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Flexural behavior of large-size RC beams strengthened with side near surface mounted (SNSM) CFRP strips

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ABSTRACT

Taking the reinforcement of monorail guide-way as the background, the effectiveness of SNSM carbon fiber reinforced polymer (CFRP) strengthening technique applied for the large-size reinforced concrete (RC) beams was evaluated. First, considering the effect of curing condition, the single shear pull-out tests of NSM CFRP were carried out to determine proper curing temperature and time. Second, considering the influence of CFRP spacing, prestress level of CFRP and longitudinal reinforcement ratio, the flexural experiments of strengthened beam with SNSM CFRP technique were carried out by four-point loading method. The results showed that the bond behavior between CFRP and concrete represented a negative quadratic curve with curing temperature and a positive arc-tangent curve with curing time. The flexural capacity of strengthened beams was obvious higher than the un-strengthened beam, which were increasing with the improvement of prestress level and the reduction of CFRP spacing. However, the improvement of flexural capacity of strengthened beam with prestressed CFRP was not obvious with the increase of prestress level, and the longitudinal reinforcement ratio had a negative impact on the flexural capacity. Finally, considering above-mentioned factors, a predicted model of flexural capacity and mid-span deflection for the beam strengthened with SNSM CFRP was developed and validated.

1. Introduction

In recent years, more and more cities are starting to build monorail transportation because of its the advantage of strong adaptability to complex terrain, climbing ability, small turning radius and low cost and so on (Fig. 1a). The main features of the guide-way include narrow cross-section, limited operating space at the bottom and the two side for the vehicle walking surface (Fig. 1b). When the flexural zone of guide-way suffers minor damage, it needs to be repaired and strengthened in the side of the guide-way with near surface mounted (NSM) carbon fiber-reinforced plastics (CFRP) technique, which can maintain the size of original structure and ensure the normal operation of monorail vehicle. However, in view of the fact that adhesive material, widely used currently, needs 3–7 days to cure at ambient temperature for the strengthened structure to loading, which is unacceptable for monorail traffic. If a special adhesive material is used that can shorten curing cycle, the repair cost will be increased greatly. Therefore, it is necessary to explore an economical and applicable reinforcement method for the actual situation of monorail traffic.

The NSM strengthened technique with FRP has been developed in recent years, since it can effectively increase the flexural capacity and avoid stripped damage of CFRP compared with the external strengthened technique. In this NSM technique, FRP strips are embedded into thin grooves on the concrete cover with epoxy resin. Not only does it maintain the cross-sectional dimensions, it also improves the durability of the strengthened structure and enhances the bond performance of CFRP.

Existing literatures show that a number of experiments have been conducted on the bond performance between NSM CFRP and concrete at ambient conditions. From the perspective of research results, the NSM CFRP can exhibit satisfactory bond properties when the specimens were cured at ambient conditions. However, due to the sensitivity of epoxy resin to temperature, when the specimens are tested after being cured for a predetermined time at a given temperature, the bond behavior between CFRP and concrete is more worthy of attention. In contrast to bond properties at ambient conditions, the bond behavior of NSM CFRP technique, considering the influence of temperature, is not well studied in the literature.

Regarding the bond behavior with NSM technique, Omar Moussa investigated the early-age development of the mechanical properties (tensile stiffness and strength) of epoxy adhesives that was subjected to the same low-temperature curing (5, 10, 25, 40 and 70 °C). The results indicate that the evolution of the mechanical properties of epoxy adhesives strongly depends on the curing temperature [1].In the literature

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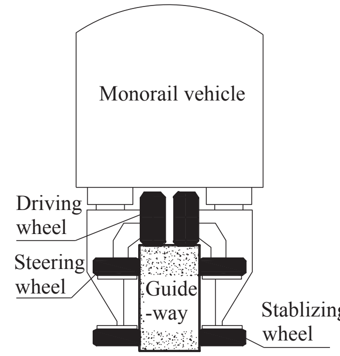
(a) Close-up view of monorail



(b) Monorail schematic

Fig. 1. Monorail traffic.

[2], to compare the influence of different curing conditions on bond performance, the single shear pull-out tests of concrete specimens strengthened with NSM CFRP strip were conducted considering three different curing temperatures (20, 30 and 40 °C) and five different curing time (6 h, 8 h, 10 h, 12 h and 72 h). In addition, considering the effect of drastic changes of ambient temperature, Lee also investigated the bond performance of NSM CFRP strengthening specimens with different filling materials subjected to various numbers of temperature cycles from −15°C to 55 °C [3]. Hu [4,5] investigated the bond performance of externally bonded CFRP strips with pull-off tests at range of 4–180 °C. The results report that the glass transition temperature of epoxy adhesive have a negative impact on the bond strength of NSM-FRP strengthening systems. When the temperature was near the glass transition temperature, the bond behavior of structural adhesive had suffered a serious drop. To study the bond performance of strengthened structure with NSM technique that was exposed to the fire environment, a high strength self-compacting cement base with graphene oxide (IHSSC-CA) was developed as a filling material. Mohammed [6] presented the research in which the behavior of NSM CFRP strengthening technique using IHSSC-CA as a filling materials under high temperatures of 400, 600, 700 and 800 °C was investigated by single-shear pull-out tests. Yu [7] investigated the tensile strength and elastic modulus properties of the NSM CFRP (strip and rod) in 20–600 °C temperature range by pull-out tests. The results show that the effect of curing temperature on tensile strength and elastic modulus are obvious.

As for the flexural behavior of strengthened beams, the NSM strengthening technique with FRP have been confirmed to possess better durability, fatigue resistance and bond performance compared to the Externally-Bonded (EB) FRP strengthening technique [8]. Hong [9] investigated the flexural capacity of RC beam strengthened with NSM technique at the bottom of beam considering the effect of section geometry, compressive strength of concrete, tensile reinforcing bar ratio and the number of CFRP strips. As it were difficult for the bottom grooves of the strengthened beam to be cut up to the faces of the supporting, Sharaky [10] investigated the flexural behavior of strengthened RC beams with NSM FRP bars of limited bond length in order to replicate the actual work-place conditions as much as possible considering the effects of material type, epoxy properties, bar size and the number of NSM bars.

Though the NSM method performs well in the lab tests, it does face some problems in the actual work-place conditions. The bottom of the strengthened beam with the NSM technique must have sufficient width to ensure the properly distance between the groove and a necessary edge clearance, the lack of which would cause localized cover separation, beam bottom edge cover separation and premature failure by debonding due to overlapping stresses.[11]. In response to this, a side near surface mounted (SNSM) technique was proposed by Hosen [12], where placed the NSM reinforcements at the side of the strengthened beam. The results show that the technique not only solved the problem of overlapping stresses, but also increase the flexural capacity of the strengthened beam against the concrete cover separation failure. Considering the effect of the amount of strengthening reinforcement, bonded length and end anchorage and pre-crack and so on, the flexural behavior of RC beams strengthened by the SNSM technique using GFRP bars were investigated [13–15].

However, the SNSM FRP technique still can't resolve the deformation incompatibility between the high strength concrete and FRP, which results in a rather limited contribution of FRP to the flexural capacity of the strengthened structure. Therefore, the scholars present the prestressed NSM FPR technique, which can achieve a higher bond capacity and improve the utilization of FRP materials. Peng [16] compared the flexural performance of strengthened beams with EB FRP plates and prestressed NSM FRP strips through 7 rectangular RC beams test. Badawi [17–18] investigated flexural behavior of RC beams strengthened with prestressed NSM FRP rods. The results indicate that the NSM prestressed FRP strengthening technique can effective improve the yield load and ultimate load of the strengthened beams compared to that of the un-strengthened beam. Hajihashemi [19] carried out the experiments of five small-size RC beams strengthened with prestressed NSM FRP methods (prestress level of 5–30%). The results show that the yield load of prestressed strengthened beams is increased by 9%, the ultimate load is increased by 15%, and the crack width is reduced by 22–52% compared to that of the control beam. Choi [20] investigated the flexural behavior of strengthened RC T-beams considering the prestress level and the unbounded length at the mid-span of the beam, which showed that the prestressed strengthened beam with NSM technique could increase the ultimate carrying capacity obviously. Rezazadeh [21] assessed the effect of the prestress level (20%, 30% and 40%) on the flexural performance of strengthened RC beams with NSM CFRP. The results show that prestressing can not only improve the flexural carrying capacity, but have an impact on the failure mode of the strengthened beam. Similar failure mode and flexural behavior were observed by Hosseini et al. [22–23], who carried out three RC slabs strengthened with prestressed NSM laminates. Rezazadeh [24] proposed a NSM hybrid technique, which combined non-prestressed and prestressed CFRP laminates in order to provide a good balance in terms of load-carrying and ultimate displacement capacity to the strengthened beams.

At present, the research on flexural experiments of RC beams using SNSM strengthened technique was mainly focused on small-scale and low-strength RC beams, which were inconsistent with actual RC beams. However, considering the effect of curing condition (low temperature), the research results on the flexural behavior of RC beam strengthened with SNSM CFRP were still not adequate.

In the paper, first, to explore a reasonable combination of curing temperature and time, the single shear pull-out experiments of NSM