IStructE – Research into Practice Essay Competition
How your research was successfully applied in structural engineering practice

Assessment and Retrofit of Deficient RC Structures using Advanced Composites

Summary

Existing reinforced concrete (RC) structures built before the introduction of modern seismic codes contribute significantly to the disastrous consequences of earthquakes. The majority of these structures are substandard and deficient in light of our current knowledge and design codes.

During my post-graduate studies, I was involved in national and international research projects focusing on the assessment of seismic vulnerability of existing buildings and the use of advanced composite materials (Fibre Reinforced Polymers, FRPs) for structural rehabilitation, appropriate to Turkey and New Zealand`s earthquake-risk building stocks. These projects were sponsored by NATO (Scientific Affairs Division) and New Zealand`s Foundation for Research Science & Technology. During this period, I collaborated with a broad spectrum of people from different disciplines and backgrounds (e.g., independent researchers, practising structural designers, manufacturers, and local government building officials).

Following meticulous analytical and numerical modelling, as well as verification methods that included extensive experimental work, I successfully developed simple but accurate assessment and design procedures for FRP retrofit solutions. I used these cost-effective and low-invasive techniques to mitigate the poor performance of RC frames with infill masonry panels (which is a common construction practice in Turkey and Mediterranean countries) and deficient RC corner beam-column joints with and without slabs.

The experience and knowledge I gained from these projects were disseminated by presentations at numerous conferences, in peer-reviewed journal papers and industry technical guidelines. My research informed the drafting of national codes used by practicising engineers. The project outcomes were ultimately incorporated into the Turkish Earthquake Code and New Zealand Seismic Assessment Guidelines to be used by structural engineers nationwide. My research underpins current best practice for the international community of civil engineers.

Seismic strengthening of infilled RC frames with composite materials

[MSc Research Project – Bogazici University, Istanbul, Turkey, 2001-2005]

Following the two major earthquakes that struck Turkey in 1999, there was a broad recognition by Turkey's governmental, non-governmental and academic institutions of the urgent need for an appropriate seismic risk mitigation strategy, as well as systematic retrofitting of key structures, using a rationalised policy[1].

A significant amount of research had previously been devoted to the study of various strengthening techniques to enhance the seismic performance of the predominant structural system of the region, which is reinforced concrete frames with unreinforced masonry infill panels (Fig. 1(a)). Although strengthening RC frames by introducing RC infills to selected frame bays in both directions proved to be an effective seismic rehabilitation technique, the construction work involved is tremendously demanding and the procedure requires evacuation of the building for several months. As a result, its applicability in the rehabilitation of existing structures was neither feasible nor practical at that time.

To overcome these shortcomings, during my MSc` studies I participated in an international research programme, which was carried out as NATO Project 977231 “Seismic Assessment and Rehabilitation of Existing Buildings” and led by Middle East Technical University[2]. The aim was to develop efficient, economical, and easily applicable strengthening techniques for existing non-ductile RC frames in Turkey.

In this context, an alternative strengthening method consisting of externally bonded carbon fibre reinforced polymer strips (CFRPs) applied to the brick infilled reinforced concrete frames was proposed and experimentally validated. By this method, it was intended to convert the non-load bearing existing masonry panels to form a new lateral load-resisting system by strengthening and integrating them within the existing structural system. Compared to conventional retrofitting techniques (notably jackets of in-situ concrete and shotcrete), FRPs provide more cost effective and easier solutions, with less disruption to the building operation and occupants. Generation of debris, waste, noise and air pollution is minimised within the building and its surroundings, thus reducing the risk of accidents and health hazards.

In the laboratory, five one-third scale, one-bay, two-storey models were constructed with common deficiencies observed in existing RC frames (e.g., low concrete strength, insufficient lap splice length, poor confinement, and lack of joint reinforcement) and tested under reversed cyclic lateral loading[3]. A number of models, each reinforced with identical uni-directional CFRP strips applied in a cross-overlay formation, were tested with varying CFRP anchorage lengths. FRP anchor dowels, prepared by twisting the strips of CFRP sheets, folding into two and screwing into pre-drilled holes with epoxy resin, were used to reduce the delamination/debonding of the CFRP sheets from the surface of the wall. To demonstrate the actual application in practice, frames and infills were constructed by professional construction workers. FRP retrofitting of all specimens was undertaken by a specialist contracting service (Fig. 1(b)).

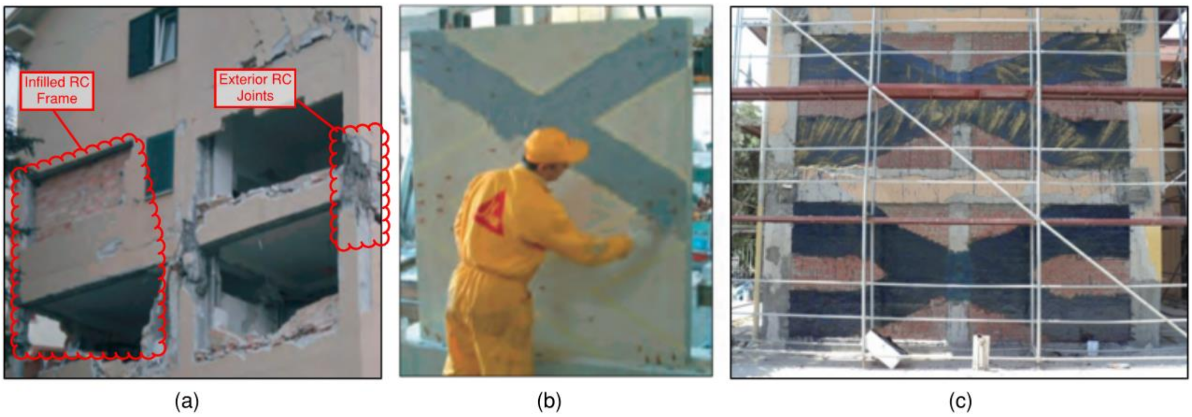

Figure 1: (a) A view of heavily damaged deficient RC frame; (b) Infill frame strengthening of a test specimen; (c) FRP strengthened RC frame of an office building in Istanbul

This pre-earthquake retrofitting approach was a relatively novel technique in comparison to the introduction of new cast-in-place concrete walls. Most of the previously recorded studies were based on small scale prototypes and utilising strengthening of individual RC members or brick walls. The majority of the work conducted by others related to brick-wall strengthening of the out-of-plane response of walls with externally bonded FRP.

The work undertaken during my MSc studies indicated that the proposed FRP retrofit scheme yielded a significant enhancement in the response of the walls under seismic loading. For building stability, the masonry infills in the existing RC frames, formerly regarded as non-structural elements, can successfully be transformed into structural walls. The strengthened specimens yielded a gradual and prolonged failure, more energy dissipation and increased apparent post-peak strength. Following verification through analytical studies, structural models were developed to estimate the behaviour of FRP strengthened RC frames with infill walls.

Assessment and design procedure for FRP retrofitted RC corner beam-column joints

[PhD Research Project – University of Canterbury, Christchurch, New Zealand, 2006-2011]

During my PhD, I was involved in an extensive research project on deficient concrete beam-column joints (Fig. 1(a)) to develop assessment methodologies and feasible seismic retrofit solutions based on the use of FRPs. This research was part of a multi-year project funded by the Foundation of Research Science and Technology (FRST) for “Retrofit Solutions for New Zealand Multi-Storey Buildings”[4]. The work has taken me to Italy, Germany, China and Switzerland, and allowed me to present at numerous international earthquake conferences and collaborate with various international research groups.

Scarce information is available in the literature on the response of deficient and retrofitted exterior joints under multi-dimensional earthquake conditions (varying axial load and biaxial bending). Most of the studies concentrated on the two-dimensional response, thus subjecting the specimens to uni-directional cyclic loads under constant axial load. In addition, relatively limited work has been dedicated to the development of a simple, but reliable analysis and design procedure for FRP-strengthened joints.

To address these issues, I designed and carried out a series of quasi-static tests on 2/3 scale deficient beam-column joint sub-assemblies under varying multi-axial load demands[5] (Fig. 2(a)). In the next stage, I developed a design procedure and an analytical model together with a practical retrofit strategy for improving the performance of deficient RC beam-column joints using FRP materials (Fig. 2(b)). Further tests including a shake table assessment of a non-ductile 3-storey 2/5 scale RC frame model structure and finite element studies were also carried out to validate the proposed assessment and retrofit solutions[6,7].

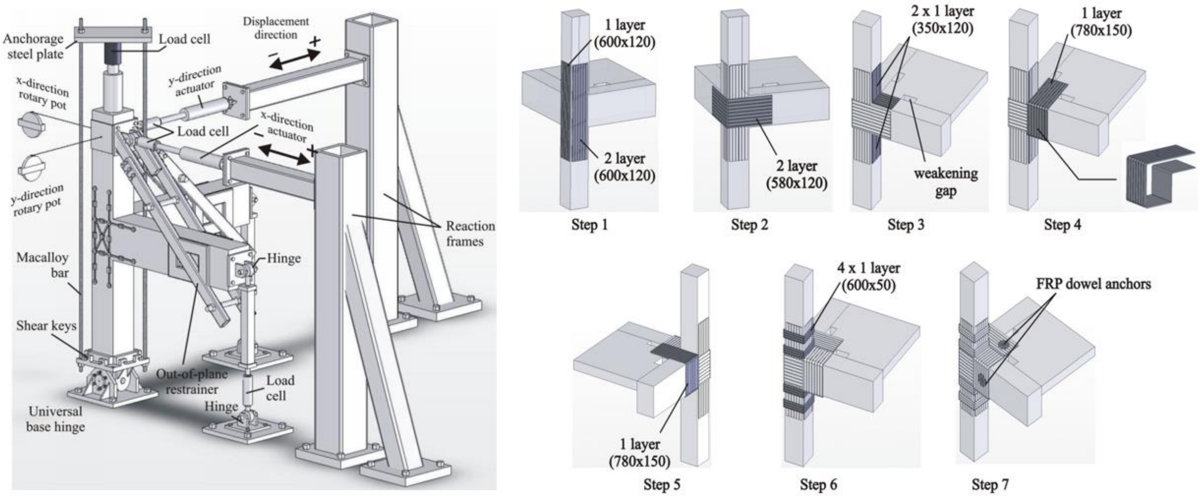

Figure 2: (a) Test specimen and setup designed for multiaxial loading; (b)FRP retrofit scheme proposed and verified via tests and analytical studies

The test outcomes highlighted that when underestimating or overlooking multi-axial load demand, an incorrect and non-conservative assessment of the sequence of events could occur, leading to inadequate design of retrofit intervention. However, if multi-axial demand is taken into account properly in the design, the proposed retrofit solutions have been proven to provide significant improvements in the seismic performance.

Dissemination of Knowledge and Impact on Construction Industry

The years of experience gained from my projects has been successfully demonstrated on many occasions both in the research community and the construction industry. This collective knowledge has been actively used to refine existing models and has paved the way for economically feasible rehabilitation techniques for structural engineers confronted with the huge stock of structures, waiting for rehabilitation either before or retrofitting after an impending earthquake. Development and standardisation of simple, cost-effective structural retrofitting solutions, that can fulfil the requirements for public safety with the least disruption to occupancy, will enhance public safety and improve quality of life, at a cost that both the owners and the national economy can bear. This is an area in which engineering research is at the forefront of providing a solution to mitigate the needless loss of life during earthquake.

The dissemination of knowledge has been achieved through publication in a textbook chapter[2], highly regarded academic journals[3,5], and state-of-the art technical guidelines[8]. The project outcomes were ultimately incorporated into the Turkish Earthquake Code[9] (Fig.1(c)) and the New Zealand Seismic Assessment Guidelines, which are used by structural engineers nationwide[10,11].

I also conveniently utilised my research project outcomes to further benefit the construction industry. I was seconded to the University of Canterbury Quake Centre (http://courses.quakecentre.co.nz/) to produce the online seismic engineering courses for structural engineers. UC Quake Centre is a partnership between the New Zealand Government, the University of Canterbury, and several leading industry groups.

In the aftermath of the 2010-2011 Christchurch earthquakes, I have played an active role in recovery activities, undertaken various project consultancies and prepared reports for Christchurch City Council[12]. In recognation of all these activities and the outstanding contribution to public service and to the engineering profession, I received the Fulton-Downer Gold Medal - The President's Award in 2011 awarded by Engineering New Zealand which is the professional engineering body in New Zealand.

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