DAMAGE ASSESSMENT AND RESIDUAL CAPACITY OF RC BEAMS SUBJECTED TO LOW-CYCLE FATIGUE

A. Malek¹, A. Scott², S. Pampanin³

ABSTRACT

This paper presents the preliminary results of an extensive experimental campaign of investigation on the damage assessment and residual capacity of RC beams at the University of Canterbury using low-cycle fatigue approach. In the first stage, the structural behavior of an RC beam under constant-amplitude fatigue loading at ±2% was examined. This provided a basis to determine the total number of cycles required to failure (i.e., fatigue life), and also to assess the fatigue damage in terms of degradation in strength, stiffness and energy dissipation capacity over the fatigue life of the specimen. In the second stage, two companion RC beams were subjected to 70% and 90% of their fatigue life at ±2% drift, re-centered and then monotonically loaded up to failure. Furthermore, one reference intact beam was subjected to similar monotonic loading up to failure. To determine the residual monotonic flexural capacity of the beams, the lateral force–displacement curves of both cyclically pre-damaged specimens and the undamaged specimen were compared. The evolution of fatigue damage represented three different regions: initial degradation up to about 10% of fatigue life, followed by a gradual decay up to about 70% of fatigue life, and the third stage, consisting of significant drops due to fracture of longitudinal reinforcement. The study showed that 70% is the fraction of fatigue life that may be considered as the threshold beyond which the failure of the test specimen is inevitable. It was also observed that the application of 70% of the fatigue life degrades strength and secant stiffness in the subsequent residual monotonic behavior of the specimen by up to 38% and 72%, respectively but there is almost no degradation in deformation capacity up to 12.5% drift.

¹Ph.D student, Dept. of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand, (email: annmalek@gmail.com)
²Senior lecturer, Dept. of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand, (email: allan.scott@canterbury.ac.nz)
³Professor, Dept. of Civil Engineering, University of Rome ‘La Sapienza’, Rome, Italy; Dept. of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand. (email: stefano.pampanin@uniroma1.it)

This paper presents the preliminary results of an extensive experimental campaign of investigation on the damage assessment and residual capacity of RC beams at the University of Canterbury using low-cycle fatigue loading approach. In the first stage, the structural behavior of an RC beam under constant-amplitude fatigue loading at ±2% was examined. This provided a basis to determine the total number of cycles required to failure (i.e., fatigue life), and also to assess the fatigue damage in terms of degradation in strength, stiffness and energy dissipation capacity over the fatigue life of the specimen. In the second stage, two companion RC beams were subjected to 70% and 90% of their fatigue life at ±2% drift, re-centered and then monotonically loaded up to failure. Furthermore, one reference intact beam was subjected to similar monotonic loading up to failure. To determine the residual monotonic flexural capacity of the beams, the lateral force–displacement curves of both cyclically pre-damaged specimens and the undamaged specimen were compared. The evolution of fatigue damage represented three different regions: initial degradation up to about 10% of fatigue life, followed by a gradual decay up to about 70% of fatigue life, and the third stage, consisting of significant drops due to fracture of longitudinal reinforcement. The study showed that 70% is the fraction of fatigue life that may be considered as the threshold beyond which the failure of the test specimen is inevitable. It was also observed that the application of 70% of the fatigue life degrades strength and secant stiffness in the subsequent residual monotonic behavior of the specimen by up to 38% and 72%, respectively but there is almost no degradation in deformation capacity up to 12.5% drift.

Introduction

After a seismic event, the safety and effects of aftershocks on damaged reinforced concrete (RC) buildings are major concerns. This requires quantitative damage assessment to evaluate the residual seismic capacity and to identify appropriate courses of action to be taken on the damaged buildings. Appraisal of post-event capacity of damaged RC buildings is therefore an essential task for quick recovery of damaged communities as the outcome will allow demolition, repair or even reoccupation of the existing concrete building without any further action to be considered.

Residual seismic capacity of earthquake-damaged RC buildings can be assessed at three levels: material level [1], component level—the residual axial capacity of previously damaged RC columns/bridge piers [2-5] and beam–column joints [6]—and at system level [7, 8]. However, there is little information found in the literature on the remaining flexural capacity of RC beams.

The majority of modern RC buildings are designed to withstand seismic loads through a trade-off between strength, for controlled damage, and formation of plastic hinges in pre-determined locations [9]. This capacity design philosophy permits RC buildings to dissipate a significant amount of energy and achieve large ductility demands while ensuring life safety of building occupants. The aftermath of the Canterbury earthquakes of 2010–2011 highlighted the lack of resources for evaluating the residual capacity of many RC buildings that had experienced intermediate levels of damage, resulting in the demolition of approximately 60% of multi-story
To experimentally determine the residual capacity of an RC member, three main challenges need to be answered: which loading protocol should be considered to cause the damage to the RC member (e.g., ground motion, incremental cyclic loading protocol or constant amplitude cyclic loading protocol), and secondly, with respect to which loading protocol the residual capacity should be assessed, and finally, what form of remaining capacity (e.g., axial/flexural capacity) should be evaluated. That is because the structural capacity/performance of RC members is not unique and is substantially reliant on the previously applied cyclic-loading history. Thus, due to the difference in loading history/protocols by which RC members are damaged and also the subsequent reloading regime for determining residual capacity, no unique residual capacity can be reported. There is a need therefore to adopt a more unified and standardized approach to assess damage and the residual capacity of concrete and RC members.

The assessment of damage associated with earthquakes in RC buildings can be conveniently approximated by using a low-cycle fatigue approach. Seismic loading causes a limited number of relatively large inelastic cycles along with cycles with much smaller demands that are in line with the concept of low-cycle fatigue. Low-cycle fatigue particularly refers to the range of loading cycles from 1 to approximately 1000 cycles, to which an RC building may be subjected during earthquakes over its lifespan. In the case of RC members, there are limited studies in the literature in which the low-cycle fatigue behavior of RC bridge piers and beam–column joints has been investigated by applying a constant-amplitude cyclic loading protocol. However, the fatigue–life relationship proposed for bridge piers was based on the number of cycles that specimens underwent at constant-amplitude cyclic loading at ±4%, ±5.5% and ±7% drift that were too high for seismically designed RC piers from the buildings code perspective. In the study conducted by Erberik and Sucuoğlu, the exterior beam–column joints were constructed using plain bars for both longitudinal and stirrups, which substantially does not provide the perfect bond between reinforcement and the surrounding concrete.

Since the elements of RC buildings located in earthquake-prone areas are expected to experience loading reversals, it is of great interest to assess the performance, degradation and eventually the residual capacity of RC beams from a fatigue perspective. Satisfactorily, the implementation of low-cycle fatigue concept in this study for loading protocol and quantifying damage at any desired fractions of fatigue life (i.e., required number of cycles to failure) seems promising to expedite a more generalized procedure for assessment of damage and residual capacity.

Based on what discussed earlier, there is a need to address the residual capacity of RC beams in a more standardized way in terms of fractions of their fatigue life. In this study, low-cycle fatigue damage development associated with an RC beam under constant-amplitude cyclic loading at ±2% was first established. Then, another two specimens were subjected to 70% and 90% of the required number of cycles to failure (i.e., fatigue life), re-centered and then monotonically pulled until failure. Finally, the monotonic results of pre-damaged specimens were compared to the behavior of an intact specimen loaded monotonically up to failure.

**Experimental program**

**Test setup and loading protocols**

Four RC beams were tested in a cantilever scheme, as shown in Figure 1. The reaction
frame used for the tests consisted of steel braced frames anchored to the RC strong floor. The RC cantilever beams were tested vertically because of the ease of applying a lateral load and erecting the experiment. The beam specimen was clamped by a steel footing, 500 HCC 413 wide flange steel sections, by bolting four threaded bars (M24, Grade 8.8), already cast into the specimen. Four high-strength M36 bolts were then used to fasten steel blocks to the strong floor. Hilti RE-500 epoxy was used to fully fill the gap between the end plate (welded to footings) and the outer face of the specimen.

A 400 kN capacity hydraulic actuator with stroke of ±210 mm was located approximately at the theoretical point of contraflexure with a cantilever length of 1570 mm. The applied load was measured using the load cell positioned in the head of the actuator and a string potentiometer was used to record the displacement occurring at the level of applied loading. In the case of fatigue tests, a quasi-static displacement-controlled constant amplitude cycling loading protocol was applied at the drift (chord rotation) of ±2% at a rate of 0.5 mm/s. This provided a basis to determine the low-cycle fatigue characteristics of the test beams until a fracture of the bar happened. Monotonic testing was also conducted on one undamaged beam to capture its monotonic flexural capacity.

![Test setup](image)

**Figure 1 Test setup**

**Specimen details**

The beams used in this study were 2850 mm long with rectangular cross sections of 250 × 350 mm, as shown in Figure 2. The specimens were built at half scale and designed in accordance with New Zealand code of practice for the design of concrete structures [15]. The longitudinal reinforcements in tension and compression were four bars with nominal diameters of 16 mm. The shear reinforcement, which was designed to ensure flexural failure in the beams, consisted of 10 mm stirrups at a spacing of 75 mm over 1455 mm of the length from the support side and 125 mm over a 1395 mm length of the beam. Both reinforcements used in the specimens were Grade 300E deformed bars. The mechanical properties of the reinforcing steel were determined using experimental tensile tests on the coupon rebar; the mean yielding strength and modulus of elasticity of the longitudinal steel reinforcement were 297 MPa and 202 GPa, respectively, with a yield strain of 0.00147. The average of the concrete compressive strengths ($f'_c$) of the RC beams was determined from compression tests on three concrete cylinders (200 mm × 100 mm), on the same
date of testing, and was found to be 36 MPa.

Figure 2 Reinforcement details for RC beams

Experimental results

Monotonic test

Figure 3 shows the monotonic load–deformation capacity of the RC beam. The specimen behaved approximately linearly and elastically up to 52.6 kN (0.75% drift) and then showed a gradual increase over the post-yield range, reaching the maximum lateral load of 72 kN at 13% drift. No indication of bar buckling or fracture of reinforcement was observed on either the compression or tension side. Stirrups underwent significant deformations, but no fracture occurred. The first sign of flexural cracks was captured at 0.2% drift, followed by the emergence of more cracking up to 0.75% drift, where a significant increase in maximum crack size, up to 0.45 mm, was observed. This drift level is very distinct, since it corresponds to yielding of bars that results in an increase in crack width. Beyond this point, the rate of increase in crack width increased considerably. At 2.8% drift, vertical cracking emerged on the compression side; however, no sign of noticeable spalling of cover concrete appeared during the test.

Figure 3 (a) Monotonic force–displacement behavior; (b) damage status at 13% drift
Fatigue test

Having applied a constant-amplitude cyclic loading regime between consecutive push and pull cycles at ±2% drift, the total number of cycles that RC beams sustained before failure ($N_f$) was found to be 237 cycles. Observations showed the first cycle was sufficient to develop well-dispersed cracks along the length of the specimen. Cracks propagated along the height of the datum level (top of steel footing), and deformation of hoops, and buckling of longitudinal bars started. The maximum measured crack widths on either side were between 2.6 mm and 2.7 mm. Crack mapping and crack measurement were conducted every 30 cycles in this test. At the end of the 90th cycle ($n/N_f = 0.38$), significant spalling of concrete cover in a length of 260 mm occurred on the compression side, causing the stirrups to be exposed. As shown in Figure 4, generally the hysteresis loop showed stable behavior, and strength and stiffness degradation occurred at a gradual rate. Apart from the first cycle, in which the marked pinching starts, during cycles 60–90 significant pinching was also observed. No sign of obvious buckling in the plastic hinge zone was observed even at the end of the test. Despite significant deformation of stirrups, no fracture was observed.

![Hysteresis loop](image)

**Figure 4** Force–displacement response of RC beams subject to fatigue loading at 2% drift

Figure 5 shows the typical failure mode of test beams due to low-cycle fatigue fracture of the longitudinal bar. In all the experiments, longitudinal bars snapped on the side first subjected to tension.
Fatigue damage denotes the deterioration in the mechanical properties (e.g., strength, stiffness) of the RC beam under reversals of loading. Figure 6(a) shows the ratio of the maximum lateral force achieved in each consecutive cycle ($F_{\text{max}}$) to the maximum lateral force achieved in the first cycle ($F_{\text{max},0}$). As can be seen, the initial phase starts with a decrease up to about 10% of fatigue life, followed by a gradual descending trend during the second stage up to 0.7 of fatigue life, where the first bar fracture occurs. The third stage, consisting of the last 20%–30% of fatigue life includes significant drops due to fracture of the longitudinal reinforcement. The study showed that 70% of fatigue life is a limit beyond which bar fracture occurs in all the experiments. This implies that this fraction of fatigue life may be considered as a threshold beyond which the failure of the test specimen is inevitable.

The fatigue loading resulted in progressive damage with a marked degradation in stiffness of the RC beams. Such damage can be represented by introducing the characteristic parameters of secant modulus, calculated as the ratio of maximum force to corresponding displacement [16]. Figure 6(b) shows the ratio between the secant modulus of the test beam ($K_\text{s}$) in each cycle and its secant modulus in the first cycle ($K_{\text{s},0}$). As can be seen, the behavior of the test beams is similar to that shown in the strength deterioration spectrums.

During low-cycle fatigue, energy induced to an RC specimen is dissipated through damping mechanisms along with plastic deformation, resulting in structural damage (e.g., plastic hinge). In fact, fatigue damage is the consequence of plastic energy, which is dissipated during consecutive excursions. Figure 6(c) shows the process of dissipation of energy, represented as a form of dimensionless ratio of dissipated energy in each cycle ($E_D$) to dissipated energy in the first cycle ($E_{D,0}$), against the fatigue life of the RC beam. The dissipated energy was calculated from numerical integration of the area enclosed under the hysteresis loops. As shown, there is a significant loss, specifically after the first cycle, which indicates that the area formed during the first reversal is considerably higher than in the subsequent cycles. Results showed the rate of deterioration in the dissipation energy spectrum is higher than in the strength or stiffness spectrums. Overall, the ability of damaged RC beams to dissipate the input energy at 20% of fatigue life diminishes to about 40% of its dissipation capacity during the first cycle.
Figure 6 Fatigue damage evolution: (a) degradation in strength capacity; (b) degradation of secant modulus; (c) degradation in energy dissipation capacity

Residual capacity

To determine the residual lateral load–displacement capacity of RC beams in this study, a two-phase experimental program was carried out. In the first phase, two intact RC beams were subjected to two prescribed fractions of fatigue life at 2% drift level. In the second phase, the previously damaged RC beams were re-centered and subjected to a monotonic lateral loading test. The experiments were tagged using a 3-component ID according to their variables. The first part denotes the status of the test specimen (R, Residual), the second is the fraction of fatigue life at which the fatigue loading stopped ($n/N_f = 0.7$ or $0.9$), and the last component represents the drift level at which fatigue loading was conducted.

Figure 7 shows the residual force–displacement relationships of damaged specimens reloaded monotonically after fatigue loading. The force–displacement of the intact specimen subjected only to monotononic loading is also shown for comparison purposes. It can be seen that the minimum level of damage in terms of reduction in strength, secant stiffness and deformation capacity is related to the response of the damaged beam that was subjected to 70% of its fatigue life at 2% drift (R-0.7-2%). The residual monotonic behavior of the beam that experienced 90% of its fatigue life (R-0.9-2%) is initially similar to its companion specimen, up to 7.3% drift where a marked drop happened because of bar fracture. The specimen still retained its strength up to 12.5% drift, beyond which it lost its strength. As expected, the higher the number of cycles to which the specimen was subjected (i.e., higher ratio of $n/N_f$), the larger the degradation in
mechanical properties observed. Generally, the application of 70% of the fatigue life degrades strength and stiffness capacities in the subsequent monotonic behavior of the specimen, but there is almost no degradation in deformation capacity. However, it should be noted that the test was terminated at a lateral displacement of 197 mm, due to the limitation in the stroke capacity of the actuator.

Comparing the secant stiffness of the intact specimen with the secant stiffness of the beams monotonically tested after subjection to 70% and 90% of their fatigue life showed that subjection to 70% and 90% of fatigue life caused the secant stiffness of the residual force–displacement curves to degrade from 4.1 kN/mm to 1.38 kN/mm and 1.14 kN/mm, denoting a decrease of 65% and 72%, respectively. Additionally, in the case of the residual monotonic bearing strength of the beam, it was found that pre-damaging specimens to 70% and 90% of their fatigue life at 2% drift resulted in a reduction of 9% and 38% in residual strength capacity, respectively.

![Figure 7 Residual force–displacement capacity of pre-damaged beams](image)

**Conclusions**

This paper presented the preliminary results of an extensive investigation into the development of damage, material degradation, residual mechanical capacity and damage assessment of RC beams subjected to fatigue loading. The following conclusions can be drawn, based on the results of this study:

- The spectrums did not show the classic S-shaped trend as in the case of low-cycle fatigue loading, but three different regions can still be identified. Initial degradation occurs up to about 10% of fatigue life, followed by a gradual decay up to about 70% of fatigue life, and a third stage, consisting of significant drops due to fracture of longitudinal reinforcement. The study showed 70% of fatigue life was identified as the fraction of fatigue life that may be considered as the threshold beyond which the failure of the test specimen is inevitable. Results showed the rate of deterioration in the dissipation energy spectrum is higher than
in the strength or stiffness spectrums. Considering the deterioration of energy dissipation capacity of the RC beam due to the development of fatigue damage at ±2% drift, it was found that at 70% of fatigue life (i.e., $n/N_f = 0.7$), the residual energy dissipation ability of the damaged RC beam degrades to about 30% of its energy dissipation capacity associated with the first cycle.

• Having monotonically reloaded damaged specimens, previously subjected to different ratios of fatigue, the residual force–displacement relationships were established. In terms of residual monotonic strength and residual secant stiffness of the beams, it was found that pre-damaging specimens to 70% and 90% of their fatigue life at 2% drift, resulted in a reduction of 9% and 38% in the case of residual strength capacity, and a decrease of 65% and 72%, for secant stiffness, respectively. However, in a range of maximum applied displacement (i.e., drift of 12.5%), the study showed that the damaged beams can still show approximately similar levels of deformation capacity to the intact one up to 12.5% drift.

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