FLOOR DIAPHRAGM STRENGTHENING OF CONCRETE STRUCTURES WITH FRP

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SUMMARY

Elements of reinforced concrete (RC) structures such as beams, columns and shear walls are typically the main load resisting elements during a seismic event. The floor diaphragm is also critical to ensure that the overall seismic performance of the structure is acceptable. Diaphragm action ensures that inertial loads are transferred to the seismic resisting elements to create a complete load path for earthquake generated loads. Poor diaphragm capacity may result in unacceptable earthquake performance and the building may therefore require diaphragm strengthening to achieve New Zealand Building Code life safety objectives.

Amongst the various techniques to improve connections and to improve the diaphragm capacity, the use of fibre-reinforced polymer (FRP) composites as externally bonded reinforcement (EBR-FRP) systems is popular, primarily because FRP materials do not add to the weight of the structure and are relatively easier and more flexible to install than conventional materials like steel or concrete.

Several design guidelines, such as ACI440.2R-17 (USA), CNR-DT200 (Italy) and the fib Bulletin 14 (Europe) are available to designers but no guidance is provided in these documents regarding the specific strengthening of floor diaphragms. Further, there is limited available literature on the strengthening of diaphragms using FRP as a solution. Engineers therefore generally have to resort to innovative design solutions. A concise summary of the use of FRP for floor diaphragm strengthening is presented in this paper with a focus on two projects that required innovative thinking in order to develop solutions to difficult and complex problems.
INTRODUCTION

Our understanding of the seismic response of reinforced concrete (RC) structures is constantly improving as more research is completed and more knowledge is gained from observing performance of actual buildings in earthquakes. Such new understanding can mean that existing structures may not meet the requirements of updated design Standards. As a result, strengthening interventions may be required so existing structures can meet the life safety objectives of the New Zealand Building Code.

Whilst a new framework has been established under the earthquake-prone building (EPB) methodology to assess and identify buildings that may pose an unacceptable earthquake risk no nationally recognized guidance exists for the design of strengthening systems, although guidance exists in other jurisdictions (ASCE/SEI 41 2017). Among the numerous methods to improve the seismic performance of existing buildings, externally bonded fibre-reinforced polymer systems (EBR-FRP) are popular. The main reason for this popularity is that EBR-FRP materials have a very high strength-to-weight ratio: this avoids adding more seismic weight to the structure while substantial strength can be imparted to the structure. In addition to that, FRP materials are unobtrusive, lightweight and versatile. To support the development of design solutions New Zealand engineers often refer to the American Concrete Institute Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R 2017), as well as published research or in-house testing.

A primary concern relates to how to address potential seismic performance issues of hollowcore floor systems in existing buildings, particularly flexible buildings. The use of precast prestressed hollowcore units was prevalent in multi-storey construction in New Zealand in the 1980s and 1990s, especially in Wellington (Lindsay 2004; MacPherson 2005; Corney 2018). Pre-stressed hollow core systems consist of dry-cast extruded sections containing circular or oval-shaped voids to reduce the weight without reducing strength or stiffness requirements. When they are installed in a building they have a concrete topping poured over the hollowcore units that, in conjunction with reinforcing installed in the topping and adjoining structural elements, provides diaphragm action. Contemporary analysis indicates that the connections between the hollowcore floor systems and the supporting frames or walls that provide lateral resistance is often deficient and/or lacks redundancy (Conrey et al. 2014; Corney et al. 2018). A large number of existing multi-storey buildings that have been constructed with hollowcore floor systems may be vulnerable in a seismic event and therefore may require seismic strengthening. The seismic performance of hollow core floor systems in flexible frame buildings prone to beam elongation has been investigated in the past (Bull 2004), and a recent effort has been launched in New Zealand to address this situation and develop standardised methods to improve the seismic performance of precast concrete floor systems (Brooke et al. 2019). In the meantime, New Zealand engineers are designing various strengthening solutions to improve the floor diaphragm action, with the use of FRP popular. However, little research has been carried out on the use of FRP materials when used for the seismic strengthening for floor diaphragms. (Ormeno et al. 2019), and design guidance for diaphragm strengthening are not included in the main FRP design guidelines such as ACI 440 (2017), CNR-DT200 (2013) or fib bulletin 14 (2001).

The objective of this paper is to report on two examples of floor diaphragm strengthening solutions using FRP currently being applied to existing buildings. Common features as well as differences are highlighted in addition to knowledge gaps and research opportunities.
PROJECT ONE

The first project is a building in Wellington that incorporates precast walls as the lateral load resisting system, gravity-load resisting precast concrete columns and a hollowcore floor system connected to perimeter bond beams. The hollowcore floor system consisted of a 200 mm thick precast unit with a 50 mm concrete topping with a 665 cold drawn mesh (5.3 mm wire diameter in a square mesh 150 mm by 150 mm). The hollowcore floor system of this structure did not have acceptable tension capacity for the expected seismic demands, due to the brittleness and small size of the reinforcing mesh within the topping resulting in no effective diaphragm action. The connection between the hollowcore floor system and the perimeter bond beam was also/therefore deficient.

The strengthening solution consisted of an orthogonal grid of FRP strips designed to sustain the tension loads in the diaphragm, as illustrated in Figure 1. A perimeter anchoring system was implemented in the design to transfer the loads from the strips bonded to the topping of the hollowcore floor system to the perimeter bond beam, and to achieve effective diaphragm action. The perimeter anchoring consisted of FRP strips bonded to steel plates, which were embedded into the concrete topping and anchored to the bond beam using post-installed adhesive anchors. This perimeter anchorage was designed to provide redundancy for larger-than-expected earthquake demands, with the design level loads being transferred by the bond strength between the FRP sheets and the concrete topping.

The engineers were of the opinion that the strain and tensile capacity of the FRP-to-concrete bond, obtained from the provisions of ACI 440 (2017) or CNR-DT200 (2013), had to be substantiated. On-site testing was therefore undertaken in order to realise this goal (Ormeno et al. 2019). The on-site testing revealed that the tensile strain could not be accurately calculated using ACI (2017), while the provisions of CNR (2013) yielded an accurate tensile strength. The actual required bond length did not correlate with either of the two documents, with the results from the application of the provisions of the documents being unconservative.
(a) Lay out of the main FRP reinforcement

(b) Lay out of the perimeter FRP reinforcement, with 1 layer in pink and 2 layers in blue

(c) Detail of the perimeter anchorage (in section)

Figure 1 FRP reinforcement layout and details of project 1 (Ormeno et al. 2019)
Project Two

The second project is a heritage building in Auckland, built in 1923-1926. The building has perimeter reinforced concrete walls as the lateral load resisting system. A hollowcore floor system with a 38.1 mm topping and a 666 mesh was installed during building alterations around 1968 (Marteddu et al. 2018). A recent detailed seismic assessment concluded that the concrete floor system would not be able to transmit earthquake generated tension forces between the reinforced concrete walls. The same approach as for Project One was followed, namely, installing FRP strips in two orthogonal directions as illustrated in Figure 2.
The perimeter FRP strip was anchored to the perimeter walls using FRP anchors to ensure the load path continuity. The FRP anchors consisted of bundles of fibres soaked into epoxy with one end introduced into a hole predrilled into the structural element, while the other was bonded to the FRP sheet (del Rey Castillo et al. 2019a; del Rey Castillo et al. 2019b). A challenge to the FRP installation occurred when the carpet was removed, as it was discovered that the concrete had deteriorated significantly damaged and the steel reinforcement had corroded in places (refer figure 3a). Supplementary FRP was therefore required. Additionally, the poor condition of the substrate required FRP “plug” anchors in the bottom right corner of the building (refer Figure 2c). The FRP layout before applying a final protective cementitious layer is shown in Figure 3b.

(a) State of the hollow core floor before FRP installation  
(b) State of the floor after FRP installation

Figure 3 Pictures of the floor from Project 2

DISCUSSION, CONCLUSIONS AND FURTHER RESEARCH NEEDS

FRP can be used to improve the seismic performance of precast floor systems so they achieve increased diaphragm capacity. The common methods used in the design of FRP strengthening of floor diaphragms are (i) the use of an orthogonal grid of FRP strips, and (ii) a boundary layer of FRP which is anchored to the bond beam or perimeter wall. However, the methods used by engineers and contractors to anchor those boundary sheets to the perimeter vary. For instance, Project One utilised post-installed anchors and steel plates to transfer the load, while Project Two utilised FRP anchors.

As identified by the engineers from Project One, the provisions of ACI 440 and CNR-DT200 do not provide reliable values for FRP-to-concrete bond strength and strain for floor diaphragm applications. Further research therefore needs to be conducted in order to develop accurate models to predict the load that can be transferred by bonding to existing concrete. Furthermore, the load transfer will depend upon the presence, size and configuration of plug anchors, and hence this influence will need to be determined. Given the lack of design guidance to date on FRP diaphragm strengthening in existing buildings, the authors believe that addressing these problems by further research should be prioritised.
While the commonly observed approach of anchoring the orthogonal grid of sheets into the perimeter is reasonable, there is no research data to support this decision and their reliability is unproven. There is also no research data to provide guidance on the type of anchorage to determine if the reliability of their performance. Finally, the behaviour of the overall strengthening approach at a system level needs to be verified, especially considering the complex load paths with various stress mechanisms involved in floor diaphragms and how these mechanisms interact or are influenced by the overall building response.

REFERENCES


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