previous results demonstrate that the mechanical fracture mechanism of the fiber reinforced concrete is very complex and more experiments should be implemented to further reveal the mechanical properties of the fiber reinforced concrete under abnormal conditions.

In the point of view of condition monitoring and health management, it is crucial to extract useful information from the mechanical properties of the fiber reinforced concrete to detect early failures. However, there is very limited study has been done to address this issue. For this reason, in order to investigate the relationship between the mechanical characteristics of steel fiber reinforced concrete and the crack, experiment tests have been carried out on four specimens to reveal the distinct mechanical characteristics of the cracks of steel fiber reinforced concrete for the purpose of structure health monitoring. The experiment results demonstrate that a critical value for the crack opening displacement can be used as an index value to detect the crack fault in the fiber reinforced concrete components. The contribution of this study is that it is the first time to extract the alarm limit using the mechanical properties of steel fiber reinforced concrete crack to monitoring the structure health condition.

MATERIALS AND METHODS

The causes of concrete cracks: There are several reasons causing the concrete cracks. In this study, we have summarized them systematically to give an overview of the causes of concrete cracks.

Unqualified raw materials: Unqualified raw materials can introduce concrete defects such as cement expired, improper selection of varieties, construction aggregate reaction, unreasonable ratio, improper selection of admixture, high cement hydration heat, excessive harmful material in aggregate, poor performance of reinforced technology, etc.

Non-standard operations: There are many illegal construction operations to cause concrete cracks. These non-standard operations include the inaccuracy dosing, non-uniformity mixing, too long transportation time, too fast pouring and serious vibration, insufficient maintenance, etc. It is necessary to adopt mandatory standard to ensure enough conserving and watering in the concrete maintenance. Now the non-covering phenomenon is general and the water cannot guarantee regular wet; at the same time the construction speed is too fast with early loading. If the loading is added too early, it will cause the concrete damage. If the reinforced concrete cover is trampled to bend or is too thick, the bearing capacity in construction will be dropt down. The sinking or deformation of the formwork trestles and the premature of disassembling formwork also can lead to cracks.

The influence of temperature and humidity: The temperature and humidity change can induce concrete crack. In the period of concrete hardening the cement may give off a lot of hydration heat and the internal temperature rises, resulting in large tensile stress in the concrete surface. In the process of cooling, due to the constraint of the based or old concrete, tensile stress will appear in the concrete surface. In addition, the decrease of the temperature also can cause large stress in the concrete surface. When these tensile stresses of concrete exceed the crack resistance, cracks will appear in the concrete. The internal concrete humidity changes very small and slowly, but the surface humidity always changes greatly. In this condition, if insufficient maintenance, the surface drying shrinkage deformation will be constrained by the inside concrete and lead to cracks.

The shrinkage cracks: A lot of concrete structures may appear visible cracks during the construction period or not long time after the completion. These concrete structures include the bridges, roads, tunnels, ports, dams, buildings, etc. Especially in recent years, with the widely application of early strength concrete, concrete structure degradation is more and more quickly. This is because a lot of people ignored the shrinkage influence of concrete itself.

In the early stage of the hardening, the stress produced by the temperature deformation and the self-grown volume deformation is the important driving force which can induce concrete cracks. After dismantling formwork, drying shrinkage deformation intensifies the accumulation of internal stress further. As well known, the concrete temperature deformation is determined by the temperature and thermal expansion coefficient during hardening period. The concrete thermal expansion coefficient varies continually with the cement hydration process. Especially in the early hydration, the concrete thermal expansion coefficient changes obviously. The concrete with high activity, low water cement ratio with big grinding fineness in 20×106, especially the high strength concrete mixed with the silicon ashes, the contraction deformation is remarkable at the early stage. The tensile stress caused by shrinkage strain and the stress relaxation effect caused by viscoelasticity are the essence for most of the concrete cracks.

On the other hand, the liquidity of commercial concrete is good due to the pumping, so generally the slump of commercial concrete is large, as well as the water cement. To guarantee the water cement ratio, it should increase the dosage of cement. As a result, the concrete emerge shrinkage cracks will appear in induration.

Other causes of concrete cracks: The structure cracks caused by the loading influence generally have strong regularity, which can get the right conclusion through the calculation analysis. The additional stress of upper structures can induce floor cracks due to the unevenness of the ground settlements. The cracks produced by uneven settlements belong to penetrating cracks and the trend is relevant with settlement situation. The pre-embedded pipe line along the pipeline direction may appear surface cracks, in the local part may appear spread or polygon and irregular cracks. When the diameter of the embed line pipe is small, the width of the house is small and the layout of pipe line is not perpendicular to the direction of concrete shrinkage and tension, the floor cracks generally can be avoid. Conversely, when embed line pipe diameter is large, launch width is also large and the layout of pipe line is perpendicular to the direction of concrete shrinkage and tension, then it is easy to find floor cracks.

Prevention and control strategies for concrete cracks: Since a tiny crack would cause a severe accident in the steel fiber reinforced concrete, it is crucial to adopt effective prevention and control strategies to ensure the safety of structures. In this study, we have overviewed some ordinary methods of damage prevention and control.

Quality ensurance of raw materials: It is necessary to control the raw materials strictly and to construct structures according to the standard requirement. The cement into the construction area must have quality certificates for review. Because the cement test result often comes out up to 28 days in general, the time cement into construction area needs control reasonably. At the same time, the mixing proportion need be checked repeatedly, the rebar need have qualified certificate for checking and only qualified product after checking can be used. In addition, accurate dosing, even mixing, suitable transportation time, close-grained vibrating, maintenance according to the rules are all necessary. At the same time it is necessary to construct structures in accordance with the mandatory and standard requirements strictly. Try to delay the dismantling formwork time and choose the low alkali cement less than 0.6% and control the total alkali amount of raw materials. In addition it is necessary to do aggregate activity inspection, restrain alkali aggregate reaction through necessary methods such as isolated from the water and wet air and so on.

Temperature controlling: In order to prevent the cracks, it is necessary to control the temperature. There are two ways to reduce the temperature stress. One is to control temperature and the other is to improve constraint conditions. There are many strategies for temperature controlling such as adopting the improved aggregate gradation, using dry and rigid concrete and pouring mixture, adding air-entraining agent or plasticizing agent strategies to reduce the dosage of cement. In addition, pouring water in mixing concrete or reducing the concreting temperature though water cooling gravel are also good methods. It is necessary to reduce thickness when casting in hot weather and the heat can eliminate through the casting surface. The pipe embedded in concrete, with cold water cooling and set the reasonable dismantling formwork time are all necessary. When temperatures drop sharply the surface need heat preservation, in order to avoid produce temperature gradient on concrete surface. For the casting surface or thin-walled structure of the long term exposure of concrete, there are some measures for heat preservation in the cold season such as improving the seam and block rationally, avoiding the excessive rise of foundation, arranging construction process reasonably, avoiding the big attitude difference and lateral long-term exposure, etc. In addition, it can improve the performance of concrete, improve anti-cracking ability, strengthen maintenance and prevent surface drying shrinkage to realize the temperature controlling. Especially, ensuring the concrete quality is very important to prevent cracks. Thus it is necessary to pay more attention to avoid cracks throughout the floor. If the cracks have generated, resuming its structure integrity is very difficult; therefore in the construction should give priority to prevent the occurrence of penetrating cracks.

Self-constriction restraint: The self-constriction can be restrained by mixing coal ash and admixture. The concrete self-constriction depends on the dry degree of the internal cement stone, the elastic modulus and creep coefficient of the cement stone. In the early stage the elastic modulus is low, the creep coefficient is big and hence the drying speed is the main factor for self-constriction. The hydration of coal ash changes slowly in the system cement paste. So in the same water-binder ratio condition, replacing part of the cement with coal ash is equivalent to increase effective water cement ratio in early time. Then the coal ash can reduce the drying speed of internal concrete and reduce shrinkage significantly. Due to the reduction of the dosage of cement, the hydration heat of the concrete can be reduced in a great extent with the temperature shrinkage decreased. The internal dry degree of the coal ash increases by continuous hydration in the later stage, but now the concrete has high elastic modulus and low creep coefficient. Hence it will produce self-constriction much smaller than the earlier in the same dry degree situation.

Early curing: The early curing can reduce cracks with self-constriction reduced effectively. According to the self-constriction principle mentioned above, if the later for maintenance, the smaller for the boundary radius of curved liquid surface and hence the greater for pressure need to be added. Consequently, the maintenance is more difficult. When the internal resistance of concrete capillary wall is more than the tension of the water surface, the water can not migrate into inside, then the surface water fails to play a maintenance role for internal concrete. So in the actual construction process, early maintenance have great influence on self-constriction of the high performance concrete.

Experiment set-up for the fiber reinforced concrete specimens: Although there are useful crack prevention and control strategies in practice, they are all solutions in macroscopic. This means, these methods mentioned above cannot detect cracks consciously. However, detecting early cracks in advance is very important for the structure health monitoring, which could provide suitable maintenance strategies to repair the structures. To monitoring the cracks, it is imperative to research the damage mechanism of the fiber reinforced concrete.

In order to investigate the mechanical properties of the fiber reinforced concrete crack, the experimental tests

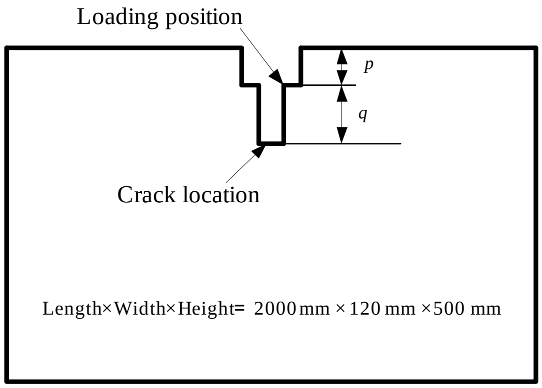

Fig. 1: The profile of the testing specimens

Table 1: The loading experimental parameters

Specimen no.	Parameter (p/mm)	Parameter (q/mm)	Max load (P/kN)
1	50	50	7.2
2	50	100	15.3
3	100	50	6.8
4	100	100	13.5

have been carried out on four specimens using a universal testing machine in this study. The profile of the testing specimens is shown in Fig. 1. The proportion of the fiber reinforced concrete specimens was as cement mixing: water: sand: stone = 1: 0.47: 1.40: 2.85. The quality of the steel fiber accounted for 4% of the total weight of the specimens. The dry mix method was adopted and the experiments were carried out after one month when the specimens were in good condition.

In Fig. 1, parameter p denotes the distance from the loading point to the specimen top surface and parameter q denotes the distance from the loading point to the crack top point. Since the crack location has great influence on the mechanical properties, different values of parameter p and q were used to investigate the fractural mechanism of the fiber reinforced concrete. The loading experimental parameters are listed in Table 1.

In the experiments, a key groove was used to generate horizontal force, i.e., the loading force P can be decomposed into horizontal force component F_1 and vertical force component F_2:

$$F_1 = \frac{P}{2}\cos\gamma \tag{1}$$

$$F_2 = -\frac{P}{2}\sin\gamma \tag{2}$$

where, γ is the angle of the key groove and $\gamma = 20$ in the experiment tests.

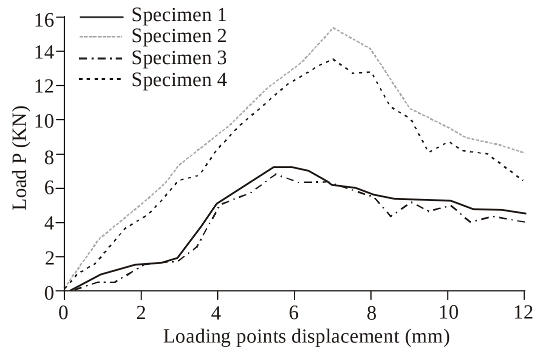

Fig. 2: The relationship of the load and the loading point displacement

For each specimen, eight strain gauges were installed close to the loading point along the vertical direction with an equal interval. The size of the strain gauge was 30×12 mm, the electric resistance was 120 Ω and the strain gauges coefficient was 2.1. The specimens were experimented from the crack stage to fracture. The relationship of the crack development and the load was analyzed.

EXPERIMENTAL RESULTS AND DISCUSSION

The relationship of the load and the loading point displacement is shown in Fig. 2. It can be seen in the figure that the specimens do not break down at the max load point, which is different from the ordinary concrete. This is because the fiber has enhanced the toughness of the concrete and hence increased the crack control ability. The interaction between the fibers and the cracks improves the strength and toughness against the crack opening and developing. As a result, the fracture processing has showed a strong ductile fracture character. The bridge effect has arisen to constrain the crack development. The results agree well with the experiments reported by Gao *et al*. (2005), Xu *et al*. (2007) and Zhang *et al*. (2000).

The relationships between the Crack Opening Displacement (COD) and the load of the four testing specimens are shown in Fig. 3 and 4. It can be seen in the figures that in the early stage of the loading processing, the COD is proportional to the load P. Hence, in the early stage, the elastic deformation is occurred before the load reaching to its maximum value. Under maximum load, the plastic deformation makes the crack open quickly and when the strength of extension is come over, the load value drops significantly and the crack develops rapidly to fracture. It emphasizes that the crest of the load can be an index of a damage caused by the rapid opening of the crack. The results agree with the theoretic analysis in Zhang *et al*. (2000).

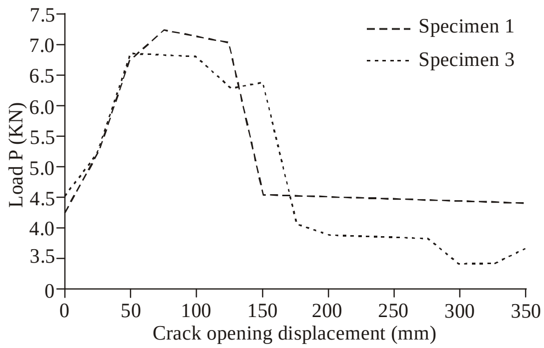

Fig. 3: The relationship of the COD and the load for specimens 1 and 3

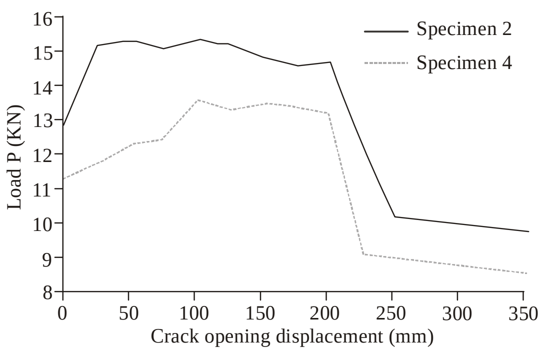

Fig. 4: The relationship of the COD and the load for specimens 2 and 4

From Fig. 3 and 4 it can be noticed that the COD could be predicted by the information of the concrete load. By setting a confidence limit of the concrete load, the monitoring value of the actual stress using the strain gauges can be used to alarm the cracks and detect the crack faults. In this specific case, the confidence limit could be 6.5 kN. By comparing the actual value with this confidence limit, the situation of the COD can be calculated and hence accurate crack detection can be achieved.

CONCLUSION

The fracture process of the steel fiber reinforced concrete has stronger ductility than ordinary concrete. Hence, it cannot to use the maximum loading value to determine the crack condition for the steel fiber reinforced concrete. To investigate the mechanical characteristics of the steel fiber reinforced concrete, experimental tests have been conducted on the specimens. The analysis results demonstrate that the crack develops rapidly during the maximum load but the specimens do not fracture immediately. The fracture happens after the load dropping. Hence, a confidence limit can be selected reasonably according to the mechanical properties of the steel fiber reinforced concrete to detect early cracks. The future study will continue to establish feasible crack detection scheme for practice application.

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