Performance Analysis of a CFRP Reinforced Concrete Slab under a Transient Dynamic Loading

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Summary. The dynamic performance of a carbon fiber reinforced polymer (CFRP)-reinforced concrete slab is investigated considering nonlinear constitutive modelling of steel and concrete. The fractural characteristic of the concrete slab strengthened by CFRP layers is obtained through finite element method under a transient loading. It is found that cracks of the concrete slab are restrained and the overall stiffness of the slab is improved with the extra strengthening from the CFRP layer. The peak values of the dynamic stresses, displacement and acceleration of the concrete slab decrease with more reinforcing layers. Based on the numerical analysis, addition of two CFRP layers gives the most effective reinforcement to the concrete slab.

Background of the Research

Carbon fiber reinforced polymer (CFRP) is a new type of composite material that has extremely big strength and high strength-to-weight ratio, and has been used in structural strengthening and restoration for the past decade. In a CFRP layer the function of structural reinforcement is carbon fiber. The matrix that binds the clusters of carbon fiber is usually a polymer resin made of epoxy. Previous studies on building have shown that externally bonded CFRP layers can provide concrete slabs, i.e. the major loading-carry components of floors, with large tensile rigidity and resistance to transversally growing cracks under dynamic forces.

The response of concrete slab is nonlinear owing to the materially nonlinear force-deformation relations for both concrete and steel. Other sources of nonlinearity are transversally propagating cracks that weaken the overall structural stiffness and the complicated stress state at the interface between concrete and CFRP layer. The focus of the present study is to determine the structural dynamics and fractural behaviour of the concrete slabs with the CFRP reinforcement. Due to the complexity in the structural assemblies, the fractural response, transient displacement and stress of the slab can only be solved numerically through finite element analyses.

Structural Modelling of the CFRP Reinforced Concrete Slab

Figure 1 shows the profile of a concrete slab, where the dots represent reinforced steel bars. The layers of strengthening CFRP are located on the tensile surface of the slab and are assumed to bond firmly with the slab exterior. The dimension of a single CFRP layer is sketched in Fig.2.

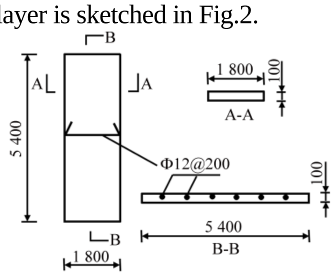


Fig.1 Profile of the concrete slab. Unit: mm.

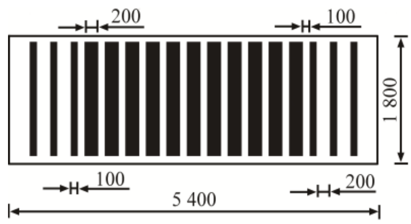


Fig.2 Layout of a CFRP layer. Unit: mm.

For the mechanical property of CFRP material, the Young's modulus is 230GPa, the ultimate tensile strength is 3400GPa. The force-deformation relation of CFRP is assumed elastically linear. For the concrete, the constitutive model of stress-strain is a multi-linear, kinematic hardening model with parameters given by Hongnestad [1], Fig.3(a). For the steel bars, the bilinear stress-strain model is used, Fig. 3(b). The onset of transverse cracks in the slab can be determined using the William-Warnke criterion of failure for concrete material [2]. The viscous damping factor for the concrete is chosen to be $0.66(1-0.072\eta)e^{30/f_{cu}}$, where η is the volumetric ratio of steel bars with respect to the total slab, and f_{cu} is the ultimate compressive strength of concrete. The ANSYS® solid65-type element, LINK8-type element and Shell181-type element are used to mesh the concrete, steel bar and CFRP layers, respectively. The full Newmark method is adopted to obtain the transient displacement, stress and acceleration of the slab.

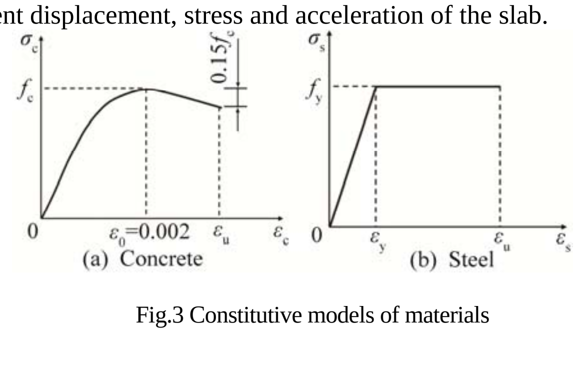


Fig.3 Constitutive models of materials

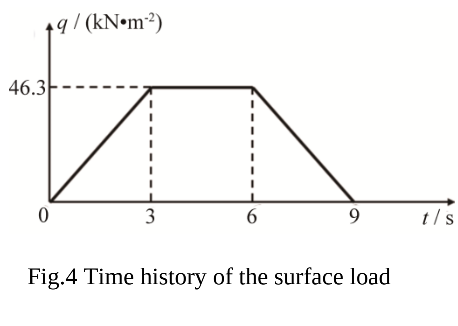
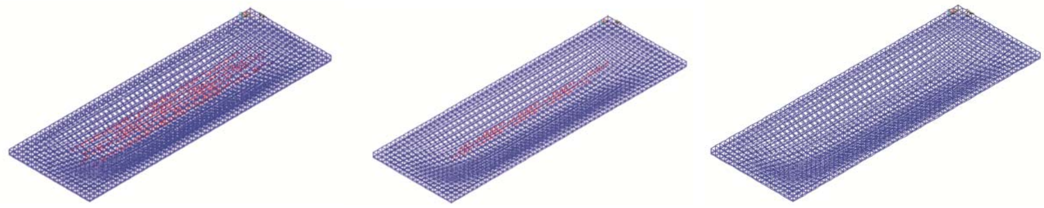


Fig.4 Time history of the surface load

Performance Analysis of the CFRP Reinforced Concrete Slab

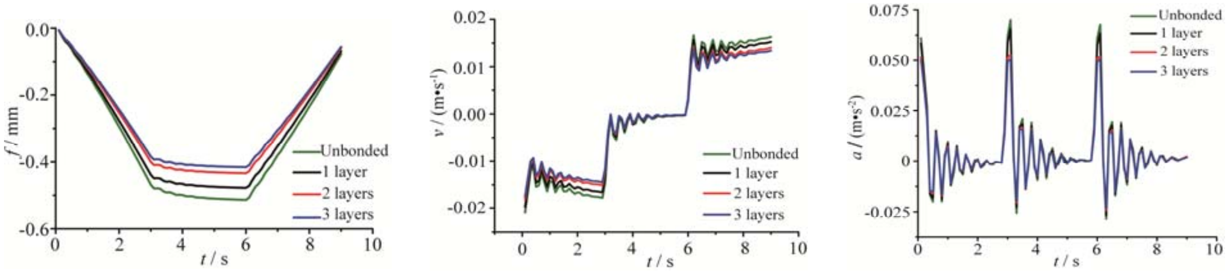
A uniformly distributed transient load of pressure/traction is applied on the surface of the concrete slab following the transient process of process in Fig. 4. The dynamical analyses are focused on how CFRP refrains transverse cracks in the slab. Figs. 5(a) and (b) show the crack distributions at the bottom of a unreinforced slab and the same one with one CFRP layer, respectively. It is seen that the propagation of transverse cracks is effectively refrained with the introduction of CFRP layer. Addition of one more CFRP layer almost eliminates all transverse cracks, Fig. 5(c).



(a) Unreinforced slab (b) Slab with one CFRP layer (c) Slab with two CFRP layers

Fig.5 Crack distribution on the concrete slab. The red dye marks the location of the cracks.

The time history of the maximum deflection at the central cross section with different magnitudes of strengthening is shown in Fig. 6(a). Increasing the number of CFRP layers leads to an effective reduction of deformation of the slab. A further comparison among the results indicates that the rate of deformation reduction does not change linearly with the number of CFRP layer. This implies that the best strengthening in this case is to use two layers of CFRP, which brings in the biggest rate of deformation reduction and still remains not costly on material expense. Figures 6(b) and (c) depict the time history of velocity at the same location. Conclusion can be drawn that adding more CFRP layers reduces the peak value of velocity on floor over the two load ramps in Fig. 4. The time history of the maximum acceleration is plotted in Fig. 6(c). Again, adding more layers of CFRP reduces the peak acceleration response of the slab. Based on the mandatory regulation of Chinese concrete buildings, i.e. JGJ-2010, the peak acceleration for comfort in this case should not exceed 0.054 m/s^2, which can be satisfied through paving two or more CFRP layers.



(a) The deflection (b) The velocity (c) The acceleration

Fig.6 Time histories of the maximum response at the central cross section with different layers of CFRP.

Finally, the dynamic stresses on the slab are evaluated with different numbers of CFRP layer. Figure 7 shows the contours of tensile stress for the unreinforced slab and the same slab strengthened by two layers of CFRP, respectively. The maximum tensile stress is 1.93 MPa, which is quite close to its ultimate value of 2.39MPa. By contrast, the maximum tensile stress drops to 1.54MPa when two layers of CFRP are attached to the slab, Fig.8.

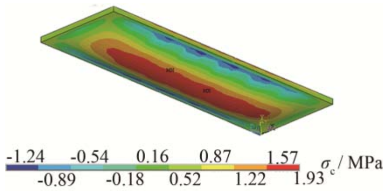


Fig.7 Stress contour of concrete slab without CFRP

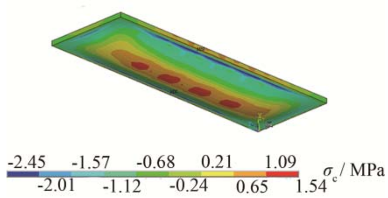


Fig.8 Stress contour of concrete slab with two CFRP layers

Conclusions

The dynamic performance of a CFRP reinforced concrete slab is studied considering nonlinear material models and dynamic loading. It is reported that CFRP is an excellent strengthening materials for concrete structures. The best strategy with the CFRP reinforcement can be determined through evaluating the fractural behaviour as well as transient displacement, acceleration and stress of the slab with different amount of CFRP consumption.

References

[1] Jiang J.J., et al. (2005) *Finite Element Analysis of Concrete Structures*, Tsinghua University Press, Beijing.

[2] William K. J., Warnke E. P. (1975) Constitutive Model for the Triaxial Behavior of Concrete. *Proc., IABSE 19th Seminar on Concrete Structures Subjected to Triaxial Stresses, Paper III-1, International Association for Bridge and Structural Engineering, Zurich, Zurich, Switzerland.*