A reinforced concrete medical building was in the process of structural remediation for flood protection purposes. During construction, an existing structural deficiency was found in the pan-joist flooring system. The 150 mm (6 inch) wide joists were designed with two 29 mm (No. 9) ASTM A615 Grade 60 (420 MPa yield) reinforcing bars at the bottom face. At the center of the joists the bottom reinforcement was spliced in the horizontal plane such that the four reinforcing bars were placed side-by-side in direct contact. The steel placement created an area of poor concrete consolidation along the entire length of the splice. The bond between the reinforcing bars and the concrete was compromised in the splice zone resulting in a reduction of the positive flexural capacity. In addition the lack of ties in the splice region contributed to a capacity reduction and to cover splitting.

Inspection of the joists found many locations where the concrete cover was either spalled off of the bottom face of the joists or was not present due to poor original consolidation, improper bond between the rebar and the concrete, and lack of confining ties. Because the improper bond was located at the splice region and was near the point of maximum moment, we concluded that the joists did not have proper flexural strength and required strengthening. Several strengthening procedures were considered. A Carbon Fiber Reinforced Polymer (CFRP) scheme was selected due to the number of joists and the tight confines created by the MEP (Mechanical, Electrical and Plumbing) systems present on the underside of the pan joist floor.

The joists were strengthened by applying CFRP laminates to the joist soffit. The CFRP strips spanned across the splice and developed beyond the splice region. The design of the CFRP allowed the existing joists to develop their original positive flexural capacity.

KEYWORDS
FRP, Shear, Bond, Splice, Pan Joist, Strengthening.

INTRODUCTION
A multistory medical school and research building was in the process of being upgraded to resist exterior flood loads when a construction deficiency due to improper splicing of the joist bottom reinforcement was found in portions of the pan-joist floor system. Several repair schemes were considered; FRP was selected due to the fact that it could be implemented quickly without impacting the construction schedule and without requiring removal and re-routing of the surrounding MEP (Mechanical, Electrical and Plumbing) systems. The repair was performed by installing FRP laminates at the joist soffits and FRP U-wrap at the splice region and at one end of the joist span.

BUILDING DESCRIPTION
The building has seven stories and a basement. It is constructed with reinforced concrete frames and a reinforced concrete pan-joist floor system. The 150 mm (6 inch) wide joists were designed with two 29 mm (No. 9) ASTM A615 Grade 60 (420 MPa yield) reinforcing bars at the bottom face. At the ground level, a roadway penetrates the width of the building. The floor system spans in the north-south direction along the long axis of the building, with a typical span of 9.8 m (32 feet) between girders spanning in the east-west direction. The roadway penetrates in the east-west direction through the full width of the building.
PROBLEM DESCRIPTION

In order to depress the roadway relative to the interior floor slab, the pan joists at the roadway were designed with a 240 mm (9.5 inches) drop in the surface elevation at the curb, located near the mid-point of the joists (Figure 1). Rather than designing the joists with a constant elevation soffit, which would be excessively deep on the high side of the curb, the designer chose to create an offset in the soffit so that the joists have a uniform depth. Because the joists spanned 9.8 m (32 feet), a non-contact lap slice was created at the center of the joists. This detailing was acceptable at the change of joist geometry and allowed for a proper transfer of the tension force in the bottom reinforcing. The location of the bars as shown on the drawings would have permitted proper concrete consolidation and allowed for proper bond between the tensile reinforcement and the surrounding concrete.

However, the as-constructed joists did not match the as-designed joists. Instead of constructing a step in the joist soffit, the joist was tapered as shown in Figure 2. While the reasons for this change are not documented, it is perceivable that the slopping soffit eased concrete forming and allowed for a more economical construction. While the joist geometry was modified, the splice location was maintained (Figure 2). The positive flexural reinforcement was placed along the bottom of the joist with a contact lap slice at the mid-span where the flexural moment reaches its maximum value.

During construction of other elements of the flood protection system, spalling of the concrete was noted on the bottom face of several joists. At the spalled areas, it was noted that the splice was constructed in a horizontal configuration (Fig. 4), such that the bottom face of the 150 mm (6 inch) wide joist were essentially covered with steel (Fig. 3). This condition did not allow for proper concrete consolidation and for the development of the full capacity of the reinforcing bars. In addition, the lack of confining stirrups reduced the splitting load further. These combined factors led to a reduction in the positive flexural capacity of the joists.

Figure 1. As-designed joists.

Figure 2. As-constructed joists
In order to assess the extent of the problem, a field investigation with the use of Ground Penetrating Radar (GPR) was performed. GPR uses high-frequency electromagnetic waves. Energy is propagated into the concrete and is partially reflected at the surface. This method acquires information within the concrete beam and is used to locate reinforcement and other items embedded in the concrete. GPR results indicated that the majority of the joists were constructed with an improper horizontal lap splice (Table 1). In order to validate the GPR results, localized chipping of the concrete was performed at some of the joists.

<table>
<thead>
<tr>
<th>Approximate percent of lap</th>
<th>Number of joists</th>
<th>Percent of joists</th>
</tr>
</thead>
<tbody>
<tr>
<td>splice installed horizontally</td>
<td></td>
<td></td>
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<tr>
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**STRUCTURAL UPGRADE**

The primary purpose of the structural upgrade was to provide a tensile force at the joist bottom equivalent to the reinforcing bars specified in the original design. Several design criteria were considered in evaluating the candidate repair solutions:

1. The repair solution could not delay the existing construction schedule.
2. The repair solution could not interfere with the existing MEP components in the basement. This was a severe limitation as the joists were obstructed by numerous MEP systems and components.

The use of an FRP system epoxy-bonded to the soffit of the existing joists was determined to be the only solution that satisfied these criteria. The use of a concrete jacket was also investigated but was not retained.
While this latter solution could provide the required strength, its implementation requited disruption and re-routing of the existing mechanical systems.

The repair was accomplished with the use of a wet layup system of CFRP sheets having a thickness of 1.0 mm (0.041 inches), an ultimate tensile strength of 875 MPa (127 ksi) and an elastic modulus of 72,400 MPa (10,500 ksi). The width of the sheets was equal to the joist width, 150 mm (6 inches). The amount of laminate plies provides a force equivalent to the tension of four 29 mm (no. 9) ASTM A619 reinforcing bars. The upgrade was done following the general recommendations of ACI 440.2R-02 (ACI Committee 440, 2002), which considers the design of the FRP for both bond capacity and tensile strength.

The laminate was required at the splice region and needed to extend beyond to allow for proper development and force transfer to the existing main reinforcement. At the north side (toward gridline 3), the laminates had enough length be properly developed. However, the available joist length in the south end (toward gridline 4) did not permit a proper development. At that location, positive mitigation was provided with the use of transverse anchorage formed by U-strips and GFRP anchors (Fig. 5).

Figure 5. Typical FRP upgrade of joist

The CFRP applied to the joist followed the soffit which was not horizontal but exhibited a geometric change at two locations (Fig. 3). At these locations the tensile force on the laminate changed direction and resulted in an outward or inward force. To balance this force U-strips with GFRP anchors were provided. GFRP anchors were sized based on tested capacity.

CONSTRUCTION

The construction adhered to the stated criteria and was performed without disruption to the existing mechanical, electrical and plumbing system located directly below the joist soffit (Fig. 6). It was completed in a timely fashion without any impact to the building operations.

As part of the construction quality control, we required that a testing laboratory independent of the design or construction team conducts a number of tests to verify the FRP properties and the construction adequacy.
Responsibilities of the testing laboratory included checking for proper surface preparation, collecting FRP coupon samples to verify the material properties, conducting on-site pull-off tests to verify adherence of the material to the concrete substrate, and checking for delamination and voids.

Verifying the actual properties of the material is essential to validate the design which was initially based on data provided by the manufacturer. The bond tests were needed to verify that the existing concrete was sound and the CFRP laminate was properly bonded to the substrate. Other tasks of the testing laboratories consisted in verifying conformance of the construction with the design documents.

However and due to the relatively recent introduction of the FRP material into the building construction market, most testing laboratories were not trained in collecting or testing FRP material. This situation was previously noted (Bouadi et. al, 2006) and presented a challenge in verifying the material properties and the construction quality. To overcome this obstacle, several steps were taken. The coupons were collected by the contractor in presence of the engineer and testing laboratory personnel to create a level of reliability. The collected samples were then submitted to an out-of-state independent specialty laboratory with prior experience in testing of CFRP coupons. The on-site bond tests and construction quality verifications were performed with general guidance and training of the testing personnel by the Engineer.

CONCLUSIONS

During a renovation of a reinforced concrete building, an existing structural deficiency was found in the pan-joist flooring system. At the mid-span of a series of concrete joists the bottom reinforcement was spliced in a horizontal plane such that four 29 mm (no. 9) ASTM A615 reinforcing bars were placed side-by-side in direct contact within the 150 mm (6 inch) width of the joists. The steel placement created an area of poor concrete consolidation and compromised the bond between the concrete and the reinforcement. The analysis concluded that the joists did not have sufficient flexural strength and needed to be upgraded. Several strengthening procedures were considered. A Carbon Fiber Reinforced Polymer (CFRP) scheme was selected due to the number of joists and the tight confines created by the MEP systems present on the underside of the pan joist system. The repair was performed by installing FRP laminate at the joist soffits and FRP U-wrap at the splice region and at one end of the joist span.

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