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Experimental studies and numerical simulation of behavior of RC beams retrofitted with HSSWM-HPM under impact loading

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ABSTRACT

High Strength Steel Wire Mesh and High Performance Mortar (HSSWM-HPM) are widely used for structural reinforcement and retrofit. Recent research suggests that HSSWM-HPM can be applied to enhance seismic loading-resistance of structures. In this study, the mechanical performance of reinforced concrete (RC) beams covered with the HSSWM-HPM under impact loading were evaluated using both laboratory experiments, and numerical simulations. In the laboratory experiments, the performance of eight full-size beams, including five retrofitted RC beams and three un-retrofitted RC beams, subjected to the drop-weight impact loading and static loading were evaluated. During the drop-weight impact tests, the contributions of the following critical parameters, including the impact loads, strains, accelerations, velocities, and deflections of the beams, and residual damage, were studied and compared among different specimens. Another comparative study on the failure pattern and the impact resistance of beams with and without reinforcement were performed in the commercial finite element software LS-DYNA. A general prediction of response time histories and maximum mid-span deflections of the beams were obtained from LS-DYNA. The results obtained from both laboratory experiments and finite element analyses indicated that the impact resistance and ductility of the RC beams were significantly improved after retrofitted with HSSWM-HPM.

1. Introduction

Reinforced concrete structures are widely used in civil engineering. In recent years, RC structures are exposed to extreme dynamic loading conditions due to direct impact. Typical examples include heavy objects falling on RC structure in constructions, splash impact during explosions, ships crashing into the bridge piers, moving vehicles hitting guardrails. The analyses of structures under dynamic loads are often complicate due to the unique characteristics of the loads such as high intensities, extreme short duration, and concentrated damages. Impact loading is a dynamic effect, and the duration of loading is measured in milliseconds. Such short duration can be 1000 times shorter than earthquakes [1]. Meanwhile, considering the plasticity of reinforced concrete, the analyses and design of RC structures under dynamic loading are very complicate; however, traditional static analyses cannot take dynamic effects into consideration which leads to inaccurate prediction of RC structure performances under dynamic loads.

A large number of tests have been conducted in order to investigate the structural response of reinforced concrete (RC) beams and slabs subjected to different rates of concentrated loading applied at the mid-span of the RC specimens. Based on the available test data [2–9] and numerical evidences [4,5,10], the recorded dynamic response exhibits substantial differences compared to that established based on static testing. The discrepancy becomes more significant as the loading rates increase.

In order to improve the impact resistance of RC structural components, such as beams, columns and slabs, retrofitted with steel plates [11–14], FRP [15–21] and High Strength Steel Wire Mesh and High Performance Mortar (HSSWM-HPM) have been studied and used in engineering practice.

Base on the retrofitting technology on ferrocement [22] and wire rope units [23,24], a new retrofitting technology with steel wire mesh and polymer mortar attached to concrete components were developed by Kim and Choi [25]. Although HSSWM-HPM laminates were being increasingly used to repair buildings, limited studies were carried out on the effect of impact loads on structures repaired with HSSWM-HPM laminates.

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In this paper, the dynamic response of RC beams strengthened with high strength steel wire mesh and high performance mortar subjected to impact loads with low velocity was investigated by drop hammer impact tests and numerical simulations. Eight full-sized beams, including five retrofitted RC beams and three un-retrofitted RC beams were designed for the laboratory experiments. Critical factors that influenced the dynamic behaviors of the RC beams including the impact hammer weight, impact velocity, reinforcement were studied. Comprehensive analyses were conducted to investigate the following five aspects: failure modes, cracks development, stress and strain, displacement, and acceleration. Furthermore, a static loading test is applied to one reinforced RC beam to confirm significant differences between the static and dynamic responses of the structure. By comparing to the test results under the static load, numerical stimulation of seven RC beams under impact loads were performed to further understand the experimental results.

2. Impact tests

In order to investigate the impact load responses of RC beams retrofitted with HSSWM-HPM, impact tests on seven RC beams were carried out, including three comparative un-retrofitted beams and four retrofitted beams. In order to distinguish different failure modes of the RC beams subjected to static loading and impact loading, a retrofitted RC beam was tested under a static load for comparison purpose. During the impact test, the impact energy was controlled by the weight and the falling height of the drop hammer. Retrofitted RC beams may turn their failure modes from a ductile mode (bending failure) at low impact energy to brittle mode (punching and diagonal shear failures) under higher impact energy. The impact responses were evaluated by comparing test results at different loading modes.

The performances of RC beams with different configurations under static and impact loads were investigated experimentally. The size of the un-retrofitted beam was 2800 × 200 × 400 mm ($l \times b \times h$) with clear span was 2400 mm. The concrete grade of the beam was C30 (with the axial compressive strength of 150 mm × 150 mm × 300 mm concrete prism is 25.67 MPa, which is shown in Table 1), and the reinforcement grade was HRB335 (HRB means Hot-rolled Ribbed-steel Bar), the yield strength is 300 MPa, the detailed design is shown in Fig. 1. The mortar contains polypropylene fibers with the grade of M50 (with the axial compressive strength of 70.7 mm × 70.7 mm × 70.7 mm mortar cube is 56.1 MPa as shown in Table 2). The type of the high strength steel wire was 6 × 7 + IWS. The diameter of steel wire was 3.2 mm or 4 mm. The longitudinal spacing of the steel wires was 30 mm, and the transverse spacing was 40 mm. The detailed design of the RC specimens was shown in Fig. 2.

As is shown in Fig. 3, the strain gauges of longitudinal rebar were installed at six locations in mid-span (see Fig. 3(a)); the strain gauges of the concrete or the mortar were located at the beam surface which can be seen in Fig. 3(b). The variation and distribution of the strain were obtained by the amplifier after the impact [26]. Specified loading cases for RC beams are listed in Table 3.

The impact tests were performed with an advanced drop hammer device (as shown in Fig. 4) which was developed by researchers in Hunan University. The beams were hinged at both ends with the drop hammer dropped freely onto the top surface of the RC beams at their mid-spans. The simple support arrangement illustrated in Fig. 4(b) consisted of free rollers 32 mm in diameter positioned so that the span between the supports was 2400 mm. In the vertical direction, the rollers were placed between two steel bearing plates. The rollers and plates extended the full width of the specimen, that is 200 mm. The weight of the hammer can be changed by adjusting the quantity of counterweights, and the impact velocity affecting the impact energy was controlled by the drop height of the hammer. Displacement transducers were installed on the mid-span and the 1/4 points of the beams as shown in Fig. 5. Accelerometers were located on the mid-span and the 1/4

Table 1
Properties of the concrete.

Concrete (C30)	Failure load of cube test (kN)	Cube strength f_{cu} (MPa)	Failure load of cylinder test (kN)	Cylinder compressive strength f_{cu} (MPa)
B-1	1156.90	51.42	651.26	36.85
B-2	1123.90	49.95	648.7	36.71
B-3	704.51	31.31	422.5	23.91
B-8	716.61	31.85	374.5	21.19
B-4	911.14	40.50	492.61	27.88
B-5	934.46	41.53	425.32	24.07
B-6	764.75	33.99	378.08	21.39
B-7	802.84	35.68	357.75	20.24

Note: Cube size is 150 × 150 × 150 mm, cylinder size is D150 × 300 mm.

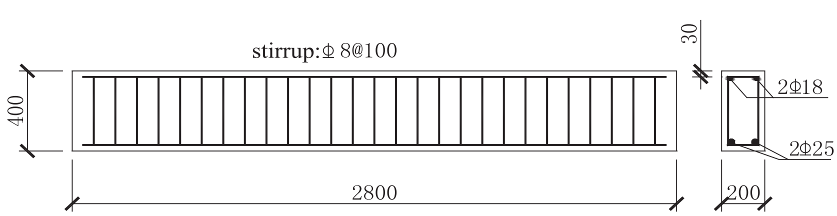

Fig. 1. Sketch of beams (Unit: mm).

Table 2
Properties of T D-JS high performance mortar.

Mortar	7d compressive strength (MPa)	28d compressive strength (MPa)	7d flexural strength (MPa)	28d flexural strength (MPa)
M50	36	56.1	7.5	10.3

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