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RESIDUAL CAPACITY AND REPAIRING OPTIONS FOR REINFORCED CONCRETE BUILDINGS

Research Report Prepared for the Natural Hazard Research Platform

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2 KEY MESSAGE FOR MEDIA

The Canterbury earthquakes sequence in 2010-2011 has represented a tough reality check, confirming the current mismatch between societal expectations over the reality of seismic performance of modern buildings. In general, albeit with some unfortunate and dramatic exceptions, modern multi-storey buildings performed as expected from a technical point of view, even more when considering the intensity of the shaking they were subjected to.

According to the internationally accepted ‘performance-based design’ philosophy, buildings withstood the earthquake shaking and protected life of occupants, by damaging themselves in a number of controlled and discrete locations. Nevertheless, in many cases, as reparability of those discrete location was not part of the original target nor of the building technology adopted (now available in the form of low-damage structural systems), these buildings were deemed too expensive to be repaired and were consequently demolished.

This research project contributed to gain a better understanding on this delicate topic and to provide further evidence-based information to be used by main end-users and stakeholders in order to a) assess the residual capacity of damaged reinforced concrete buildings and their vulnerability to further aftershocks, b) evaluate the feasibility of alternative repairing options; c) support the delicate decision-making process of repair vs. demolition/replacement.

The project has confirmed the high complexity of evaluating the post-earthquake capacity of a damaged building, and, with that, its reparability options.

Targeting ‘Life Safety’ is clearly not sufficient enough. A paradigm shift towards control of damage and actual reparability is crucially needed for the next generation of structures and infrastructures.

3 ABSTRACT

The Canterbury earthquakes sequence in 2010-2011 has represented a tough reality check, confirming the current mismatch between societal expectations over the reality of seismic performance of modern buildings. In general, albeit with some unfortunate and dramatic exceptions, modern multi-storey buildings performed as expected from a technical point of view, even more when considering the intensity of the shaking they were subjected to.

One of the most controversial issues has been the evident difficulty and lack of knowledge/guidelines in terms of: a) evaluation of the residual capacity of a damaged building to sustain subsequent aftershocks; b) selection and implementation of a set of reliable repairing techniques to bring back the structure "at least" in its conditions before the earthquake; and c) capacity to predict the cost (or cost-effectiveness) of such a repair intervention, when compared to fully replacement costs and accounting for potential aftershock in the near futures.

This lack of knowledge and of common benchmarking methodology has arguably contributed in the demolition of many modern buildings with a consequent additional time and indirect losses (downtime) as well as an increase in uncertainty on the actual relocation (Christchurch , New Zealand or overseas) of the investment.

The research project aimed at gaining a better understanding and providing the main end-users and stakeholders - practitioner engineers, owners, territorial and government authorities, insurers, regulatory agency - with comprehensive evidence-based information and practical guidelines to assess the residual capacity of damage reinforced concrete buildings, to evaluate the feasibility of repairing and thus support their delicate decision-making process of repair vs. demolition/replacement.

The overall socio-economic impacts of such decisions are ultimately affecting the shaping of the future of Christchurch as a city as well as of New Zealand as a country.

This report summarises the achievement to date as well as ongoing and future research on the main research tasks namely: 1) review of available information on assessment of damaged RC buildings; 2) literature review on repairing techniques for structural concrete elements; 3) correlation between observed damage, tagging and actions taken; 4) analytical and numerical modelling of the seismic behaviour and expected damage; 5) experimental tests on building subassemblies to assess the residual life and evaluate reparability options; and 6) preparation of guidelines to support the repairing vs. replacement decision process.

A brief description of key findings on each of the tasks is accompanied with references to published papers when applicable. More information on the research methodology, results and future research needs can be found to the draft version of the UC Report 2015-4 titled "Seismic residual capacity of reinforced concrete frames", appended to this document.

Keywords: Residual capacity, plastic hinge, low-cycle fatigue, repairing options, bond deterioration, strain-ageing, cost-benefit, cumulative damage

4 INTRODUCTION

One of the most controversial issues highlighted by the Christchurch earthquake series has been the evident difficulty and lack of knowledge/guidelines in terms of: a) evaluation of the residual capacity of a damaged building to sustain subsequent aftershocks; b) selection and implementation of a set of reliable repairing techniques to bring back the structure “at least” in its conditions before the earthquake; and c) capacity to predict the cost (or cost-effectiveness) of such a repair intervention, when compared to fully replacement costs and accounting for potential aftershock in the near futures.

As a result of the complexity and uncertainty (risk) of such problem, and the possibility (unique in New Zealand when compared to most of the seismic-prone country overseas) to rely on the insurance coverage, many modern buildings, in a number somehow exceeding expectations based on statistics from past experience at international level, have ended up being demolished. This has resulted in additional time and indirect losses prior to the full reconstruction as well as in an increase in uncertainty on the actual relocation (Christchurch, NZ or overseas) of the investment.

The findings of this project are expected (and already contributing) to form a sound scientific and technical basis to facilitate the paradigm shift from Life-Safety to Damage Control towards a new generation of low-damage or at least repairable structures and infrastructures.

The main goal would be to provide engineers, insurers, Territorial (Local or Government) Authorities, Owners, Developers/Investors with a set of technical guidelines based on sound experimental/numerical evidences that can strongly support the decision making process of repair vs. demolition or replacement.

Ultimately, considering the significant socio-economic impact of such decisions, a more robust approach would hopefully positively influence not only the shaping of the future of Christchurch as a city but also of New Zealand as a whole country.

Less uncertainty on the definition of reparability solutions and repairing/strengthening costs vs. replacement costs would possibly allow, in the near future, for more targeted, and possibly risk-based, premiums to be offered by insurers. In turn and overall, this could contribute to the way forward through the recovery and rebuild phase, by attracting a wider range of investments and financial supports.

The question that this project has tried to tackle has been proven to be a serious obstacle in the first phase of recovery/rebuild. Consultant engineers have been dealing with a problem for which the answer was not yet available within the international community in the form of a simple document and, more importantly, based on robust evidences.

Moving forward, a critical missing link in the past research at international level has been evident to be the lack of considerations on costs and feasibility of post-earthquake reparability, for both the design of new structures as well as the strengthening/retrofit of existing ones.

The outcomes of this project are expected to provide some further support and technical guidance during the reconstruction and the repairing phase in better understanding and evaluating what would

be the impact - reparable or not, at what cost?- of an earthquake on the new generation of built environment. This could lead to a refined design/retrofit approach, in full respect of the principles of performance-based design and explicitly targeting or considering reparability after a design level event.

Furthermore, the wider communication of the reparability vs. irreparability threshold could lead to the adoption and wider spread of more recently developed higher performance also referred to low-damage seismic-resisting technology, capable of providing a limited and controlled level of damage – possibly for both structural and non-structural components as well as for both superstructures and soil-foundation system - under a major event.

Thus the implementation and wider dissemination of the achieved know-how could also significantly affect new regulations and policies in terms of seismic risk acceptance and reduction strategies for the whole country.

It is worth noting that, as a first step of such dissemination to the wider industry a special committee/working group, comprising the key PIs an Co-PIs of research projects related to residual capacity in New Zealand as well as of representatives from the practitioner engineers community and wider industry, has been conveyed since late 2014 under the coordination and governance of MBIE with the aim to merge the existing know-how on the topic and prepare a state-of-art document, referred to as ‘white paper’ on the topic residual capacity of reinforced concrete frames.

The key outcomes and findings of this NHRP-funded project and the general framework proposed and presented in this report are forming a core part of the white paper, due to be completed by mid-end of 2016.

5 OBJECTIVES

This research project aimed at gaining a better understanding and providing the main end-users and stakeholders - practitioner engineers, owners, territorial and government authorities, insurers, regulatory agencies - with comprehensive evidence-based information and practical guidelines to assess the residual capacity of damage reinforced concrete buildings, to evaluate the feasibility of repairing and thus support their delicate decision-making process of repair vs. demolition/replacement.

The key objectives of this research were to:

1. Gain a better understanding on what is residual capacity in structural members – i.e. at a local level - and how it is affected by factors such as low-cycle fatigue, bond deterioration, strain ageing, strain hardening, and material properties.

2. Implement, calibrate and validate analytical tools for modelling and assessment of residual capacity of those portion of structural members where inelastic action is expected, i.e. plastic hinges

3. Understand how the hysteretic behaviour of structural members deteriorates after a design level earthquake (in terms of strength, stiffness and energy dissipation), as well as whether/how it can be recovered or improved up to a certain level after implementing a repairing technique.

4. Gain a better understanding of the seismic performance of damaged reinforced concrete frame buildings after an earthquake, its residual capacity and how it improves after being repaired.

5. Suggest possible and affordable repairing techniques, and from a seismic loss estimation perspective, elucidate if a repaired structure is cost-effective when compared to the same building in its original (non-damaged, new structure or rebuilt) conditions.

6. Develop and propose methodologies to account for the residual capacity in either the design of new buildings and the assessment of existing ones.

6 METHODOLOGY

The research comprised numerical, experimental and analytical investigations, building on national and international best practice and current guidelines and closely referring to the damage-observations in Christchurch RC buildings to be used as case-study.

The research project was divided into three main sub-tasks:

1) seismic residual capacity of plastic hinges in concrete buildings;

2) residual capacity, hardening and strain-age effects on reinforcing steel;

3) steel-to-concrete cyclic bond deterioration.

These corresponds to Part I, II and III, respectively of the UC report 2015-4 “Seismic residual capacity of reinforced concrete frames” (Pampanin et al., 2015) appended to this introduction/summary report.

6.1 Seismic residual capacity of buildings

Figure 1 shows an overview of the methodology for the first task (Part I).

As can be seen from the figure, it comprised numerical, experimental and analytical investigations, carried out in two main Phases.

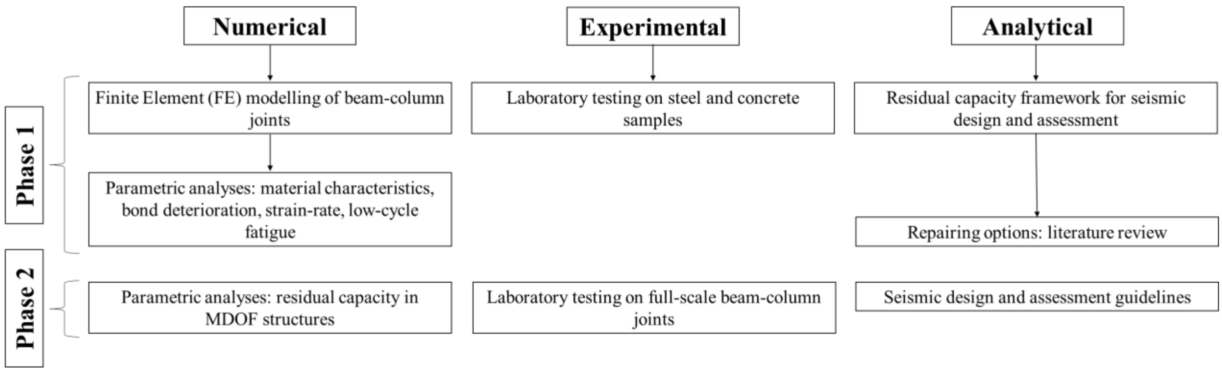

Figure 1. Flowchart of the research methodology for seismic residual capacity of buildings.

In Phase 1, parametric analyses have been performed through Finite Element (FE) simulations - using the code MASA developed at the University of Stuttgart - of capacity designed beam-column joints from previous experimental research projects, aiming at understanding, both quantitatively and qualitatively, e.g. different cracking patterns, the effect on the residual capacity of the plastic hinge of variations in key parameters as: yield and tensile strength of the rebar, concrete strength and bond deterioration; with and without considering the velocity of loading (strain-rate) and low-cycle fatigue effects.

The current study will be further extended - following the experimental campaign on real beam-column joints, see Phase 2 - and the results used to implement and calibrate a post-processing tool to

account for low-cycle fatigue of plastic hinges, which is a key component of the proposed framework to account for the seismic residual capacity of plastic hinges.

Destructive tests on steel and concrete from real specimens i.e., those beam-column joints extracted from the PwC building and tested in the UC Structural Laboratory, will be performed to calibrate the numerical model in MASA.

Different repairing options for well-designed beam column joints available in literature have been reviewed and summarised. At least one of them was planned to be, and has in fact been, implemented in the full-scale specimens and tested experimentally at the University of Canterbury.

In Phase 2, experimental tests on well-designed full-scale beam-column joints extracted from the PWC building were planned to be performed - the testing campaign started in late 2015 and is planned to be completed in January/February 2016 - in order to estimate the hysteretic behaviour, e.g. strength and stiffness deterioration, pinching effect, of damaged and repaired plastic hinges.

A framework to account for residual capacity for seismic design and assessment of buildings has been proposed. It will be further expanded and calibrated based on parametric analyses on MOF systems yet to be carried out.

As anticipated, it is worth noting that, as part of the implementation pathway of the outcomes of this project, and its dissemination to the wider industry, a special committee/working group, comprising the key PIs an Co-PIs of research projects related to residual capacity in New Zealand as well as of representatives from the practitioner engineers community and wider industry, has been conveyed since late 2014 under the coordination and governance of MBIE with the aim to merge the existing know-how on the topic and prepare a state-of-art document, referred to as ‘white paper’ on the topic residual capacity of reinforced concrete frames.

The key outcomes and findings of this NHRP-funded project and the general framework proposed and presented in this report are forming a core part of the white paper, due to be completed by mid-end of 2016.

6.2 Residual capacity, hardening and strain-age effects on reinforcing steel:

In order to investigate the residual capacity of reinforcing steel bars, a dedicated experimental campaign in the UC structural laboratory has been carried out.

Leeb and Vickers hardness tests, in combination with monotonic interrupted tensile tests, have been conducted in order to identify a robust relationship between these two quantities for a number of New Zealand steel grades.

A methodology that employs the above-mentioned relationship has been used to develop calibration curves in terms of “Vickers hardness versus plastic strain” and “remaining ductility versus Vickers hardness”. These curves allow to quantify the amount of plastic deformation that steel reinforcing bars have experienced during the 2010/2011 seismic events in Christchurch and estimate the remaining ductility. Suspected damaged bars are required to be taken in laboratory for hardness testing. A summary of the method is presented in Figure 2.

Another aspect investigated is the strain-ageing phenomenon of reinforcing steel. It affects the mechanical properties of pre-strain steel grades commonly used in New Zealand. It causes a substantial reduction of the steel ductility. This phenomenon is taken under consideration when the calibration curves are developed.

More tests are underway; the current objective is to verify whether the ribs can cause a not uniform hardness distribution in correspondence of the root of the ribs.

Strain ageing effects on the low cycle fatigue behaviour of steel reinforcing bars have not been fully investigated yet. Experiments have been initiated at the University of Canterbury since the end of 2015 and are still on going. The experimental plan consists in low cycle fatigue test of NZ grade 300E and Grade 500E in order to define their strain – life curves. The next step will consist in applying a number of cycles to the steel sample, then strain age them and finally cyclically test to fracture in order to measure the loss in life due to strain ageing.

Low cycle fatigue test will be also accompanied by hardness measurements to investigate the effect the number of cycle on hardness.

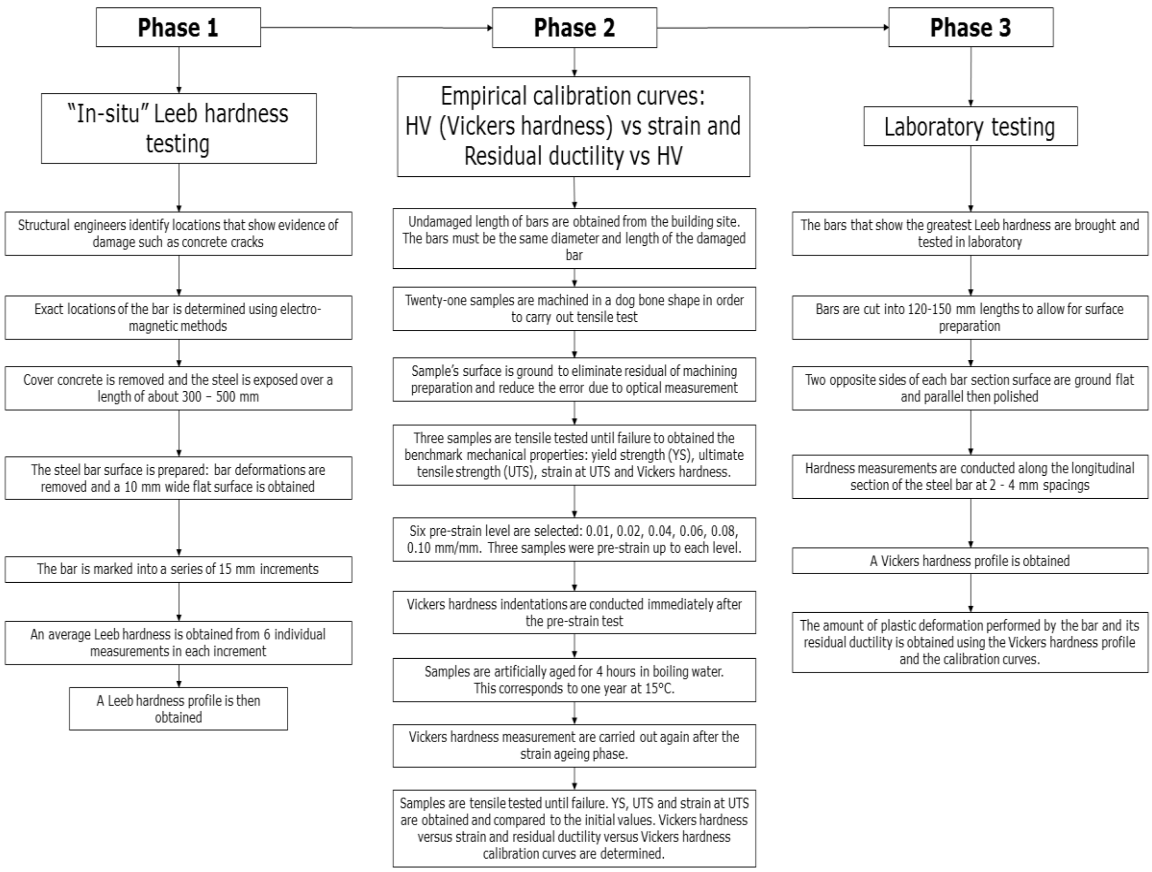

Figure 2. "Hardness method" flowchart

6.3 Steel-to-concrete cyclic bond deterioration

The repeated cycling of a structural member in the post-elastic region of the material results in a degradation of the ductility of the components of that member leading to a reduced capacity to absorb energy in future events and increases the probability of structural collapse. It is essential when inspecting structures to be able to properly assess the degree of damage and the likely remaining ductility.

The overall damage to concrete in a structural element can be the result of the loss due to a particular seismic event in addition to any pre-existing deterioration which the element had suffered over its service life.

When the material characterization of existing concrete building is required, recognition of mechanical properties of the concrete overtime provides greater insight into the concrete evaluation process. Thus, the historical overview of cement manufactured in New Zealand with specific attention on the most two important constituents; C2S and C3S has been conducted. The changes in material characterization in accordance to NZ standard were also examined in this study.

Mechanical damage in concrete members was initially simulated by applying monotonic and cyclic compression loading on small scale un-confined cylinder specimens. The purpose of this work was to evaluate various options for correlating material characterization techniques such oxygen permeability, resistivity and fluorescence microscopy with the physical material degradation and the level of damage. Experimental results showed damage in terms of endured stress level can be identified through permeability test for both monotonic and cyclic loading. In the case of unconfined small scale concrete cylinders, the number of cycles that specimen can take up to failure was determined and finally a predictive relation was proposed.

Large scale RC columns - 500 mm diameter by 1500mm height- with varying levels of confinement were subjected to axial compression until failure. Using the profile of permeability along the height of damaged RC column, the extent of damage was identified which was in excellent agreement with measured laboratory results. The experimental results on partially loaded cylinders and cores taken from damaged column showed a significant reduction in strain capacity. This could imply that damage, e.g. crushing, would occur earlier if the damaged member was subject to the next loading cycle, i.e. earthquake/aftershock.

In other words, to determine the residual capacity of a damaged RC member, stress-strain diagrams related to intact concrete are no longer valid and a revised relationship showing the damaged stress strain relationship should be used.

It is possible therefore to quantify the magnitude of damage to the concrete and the extent of the plastic hinge in reinforced concrete members using a variety of material characterization techniques. When the concrete damage is coupled with an assessment of the steel rebar damage, a more accurate assessment of the overall residual capacity of the member is possible.

This study will be extended with future work to include an assessment of bond deterioration and the development of a comprehensive finite-element model of RC cantilever beam to simulate desired plastic hinge in a beam-column joint. The model will ultimately be capable of numerically simulating

the full behaviour of a cantilever RC beam including the peak, residual post-peak capacities and also cracks caused by damage induced in the member.

7 REVIEW OF CURRENT INFORMATION, BEST PRACTICE AND GUIDELINES ON ASSESSMENT OF RESIDUAL CAPACITY OF DAMAGED RC BUILDINGS

7.1 Budget: N/A - unspecified portion of the $174,540.52 (GST ex)/annum for 32 months

7.2 Objective achieved: Yes

7.3 Discussion

At a first stage an overview of the methods for estimating the low-cycle fatigue, or fatigue life, of reinforcing bars for plastic hinges has been carried out, followed by a (preliminary) parametric analysis showing that the plastic hinge length, the beam aspect ratio and peak inter-storey drifts are key parameters when estimating the seismic residual capacity of a plastic hinge (see McKee and Ting, 2012). Later, Cuevas and Pampanin (2014a) presented a review of the current know-how and previous researches on seismic residual capacity, from a fatigue life point of view. Interestingly enough, past research has been done on bridge structures, focusing on the low-cycle fatigue of the longitudinal reinforcement only. It is evident, therefore, the lack of seismic rehabilitation assessment and rehabilitation guidelines for buildings.

Subsequently the literature review continue targeting at identifying the available procedures on estimating the seismic residual capacity of buildings by other means than from a fatigue life. FEMA 306 has proposed a quantitative procedure to assess earthquake damaged concrete and masonry wall buildings, based on nonlinear static (pushover) techniques to estimate the performance of the building in future events in both its pre-event and damage states. The performance-based method has been used to investigate the effectiveness of potential performance restoration measures.

Di Ludovico and Polese (2013) also proposed a method for the estimation of residual capacity of structural components, which relies on suitable modification factors to be applied to non-confirming RC columns typical of the Mediterranean region. The capacity - backbone - curves at the component level are first derived following the recommendations of ASCE 41-06 (now superseded by ASCE 41-13), with updated limit values as suggested in ACI 369R-11. Similar to FEMA 306, these modification factors are then applied accounting for stiffness, strength and plastic rotation degradation. The authors also proposed (preliminary) relationships between observed damage and expected level of ductility demand.

Maeda et al (2004) presented an outline and basic concept for damage evaluation of reinforced concrete buildings based on residual capacity. The approach is based on a residual capacity index consistent with the Japanese Standard for Seismic Evaluation of Existing RC buildings. In this method, the seismic residual capacity R is defined as the ratio of original seismic performance index and the post-earthquake seismic performance index, the latter being calculated with a seismic reduction factor depending on the observed level of damage.

Loporcaro et al (2015) identified the lack of information on the investigation of the residual capacity of reinforcing steel. The only method found in the literature applicable to this case was the Hardness method, in which the hardness is correlated with a plastic strain. The Leeb hardness test was typically adopted for that purpose.

A literature review on strain ageing in steel reinforcing bars was also conducted. It was identified that strain ageing causes a significant change in the mechanical properties of steel and thus influences on the residual ductility of strained bars. It was determined that its effects on the low-cycle fatigue behaviour of reinforcing steel have not been fully investigated. As such, an experimental campaign on NZ steel bars Grade 300E and 500E has been initiated at the University of Canterbury since August 2015, with the guidance of the Visiting Professor Emeritus Norman Dowling from the Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

The history of the New Zealand steel grade as well as the beam and beam-column joint requirements throughout the New Zealand Standards was also performed and tabulated for ease access when assessing buildings designed with previous codes (not published in papers yet).

7.4 List of outputs:

Cuevas, A., Pampanin, S. [2014] *"Accounting for residual capacity of reinforced concrete plastic hinges: current practice and proposed framework,"* 2014 New Zealand Society of Earthquake Engineering Conference, Auckland, New Zealand.

Cuevas, A., Pampanin, S., Carr, A., Ozboltz, J. [2015] "*Seismic residual capacity of reinforced concrete frames: Part I: General Framework*" Research Report UC 2015-4, Part I, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand.

Loporcaro, G., Pampanin, S., Kral, M.V. [2015] *"Experimental validation of the "hardness method" to estimate the residual ductility of plastically deformed steel reinforcement,"* 2015 New Zealand Society of Earthquake Engineering Conference, Rotorua, New Zealand.

McKee, T., Ting, T. [2012] *"Residual capacity and repair options for RC buildings,"* Final Years Projects, Department of Civil and Natural Resources Engineering, University of Canterbury.

Pampanin, Cuevas, Kral, Loporcaro, Scott, Malek [2015] "*Residual capacity and repairing options for reinforced concrete buildings"*, University of Canterbury, Research Report 2015-4

7.5 List of end-users:

- Practitioner engineers
- Representatives of CCC an other Councils, CERA, MBIE
- Learned Societies (SESOC, NZSEE, NZCS, CCANZ)
- Insurers

8 LITERATURE REVIEW ON REPAIRING TECHNIQUES FOR STRUCTURAL CONCRETE ELEMENTS

8.1 Budget: N/A - unspecified portion of the $174,540.52 (GST ex)/annum for 32 months

8.2 Objective achieved: Yes

8.3 Discussion

A literature review on repairing techniques for beam-column joints has been carried out, and will be part of a NZSEE 2016 paper produced as a result of the experimental testing campaign (see Section). Three different repairing techniques have been identified: 1) epoxy pressure injection, in which - after cleaning the area around the cracks - a quick-setting viscous epoxy is applied to the surface; once it has set, the epoxy is injected through different ports located at each crack; 2) vacuum impregnation, in which the specimen is covered with a polyethylene sheet to achieve vacuum, submersed in epoxy and when it is about to set, the vacuum is removed; and 3) local replacement of damaged concrete and steel.

Several tests on full-scale and small scale seismic detailed beam-column joints have been performed by previous researchers. The specimens were typically subjected to a series of reversed cyclic loading, repaired, and then subjected to the same loading history as that imposed on the original specimens. The researchers evaluated the seismic performance of the repaired specimens in terms of key hysteresis parameters as strength, stiffness and energy dissipation characteristics.

Overall the tests indicated that these repairing techniques are feasible methods to re-gain most - even if not entirely – of the key characteristics of the hysteresis loop for moderate earthquake damage elements. Worth noting that bond deterioration and thus stiffness degradation has to be typically accepted as a not-fully irrecoverable loss. Also no consideration on the fatigue life or residual capacity under future cyclic loading were typically provided. The literature review on the repairing techniques is continuing, based on the actual experience in Christchurch as well as in L'Aquila (2009).

A well-designed (1980s) full-scale (real) beam-column joints extracted from the PwC building are being tested at the University of Canterbury since the mid-end of 2015 after being repaired with epoxy injection, with its performance compared with that of a similar undamaged specimen subjected to the same loading protocol.

8.4 List of outputs:

Cuevas, A., Pampanin, S., Carr, A., Ozboltz, J. [2015] "*Seismic residual capacity of reinforced concrete frames: Part I: General Framework*" Research Report UC 2015-4, Part I, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand.

Pampanin, Cuevas, Kral, Loporcaro, Scott, Malek [2015] "*Residual capacity and repairing options for reinforced concrete buildings"*, University of Canterbury, Research Report 2015-4

Journal paper – possibly for the Bulletin of NZ Society of Earthquake Engineering - merging the findings of research aim 1.1 and 1.2 on state of art of residual capacity and repairing techniques, in preparation, to be submitted in early 2016

8.5 List of end-users:

- Practitioner engineers
- Representatives of CCC an other Councils, CERA, MBIE
- Learned Societies (SESOC, NZSEE, NZCS, CCANZ)
- Insurers

9 CORRELATION BETWEEN OBSERVED DAMAGE, TAGGING AND ACTIONS TAKEN

9.1 Budget: N/A - unspecified portion of the $174,540.52 (GST ex)/annum for 32 months

9.2 Objective achieved: Yes (Partly)

9.3 Discussion:

Full scale real specimens from the 22-storey PwC and Hotel Grand Chancellor buildings were preserved for laboratory testing at the University of Canterbury. Furthermore, a detailed damage report (internal only) of the PwC building after the 2010-2011 earthquake sequence was carried out. For that purpose, the building was stripped out and thus the structural skeleton fully exposed. Some of the observations were detailed by Giorgini et al (2013). For this specific building, the observed damage consisted in beam plastic hinging at most of the storeys, residual tilt due to permanent settlements at the foundation level, and residual inter-storey drifts.

Giorgini et al (2013) investigated the seismic behaviour of the PWC building, by non-linear time history analyses using a fixed based condition. Although the numerical model underestimated the maximum inter-storey drifts, the maximum displacements were in agreement with the observations.

A conference paper on residual strain capacity in steel rebars, specifically looking at the relationship between hardness and plastic strain in reinforcing steel bars, has been completed and presented at the NZSEE2014 conference (see Loporcaro et al, 2014). The paper aimed at developing a methodology to estimate the level of damage in reinforcing steel bars. For that purpose, laboratory-based tensile and hardness tests were performed and used to develop an empirical mathematical formulation correlating plastic strain and hardness. The hardness testing also highlighted the high dependency of plastic strain on the strain aging effects.

The methodology proposed by Loporcaro et al (2014) has been improved and applied to several hardness tests performed at the University of Canterbury. A comprehensive investigation on machined specimens taken from NZ grade 300E reinforcing bars was conducted, aiming at validating the existence of a relationship between (Vickers) hardness and plastic strain, as well as residual ductility. The tests accounted for strain ageing through an accelerated ageing process. It was demonstrated that there is consistency and accuracy with such relationships.

Due to the success of the results, the methodology was further extended for in-situ hardness tests, with the new methodology comprising three different phases: 1) In-situ Leeb hardness testing; 2) Calibration testing; and 3) Vickers hardness testing and damage assessment.

Looking at correlating the observed damage with material degradation in the concrete through low-invasive techniques used in practice, Malek et al (2015) tested concrete cylinders under monotonic axial loading up to certain stress levels. After reviewing the available techniques found in literature, they performed a combination of oxygen permeability, electrical resistivity and porosity tests in order to quantify damage on disks sawn from the one-third middle part of samples. The results showed that permeability tests can be useful to assess the damaged concrete as permeability coefficient increases

with a great sensitivity to the applied load. In addition, they implemented a stereological technique on thin sections prepared from concrete disks impregnated with fluorescent dye. Digital image processing has then been carried out using fluorescent stereomicroscope to provide quantitative information on cracks geometry. Overall, the preliminary results from this study are promising, validating the applicability of low-invasive methods for the evaluation of RC damaged elements.

The preparation of a set of ten existing case-study buildings in the CBD has been completed, with the objective of comparing alternative modelling approaches, ranging from analytical - by hand or excel spreadsheet – following the SLaMA method in NZSEE2006 currently under revisio - to numerical (simplified macro-model). A comparison of observed damage vs. predicted damage of some of these case stud buildings is anticipated to be carried out in the near future engaging international teams of modelers. At this stage the Security House building (1970s) is being used as a first case study building With reference to a three storey test building (Pavia test) as well as of a ten storey 1980s building (Red Book), a first journal paper has been submitted for publications to the Bulletin of Earthquake Engineering, BEE, (Sahin et al, 2015), outlining the step-by-step- procedure to evaluate the hierarchy of strength and sequence of events of beam-column joint subassemblies framed structures.

An important effort has been done regarding the correlation between observed damage, tagging and actual repairing vs demolition outcomes by Bocchini et al (2014), in which the damage and impacts on the built-environment after the Darfield 2010 and Christchurch 2011 earthquakes has been surveyed and collated in different databases for future seismic risk analysis and mitigation planning. The findings have been incorporated in the GEM consequences database.

Furthermore, a research group from the University of Naples has come to the University of Canterbury since September 2015 to work specifically on repairing costs based on the information gathered from the rebuild of L’Aquila (2009). It is important to mention that information on actual (or at least estimated by quantity surveyor) repairing costs in the aftermath of the Christchurch earthquake sequence from insurance companies was crucial for this task; however in spite of signed confidentiality agreements, it has not been possible to access such information. It is hoped to carry out a similar exercise for Christchurch in the near future, following a more clear understanding of the value of such information for the wider community and of the reassured possibility to maintain confidentiality on an individual building, as the information are aggregated.

Looking at the delicate decision-making process of repair/retrofit vs. demolition/replacement, as well as to what level of shaking intensity the repairing/retrofitting technique must be designed for, Ligabue et al (2015) developed a framework to assist the stakeholders with the evaluation of the effects in terms of long term losses and benefits of an increment in their initial investment, highlighting the uncertainties hidden behind the way the targeted shaking intensity or %NBS is evaluated, which is essentially deterministic. The above is important because, as stated by Ligabue et al (2015), there is a misconception that the risk and cost of intervention correlates linearly with the %NBS to be achieved by the structure, however a small increase of the targeted structural performance can result in a more than proportional reduction of risk, whilst the associated cost is strongly dependant on the repairing/retrofitting technique adopted for such purpose. The framework was exemplified by using a pre-1970 case study building, on which four different intervention schemes were applied, targeting at different %NBS so that the probability of collapse and losses under several design earthquake levels could be evaluated.

9.4 List of outputs:

Bocchini, G.M., Pomonis, A., So, E., King, A.B., Giovinazzi, S. [2014] *"The GEM earthquake consequences database and New Zealand's contributions,"* 2014 New Zealand Society of Earthquake Engineering Conference, Auckland, New Zealand.

Giorgini, S., Pampanin, S., Carr, A.J., Cubrinovski, M. [2013] *"Seismic behaviour of a 22 storey building during the Canterbury earthquakes,"* 2013 New Zealand Society of Earthquake Engineering Conference, Wellington, New Zealand.

Ligabue, V., Savoia, M., Pampanin, S. [2015] *"Repairing/retrofitting vs. replacing? Evaluating the cost-effectiveness of alternative options to support decision making,"* 2015 New Zealand Society of Earthquake Engineering Conference, Rotorua, New Zealand.

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Malek, A., Scott, A., Pampanin, S., MacRae, G. [2015] *"Assessment of post-earthquake damage in RC elements using low-invasive techniques,"* 2015 New Zealand Society of Earthquake Engineering Conference, Rotorua, New Zealand.

Pampanin, Cuevas, Kral, Loporcaro, Scott, Malek [2015] "*Residual capacity and repairing options for reinforced concrete buildings"*, University of Canterbury, Research Report 2015-4

9.5 List of end-users:

- Practitioner engineers
- Representatives of CCC an other Councils, CERA, MBIE
- Learned Societies (SESOC, NZSEE, NZCS, CCANZ)
- Insurers

10 ANALYTICAL AND NUMERICAL MODELLING OF THE SEISMIC BEHAVIOUR AND EXPECTED DAMAGE

10.1 Budget: N/A - unspecified portion of the $174,540.52 (GST ex)/annum for 32 months

10.2 Objective achieved: Yes

10.3 Discussion

3D lumped plasticity models were performed for the PwC building, as 22 storey reinforced concrete frame building designed and built in the 1980s (see Giorgini et al, 2013) considering a fixed base conditions and also soil-structure interaction. This model will be later used (part of Phase II mentioned in the methodology chapter) to understand the residual capacity of the building in terms of aftershock from global point of view, then looking at refined Finite Element (FE) modelling of the plastic hinges (in progress) and comparison with experimental testing (in progress).

For the FE modelling, the collaboration of Prof. Josko Ozbolt and Prof. Rolf Eligehausen from the University of Stuttgart was fundamental. For that purpose, the PhD Student Alberto Cuevas was awarded with a prestigious DAAD scholarship from the German Research Foundation to spend 2.5 months (from May 2014 to mid-July 2014) at the University of Stuttgart working in collaboration with Prof. Eligehausen and Prof. Ozbolt, developing the MASA (FE) model to adequately assess and predict the residual capacity of plastic hinges.

Numerical (FE) simulations on a reinforced concrete beam-column joint experimentally tested at the University of Canterbury, seismically designed following the NZS3010-2006 code requirements were performed. The simulations aimed at investigating and understanding the effect of parameters such as bond deterioration, steel and concrete material properties, and the amount of reinforcement, on the cracking pattern and nonlinear response of the plastic hinges. The pattern and level of cracking obtained with the simulations agreed with what was observed during the tests. It was also observed that, although the overall behaviour in terms of strength, stiffness and strain limits is not significantly affected by variations in the concrete tensile strength, f_t, it strongly affects the expected cracking pattern in the beam-column joints, the latter being more uniform, i.e., larger amount and less intense cracks for lower f_t values, provided th reinforcement ratio ρ_s, is sufficiently low. Furthermore, the seismic residual shear strength of the beam-column joints was observed to be influenced also by concrete compressive strength, f'_c, irrespective of the steel yield strength, f_y, and the reinforcement content, ρ_s, values. These results were presented at the 2014 Second European Conference on Earthquake Engineering and Seismology, 2ECEES, in Istanbul (Cuevas et al, 2014).

The previous numerical work was further expanded and presented during the 2015 NZSEE Conference (Cuevas and Pampanin 2015), along with a qualitative framework of the ongoing numerical investigations aiming at investigating the seismic residual capacity of beam plastic hinges. Although multiple cracks were expected to occur at the plastic hinge location - due to the longitudinal reinforcement content above the minimum required by code, large plastic deformations at few locations (one-to-two major cracks) were observed in the simulations. It was observed also that strain-

rate effects do not (according to this preliminary analyses) seem to play an important role on the cracking pattern (more investigation is under development to ascertain the above statement).

10.4 List of outputs:

Giorgini, S., Pampanin, S., Carr, A.J., Cubrinovski, M. [2013] *"Seismic behaviour of a 22 storey building during the Canterbury earthquakes,"* 2013 New Zealand Society of Earthquake Engineering Conference, Wellington, New Zealand.

Cuevas, A., Akguzel, U., Ozbolt, J., S., Pampanin, S. [2014] *"Preliminary numerical investigation on the seismic residual capacity of reinforced concrete plastic hinges,"* Second European Conference on Earthquake Engineering and Seismology, Istanbul, Turkey.

Cuevas, A., Pampanin, S. [2015] *"Effect of strain-rate and material characteristics on the seismic residual capacity of reinforced concrete plastic hinges: numerical investigation,"* 2015 New Zealand Society of Earthquake Engineering Conference, Rotorua, New Zealand.

Cuevas, A., Pampanin, S., Carr, A., Ozboltz, J. [2015] "*Seismic residual capacity of reinforced concrete frames: Part I: General Framework*" Research Report UC 2015-4, Part I, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand.

Pampanin, Cuevas, Kral, Loporcaro, Scott, Malek [2015] "*Residual capacity and repairing options for reinforced concrete buildings"*, University of Canterbury, Research Report 2015-4

10.5 List of end-users:

- Practitioner engineers
- Representatives of CCC an other Councils, CERA, MBIE
- Learned Societies (SESOC, NZSEE, NZCS, CCANZ)
- Insurers

11 EXPERIMENTAL TESTS ON BUILDING SUBASSEMBLIES TO REPRODUCE THE DAMAGE AND DIRECTLY ASSESS THE RESIDUAL "LIFE" AND EVALUATE REPAIRABILITY OPTIONS

11.1 Budget: N/A - unspecified portion of the $174,540.52 (GST ex)/annum for 32 months (also mostly co-funded outside of this NHRP project)

11.2 Objective achieved: Yes (some testing and post-processing still in progress)

11.3 Discussion:

A total of six large specimens were extracted from real buildings under demolition. 4 H-frames (full-length beam with two columns, one at each beam-end) from the 22-storey PWC building and 2 beam-column joints Grand Chancellor Hotel buildings were secured after being cut and craned, thanks to the collaboration of Industry representatives - Daniel Smith Industries, Nikau Group and Arrow International- see articles released to the media on December 2012 by Arrow International).

The tests are currently on-going. More information can be found in Pampanin et al., 2015 and Cuevas et al., 2016 (NZSEE2016). The first phase of the experimental campaign comprises the testing of three beam-column joints from the PWC building, subjected to reverse cycling loading until failure so that their seismic residual capacity can be assessed..

In essence, the first specimen (AB-1) test is considered as the benchmark, with a specified loading protocol applied until reaching failure. The second test (R-1) consists of inducing first a certain amount of damage (either under monotonic or cyclic loading) on the undamaged specimen, repaired with an epoxy pressure injection technique, and then subjected to a new loading protocol with the same characteristics as it was applied on AB-1 until reaching failure. In the third test (AB-2), the specimen will be subjected to a certain amount of damage (either under monotonic or cyclic loading), and then the unrepaired specimen will be subjected to a new loading protocol with the same characteristics as it was applied on AB-1 until reaching failure.

It is anticipated that, at the end of the experimental campaign, valuable evidence-based information on the cyclic behaviour and ultimate capacities for undamaged, damaged-repaired, and damaged-unrepaired capacity designed beam-column joints will be obtained and compared. Numerical (FE) simulations on the same beam-column joints will precede and follow up to complement the results. The (preliminary) experimental and numerical results will be presented at the NZSEE2016 conference in Christchurch.

11.4 List of outputs:

Cuevas, A., Pampanin, S. [2016] *"Preliminary experimental investigation on the seismic residual capacity of full-scale (capacity designed) beam-column joints,"* New Zealand Society of Earthquake Engineering Conference, Christchurch (in preparation).

Cuevas, A., Pampanin, S., Carr, A., Ozboltz, J. [2015] "*Seismic residual capacity of reinforced concrete frames: Part I: General Framework*" Research Report UC 2015-4, Part I, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand.

Journal paper summarizing the findings of the experimental campaign on residual capacity and repairing techniques of full-scale beam-column joints, to be submitted by early 2016.

11.5 List of end-users:

- Practitioner engineers
- Representatives of CCC an other Councils, CERA, MBIE
- Learned Societies (SESOC, NZSEE, NZCS, CCANZ)
- Insurers

12 PREPARATION OF GUIDELINES FOR END-USERS TO SUPPORT THE REPAIRING VS. REPLACEMENT DECISION PROCESS

12.1 Budget: N/A - unspecified portion of the $174,540.52 (GST ex)/annum for 32 months

12.2 Objective achieved: Yes (preparation of a MBIE committee white paper in progress)

12.3 Discussion

At a component (or plastic hinge) level, a conceptual framework to account for residual capacity of plastic hinges has been developed and outlined by Cuevas and Pampanin (2014). The framework consists of four main components: 1) seismic demand estimation; 2) cyclic demand (i.e. equivalent number of cycles); 3) relationship between plastic drift and fatigue life (i.e. cyclic capacity); and 4) remaining residual capacity.

Aiming at investigating the effect of rate of loading, bond deterioration, longitudinal reinforcement ratios as well as material characteristics, on the plastic strain and fatigue life of plastic hinges (i.e. components 3 and 4 mentioned above), the aforementioned framework has been further expanded and exemplified in Cuevas and Pampanin (2015).

Analytical and numerical investigations are under current development in order to define the most important variables involved in the formulation. Results from the experimental campaign will be used to calibrate a numerical (FE) model so that it can be used for that purpose. The results from an experimental campaign on low-cycle fatigue of NZ reinforcing steel - currently taking place at the University of Canterbury - will be also used for calibration purposes.

At a global (or whole structure) level, the displacement based design procedure accounting for residual deformations proposed by Christopoulos and Pampanin (2004) has been further developed by Cuevas and Pampanin (2014) to explicitly incorporate residual capacity in the overall process. Within the new formulation, two design check levels - one for the residual capacity and one for the residual deformations- are required, and once met, the Direct Displacement Based Design (DDBD) procedure follows as in the original formulation proposed by Priestley et al (2007). Numerical investigations are required in order to relate the plastic rotations demands at each plastic hinge with an equivalent plastic drift on the substitute SDOF structure. This numerical investigation will follow as part of this research project once the residual capacity at a component (plastic hinge) level has been calibrated.

In parallel, substantial progress has been done in a series of tasks aiming at improving the current NZSEE 2016 guidelines on Assessment and Improvement of the performance of Existing Structures.. The tasks include: 1) Refinement of simplified assessment procedures and framework for existing reinforced concrete buildings (e.g. simplified and linearized pushover method to be used by practitioners, based on a simpler "secant-stiffness" modal analysis); 2) Comparison of international codes on assessment; and 3) Further work to define damage limit states and simplified analytical force-displacement capacity curves for slender columns, typical of precast industrial buildings. The

outcomes of all this tasks will also be published in conference papers. The findings from this residual capacity project will also be used in the near future to improve the NZSEE2006 guidelines in terms of assessment of the residual capacity of damaged structures, not only of the capacity of undamaged ones.

At the end of 2014 the MBIE conveyed a dedicated working group/committee led by Prof. Ken Elwood from University of Auckland, with Prof. Stefano Pampanin, Prof. Milo Kral and Alberto Cuevas part of the committee. There has been extensive exchange of background information, e.g. unpublished information, literature review, drafted papers and set-up/analysis, future testing plan, qualitative framework, in order to draft the core part of a state-of the art document, referred to as 'white paper' on Residual Capacity. This white paper, due to completion by the end of 2016, also aims at identifying the research gaps needed in the short-medium future (months/years) to achieve a more robust (internationally peer reviewed) design/assessment guidelines on residual capacity, i.e. basis for the Detailed Engineering Evaluation approach, now renamed Detailed Damage Evaluation. Ultimately, and acknowledging that residual capacity of RC buildings is a very complex and not yet solved topic, the outcomes of this project will most likely form the basis for a larger research project, requiring continuous and comprehensive studies in the next few years.

12.4 List of outputs:

Cuevas, A., Pampanin, S. [2014] *"Accounting for residual capacity of reinforced concrete plastic hinges: current practice and proposed framework,"* 2014 New Zealand Society of Earthquake Engineering Conference, Auckland, New Zealand.

Cuevas, A., Pampanin, S. [2015] *"Effect of strain-rate and material characteristics on the seismic residual capacity of reinforced concrete plastic hinges: numerical investigation,"* 2015 New Zealand Society of Earthquake Engineering Conference, Rotorua, New Zealand.

Cuevas, A., Pampanin, S., Carr, A., Ozboltz, J. [2015] "*Seismic residual capacity of reinforced concrete frames: Part I: General Framework*" Research Report UC 2015-4, Part I, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand.

Pampanin, Cuevas, Kral, Loporcaro, Scott, Malek [2015] "*Residual capacity and repairing options for reinforced concrete buildings"*, University of Canterbury, Research Report 2015-4

12.5 List of end-users:

- Practitioner engineers
- Representatives of CCC, CERA, MBIE
- Societies (SESOC, NZSEE)

13 CONCLUSIONS AND RECOMMENDATIONS

Literature review has shown a critical lack of information in order to assess the seismic residual capacity (from a fatigue life point of view) of buildings, and when available, it deals with bridge structures focusing on the low-cycle fatigue of the longitudinal reinforcement only. It was also shown that strain ageing causes a significant change in the mechanical properties of steel and thus influences the residual ductility of strained bars. It effects the low-cycle fatigue behaviour of reinforcing steel, however, it has not been fully previously investigated.

Three different repairing techniques on well-designed beam-column joints have been identified from previous investigations: 1) epoxy pressure injection; 2) vacuum impregnation; and 3) local replacement of damaged concrete and steel. Overall the tests performed by previous researchers indicated that these repairing techniques are feasible methods to re-gain most - even if not entirely – of the key characteristics of the hysteresis loop for moderate earthquake damage elements.

As part of this research project, methodologies to estimate the level of damage in reinforcing steel bars have been proposed; and low-invasive techniques looking at correlating the observed damage with concrete degradation have been explored, being the permeability tests one of the promising tools to assess the damaged concrete.

Looking at the decision-making process of repair/retrofit vs. demolition/replacement, as well as to what level of shaking intensity the repairing/retrofitting technique must be designed for, a framework to assist the stakeholders with the evaluation of the effects in terms of long term losses and benefits of an increment in their initial investment has been proposed, highlighting the uncertainties hidden behind the deterministic approach in which the targeted shaking intensity or %NBS is evaluated.

Numerical (FE) simulations on a well-designed beam-column joint were performed. It was observed that the concrete tensile strength, f_t, strongly affects the expected cracking pattern in the beam-column joints (in particular when low reinforcement ratios are adopted), the latter being more uniform, i.e., larger amount and less intense cracks, for lower f_t values. More so, although multiple cracks were expected to occur at the plastic hinge location, due to the longitudinal reinforcement content above the minimum required by code large plastic deformations at few locations (one-to-two major cracks) were observed in the simulations. It was observed also that strain-rate effects do not (preliminary) seem to play an important role on the cracking pattern (more investigation is under development to ascertain the above statement).

Large specimens were extracted from real buildings under demolition and quasi-static cyclic testing until failure have been on-going at the University of Canterbury. The first phase of the experimental campaign comprises the testing of three beam-column joints from the PwC building, a 22-storey RC frame building designed in 1980s, aiming at investigating the cyclic behaviour and ultimate/residual capacities for undamaged, damaged-repaired (epoxy pressure injection technique), and damaged-unrepaired capacity designed beam-column joints.

At a component (or plastic hinge) level, a conceptual framework to account for residual capacity of plastic hinges was developed, consisting of four main components: 1) seismic demand estimation; 2) cyclic demand (i.e. equivalent number of cycles); 3) relationship between plastic drift and fatigue life

(i.e. cyclic capacity); and 4) remaining residual capacity. At a global (or structure) level, a displacement based design procedure accounting for residual deformations was further developed to explicitly incorporate residual capacity in the overall process.

The active and extensive participation of key members of this research project on a dedicated working-group/ committee conveyed by MBIE has been critical to set the background for the (on-going) drafting of the core part of a White Paper on Residual Capacity, looking at identifying the research gaps needed in the short-medium future to achieve a more robust understanding on residual capacity and more effective decision-making process on reparability vs. demolition.

Lastly, and acknowledging that residual capacity of RC buildings is a very complex and not yet solved topic, the outcomes of this project are expected to form the basis for a larger research multi-year and multi-unit research project, requiring further comprehensive studies, practical validation and implementation in the next few years.

14 ACKNOWLEDGEMENTS

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15 APPENDICES

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