Experimental loading protocols to evaluate the seismic performance of floor systems

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ABSTRACT

Major earthquakes, such as the Canterbury and Kaikoura events recorded in New Zealand in 2010 and 2016 respectively, highlighted that floor systems can be heavily damaged. At a reduced or full scale, quasi-static experimental tests on structural sub-assemblies can help to establish the seismic performance of structural systems. However, the experimental performance obtained with such tests is likely to be dependent on the drift protocol adopted. This paper provides an overview of the drift protocols which have been assumed in previous relevant experimental activities, with emphasis on those adopted for testing floor systems. The paper also describes the procedure used to define the loading protocol applied in the testing of a large precast concrete floor diaphragm as part of the Recast floor project at the University of Canterbury. Finally, major limits of current loading protocols, and areas of future research, are identified.

1 INTRODUCTION

As highlighted by the 2010-2011 Canterbury earthquake sequence in New Zealand, traditional floor systems can experience extensive damage and can pose significant life-safety risk. As a result, the research community has put in place an important effort to try to better identify the expected seismic performance of floor diaphragms and the efficacy of the more common retrofit solutions adopted.

At a reduced or full scale, quasi-static experimental tests on structural sub-assemblies have been conducted by a number of researchers to gain insights into the seismic performance of structural systems. However, a critical aspect of quasi-static testing procedures is associated with the dependency of the results on the specific loading protocol assumed. An analysis of available loading protocols is therefore of high importance and should help researchers obtain useful seismic performance predictions.

A large variety of unidirectional and bidirectional loading protocols have been proposed in the literature to replicate the effects of both ordinary (far-field) and near-fault ground motions. The next section provides a brief overview of some of the most commonly implemented.

1.1 Unidirectional loading protocols

A loading protocol widely adopted in past experimental activities is the CUREE-Caltech quasi-static displacement-controlled protocol described in Krawinkler et al. (2000). This is a multiple-step test, in which the deformation history consists of stepwise increasing deformation cycles as shown in Figure 1. The deformation parameter to be used to control the loading history is the inter-story drift angle. The protocol involves six cycles at a drift level equal to 0.00375, six cycles at a drift of 0.005, six cycles at a drift of 0.0075, four cycles at a drift of 0.01, two cycles at a drift of 0.015, two cycles at a drift of 0.02 and two cycles at a drift of 0.03. The test continues with increments of drift equal to 0.01, and with two cycles at each step, up to the maximum displacement of interest. A different loading protocol was also proposed to simulate the effects of near-fault events, as shown on the right side of Figure 1. The basic loading protocol was constructed assuming the SAC model buildings (3, 9, and 20 stories) designed for Los Angeles and Seattle, and the SAC ground motions records (10/50 and 20/50), Krawinkler et al. (2000). The near-fault loading history was constructed based on the response of the SAC model buildings to the SAC near-fault ground motions for the Los Angeles location, Krawinkler et al. (2000).

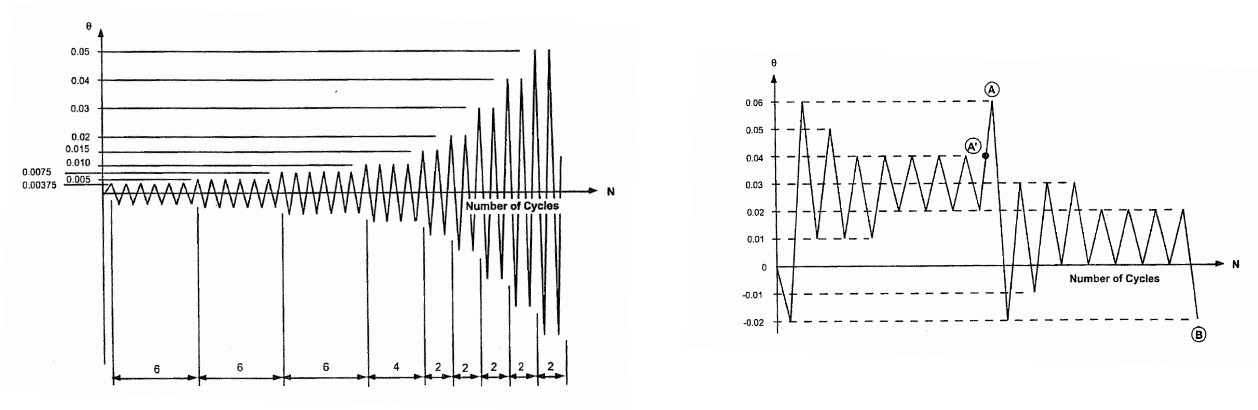


Figure 1: CUREE loading history for multiple-step test representing the effects of ordinary (on the left) and near-fault (on the right) ground motions.

The CUREE loading protocols that were proposed to represent the effects of ordinary and near-fault ground motions have been both later modified in Krawinkler et al. (2001), as shown on the left and right sides of Figure 2, respectively. The modified loading histories are defined in terms of a reference deformation, Δ, which is the maximum deformation capacity the specimen is expected to sustain. The loading history for ordinary ground motions includes *initial cycles*, *primary cycles*, and *trailing cycles*. Initial cycles are executed at the beginning of the loading history to check the instrumentation (loading equipment, displacement, and force transducers) is working properly. A primary cycle is a cycle that is larger than all of the preceding cycles and is followed by smaller cycles, which are trailing cycles. All trailing cycles have an amplitude equal to 75% of the amplitude of the preceding primary cycle. All cycles are symmetric, with identical positive and negative amplitudes, and the test should be conducted with deformation control. The loading protocol in Figure 2, representing the effects of ordinary ground motions, includes four initial cycles at 0.05Δ, seven primary cycles at $0.075\ \Delta$, 0.01Δ, 0.02Δ, 0.03Δ, 0.04Δ, 0.06Δ and 1.0Δ. The first two primary cycles are followed by three cycles while the remaining five primary cycles by two cycles, all of them at 75% of the amplitude of the primary cycle. The loading protocol described, and shown on the left side of Figure 2, is an abbreviated version of the complete basic loading protocol proposed in Krawinkler et al. (2001) which, in terms of the number of cycles and their amplitudes, is compatible with the original CUREE loading protocol introduced and shown on the right side of Figure 1.

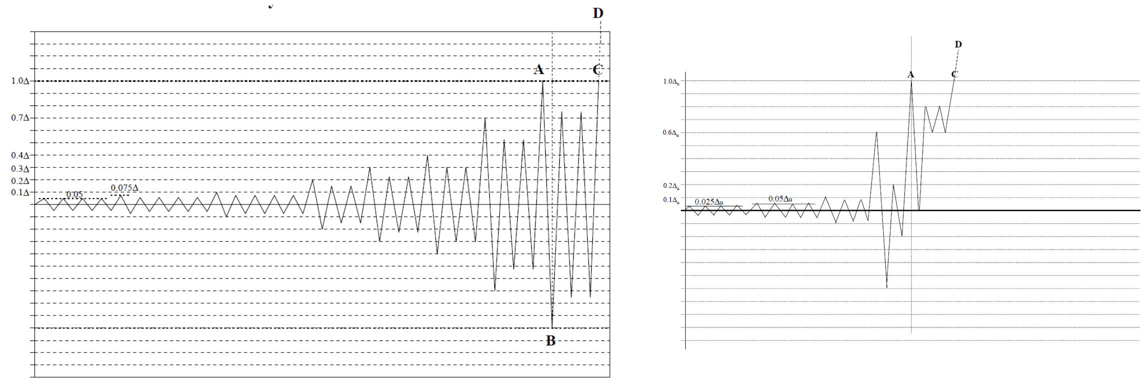


Figure 2: CUREE loading history (after Krawinkler 2001) for multiple-step test representing the effects of ordinary (on the left) and near-fault (on the right) ground motions.

Loading protocols for unidirectional and bidirectional quasi-static experimental tests have been also included in the FEMA 461 *Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Nonstructural Components* document. The quasi-static cyclic loading protocol presented in this document is intended to determine the performance characteristics of components, the behaviour of which is primarily controlled by the application of seismic forces or earthquake-induced displacements. The quasi-static cyclic procedure presented includes both a unidirectional loading protocol, Figure 3 on the left, and instructions on the orbital pattern to be followed when bidirectional tests are conducted, Figure 3 on the right. ACI 374.2R-13 has also prescribed a deformation history for tests under unidirectional load reversal and a hexagonal orbital pattern for bi-directional testing.

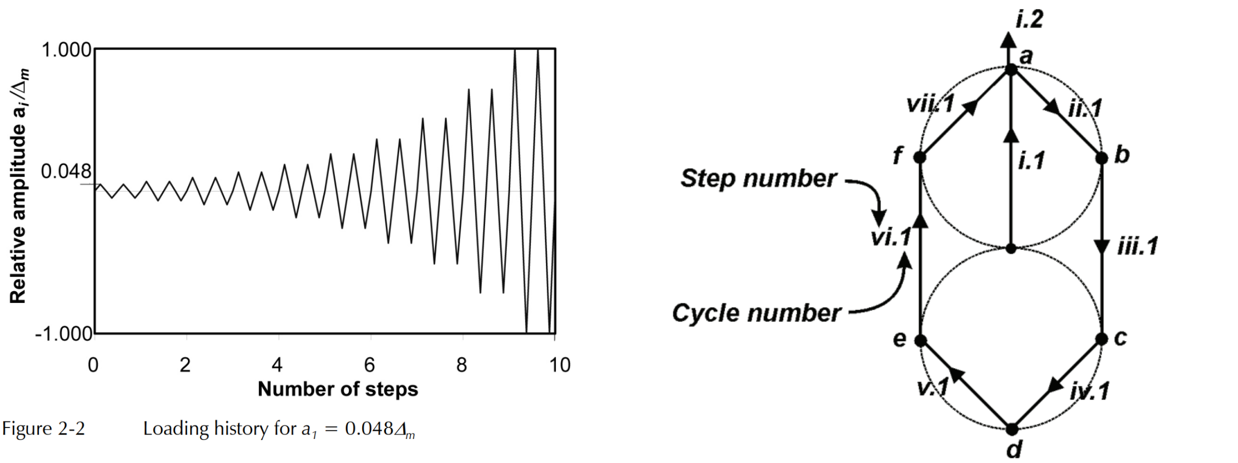


Figure 3: CUREE loading history for multiple step test representing the effects of ordinary (on the left) and near-fault (on the right) ground motions.

1.2 Bidirectional loading protocols

As for unidirectional loading protocol, several bidirectional loading protocols have been proposed in the literature. Rodrigues et al. (2013) listed seven commonly used loading paths namely, cruciform, diagonal cruciform, Rhombus, expanding square, square in each quadrant, circular and elliptical paths, as shown in Figure 4.

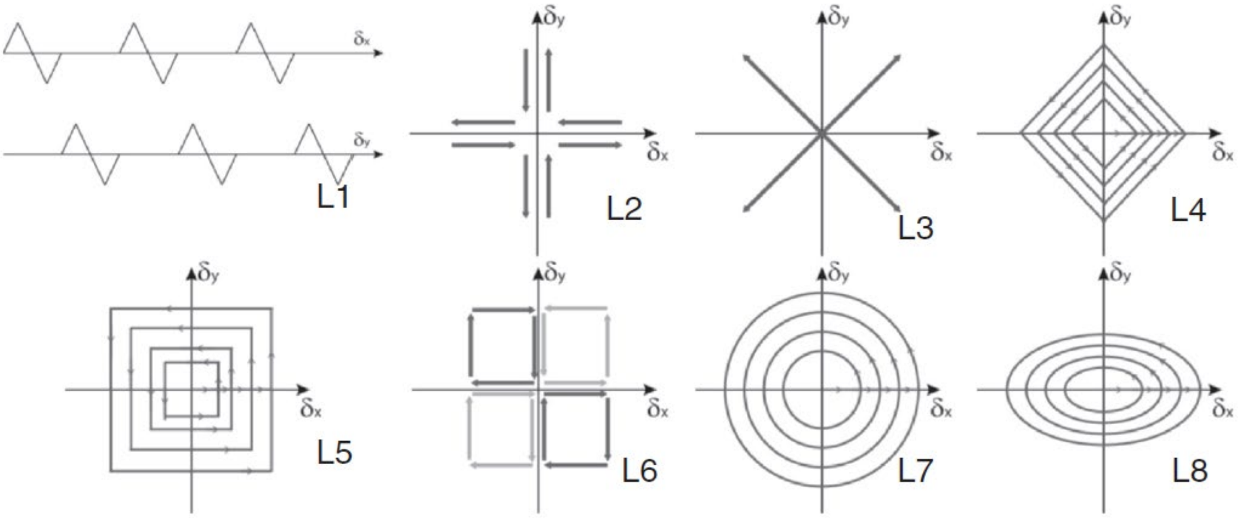


Figure 4: Typical bi-directional loading protocols identified by Rodrigues et al. (2019).

Raza et al. (2019) tested a building column under constant axial load and several bidirectional lateral actions. Three different bidirectional loading protocols, namely the linearized circular path, Figure 5 on the left, the octo-elliptical path with equal displacement demand (a=b), Figure 5 central, and the octo-elliptical path with displacement demand in the main directions with the ratio a/b=0.6. Readers are referred to Raza et al. (2019) for additional details into these bidirectional loading protocols.

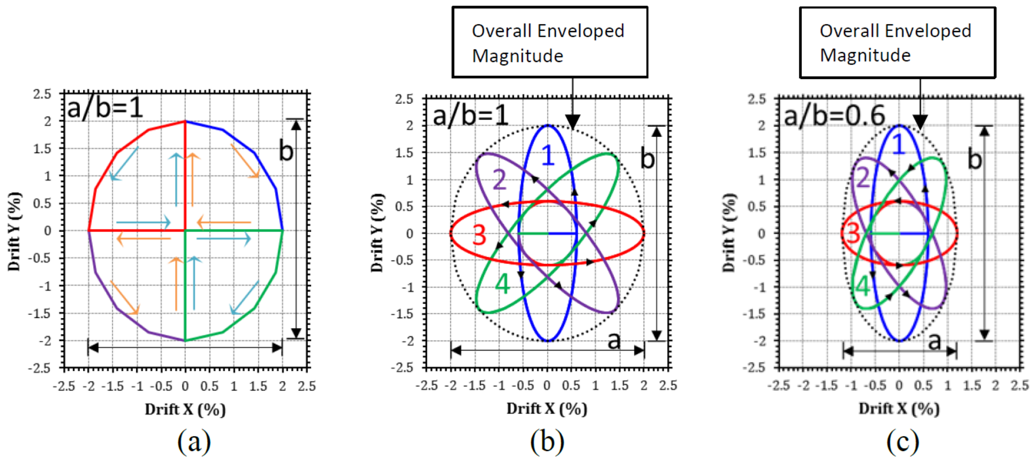


Figure 5: Loading protocols proposed by Raza et al. (2019) for bi-directional loading.

This paper presents a procedure for defining drift protocols to evaluate the performance of floor systems under a specific earthquake excitation. The proposed procedure starts with the identification of the seismic hazard and a representative structure, and involves the evaluation of the seismic demand imposed on the building structure sub-assembly being tested with a quasi-static test. The demand obtained is post-processed and simplified to obtain the final drift protocol. The procedure is described assuming a typical New Zealand mid-rise building and a Kaikoura earthquake ground motion recorded in Wellington. The results obtained have been applied to determine the loading protocol assumed for the large-scale experimental test conducted as part of the ReCast project.

Figure 6: Global view of the building sub-assembly tested during the Recast floor project.

2 THE RECAST PROJECT (PHASE-1) LOADING PROTOCOL

The Recast project is a joint project between the University of Canterbury and the University of Auckland that aims to (i) deepen the understanding of the seismic behaviour of precast concrete hollow-core floor diaphragms and (ii) identify the performance of common retrofit solutions adopted for precast concrete hollow-core floors in New Zealand. The research project includes a series of experimental activities on a large-scale building sub-assembly, shown in Figure 6, conducted at the structural engineering laboratory (SEL) of the University of Canterbury in Christchurch. This section presents the procedure adopted to determine the first of the loading protocols adopted, with the aim of investigating the effects of the Kaikoura earthquake on precast concrete floor diaphragms of typical medium-rise buildings located in the Wellington area.

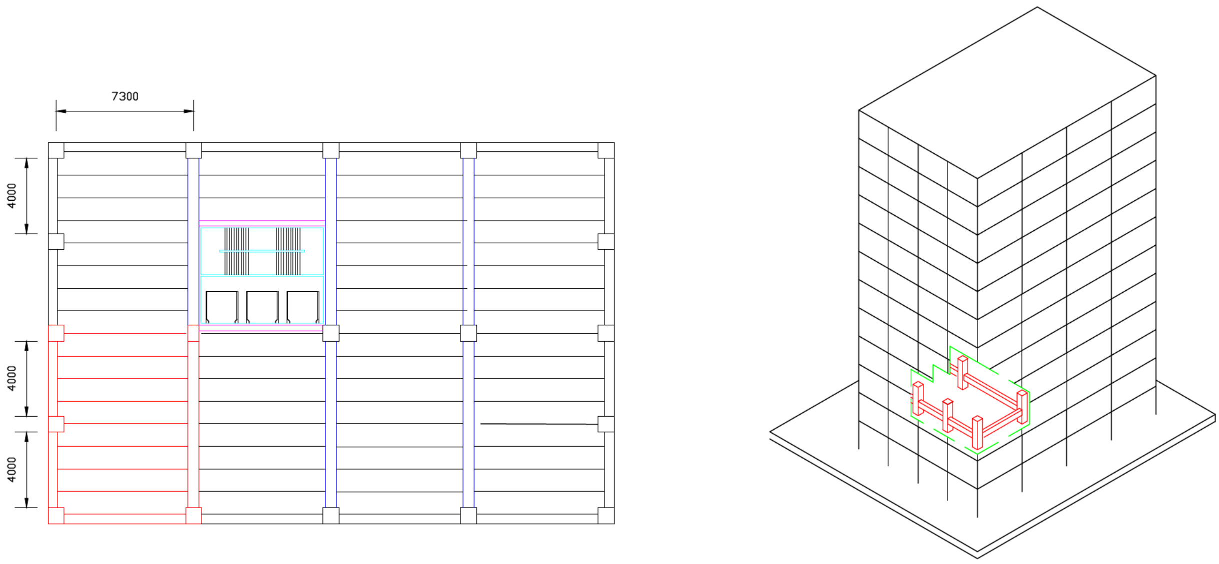


Figure 7: General view of the building model and of the sub-assembly experimentally investigated

As previously noted, the Kaikoura earthquake in 2016 caused significant damages to precast concrete floor diaphragms in the Wellington area. Given this, for the Recast project it was decided to consider a loading protocol that would impose displacement demands compatible with the demand imposed by the Kaikoura earthquake on typical medium-rise building structures located in the Wellington area.

This required (i) the design of a typical building structure, for seismic demands and design criteria specified in the previous New Zealand standard NZS 4203:1984, (ii) the development of a complete three dimensional FEM model of the building structure, and (iii) evaluation of the displacement demand imposed on this representative building by the Kaikoura earthquake by conducting nonlinear dynamic analysis. The displacement demand obtained, at the sub-assembly level, was later simplified and regularized to identify the sequence of cycles, and their amplitude, required to simulate the demand imposed.

2.1 Seismic design of a typical structural system for medium-rise buildings in Wellington

To identify a typical existing mid-rise building structure, a simulated seismic design was conducted according to the New Zealand Standard NZS4203:1984. This required a series of assumptions that have been made assuming a hypothetical building located in Wellington.

Considering the dynamic characteristics of the Kaikoura earthquake, which was particularly demanding for medium-rise buildings, it was decided to consider a thirteen storey building. The lateral resisting system, both in the transverse and longitudinal directions, was taken to be composed of concrete moment resisting frames, as seen in Figure 7. The lateral load resisting system is provided around the building perimeter, and the internal columns are assumed to carry gravity loads only, i.e. gravity columns. As shown in the generic floor plan layout reported in Figure 7, internal beams have been assumed only in the transverse direction. The floor system consists of precast concrete hollow-core floor units spanning perpendicularly to the internal beams. An allowance for stairs and elevators was also considered, as reported in Figure 7. The structural system and plan layout considered is intended to be representative of midrise building structures in Wellington and it is not related to a specific building. The building design and details are also described in the paper by De Francesco et al. (2021).

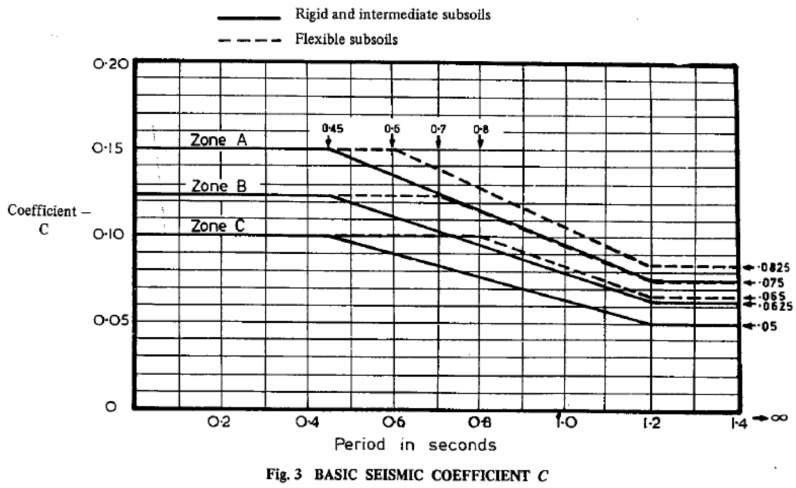


Figure 8: Seismic coefficient, NZS 4203:1984

In line with design provisions of the New Zealand Standard NZS 4203:1984, the seismic (base shear) demand, V_{base}, was obtained from the building seismic weight, $W_{Seismic}$, and the seismic coefficient, C_d, via Equation 1.

$$V_{base} = C_d \cdot W_{Seismic} \quad (1)$$

The seismic coefficient, C_d, in turn, is specified in terms of four factors, as shown in Equation 2.

$$C_d = C \cdot R \cdot S \cdot M \quad (2)$$

The basic seismic coefficient C is related to the seismic zone, subsoil flexibility, and building fundamental period, T. A value of C=0.0825 was obtained assuming the building is located in a high seismic risk zone (A) and has a fundamental period T longer than 1.2s, Figure 8. The *risk factor R* was assumed equal to 1 (buildings with normal occupancy), the *structural type factor S* equal to 0.8 (ductile frames), and the *structural material factor* equal to 0.8 (reinforced non-prestressed concrete). A base shear coefficient C_d=0.0528 was obtained as summarized in Equation 3.

$$C_d = 0.0825 * 1 * 0.8 * 0.8 = 0.0528 \quad (3)$$

The load analysis in the seismic combination resulted in a total building seismic weight of 62859kN. The weight of the generic floor was obtained summing the weight of the structural elements, beams, and columns, to the weight of the slab. The weight of the structural elements was obtained considering their geometry and a unitary concrete weight of 24kN/m^3. The unitary floor weight, which includes the weight of 200 mm hollow core precast elements and an additional 1.95kPa of superimposed load, was 4.65kPa. As a result, the unitary floor weight (including columns and beams) was 9.2kN/m^2, the total weight of the generic floor was 5238kN, and the slab weight was 2635kN.

The geometry identified consists of a symmetrical rectangular plan with main dimensions 29.2 m by 19.4 m, as per Figure 17. Constant bay lengths of 4.85 m and 7.3 m have been assumed respectively for the transverse and longitudinal directions. The inter-story height was assumed constant and equal to 4 m.

The gross section dimensions of beams and columns at the different levels of the building were assumed equal, for ease of construction and architectural aspects, but the longitudinal reinforcement ratios changes over the building height. For simplicity, reinforcement ratios of beams and columns have been changed only at half of the building height, and from level 7 to 12 the longitudinal reinforcement ratios of beams and columns are reduced to 2/3rds of the values assumed at the lower floors. The beams' longitudinal reinforcement ratio is 2 times the minimum longitudinal steel content prescribed by the New Zealand standard. The primary beams of the building perimeter have been assumed 500 mm wide and 750 mm deep. The secondary internal beams are 550 mm deep and 600 mm wide. The external columns have a square section of 850mm each side while internal gravity columns have a 600mm square section.

2.2 Assessing the likely response to Kaikoura earthquake ground motion

2.2.1 Modelling and analysis assumptions

With the design finalized, the resulting building structure was modelled in OpenSees to determine the seismic performance under the Kaikoura earthquake record. The geometry of the OpenSees building model assumed is summarized in Figure 9, for both transverse and longitudinal elevations, and in Figure 10, for the generic plan. Material nonlinearities have been modelled by fiber sections for both columns and beams, assuming the *nonlinearbeamcolumn* OpenSees element. Concentrated longitudinal and transverse mass properties have been assigned to the different nodes of the floor considering the plan layout shown in Figure 7. The damping model assumed was tangent-stiffness-proportional and the viscous damping ratio was set equal to 0.05. The Newmark time-stepping method (with γ=0.5 and β=0.25) was adopted with an integration time-step of 0.005s. Small displacement analyses were conducted. The building was found to have fundamental periods of 2.0s and 1.7s in the longitudinal and transversal directions, respectively.

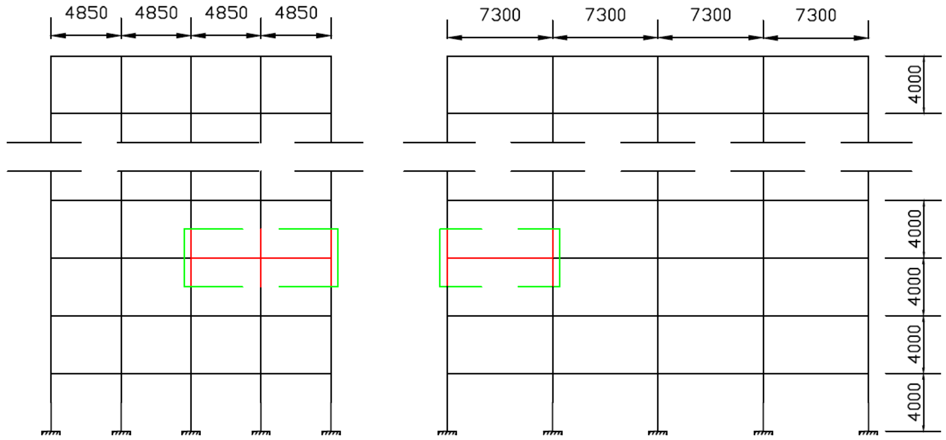


Figure 9: Transverse and longitudinal section of the building model

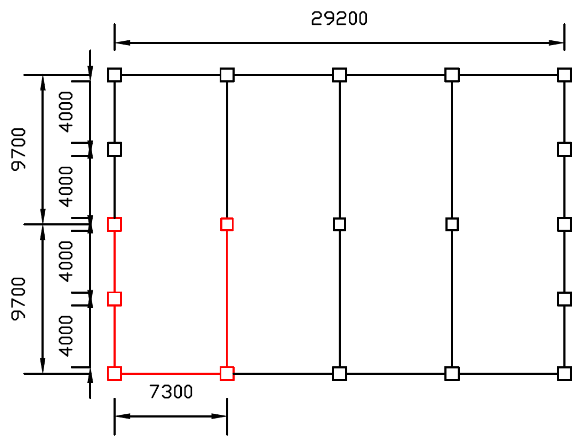


Figure 10: Plan of the building model

2.2.2 Selected ground motion

The Kaikoura earthquake event caused significant damage to floor systems of building located in Wellington. To identify the demand imposed by this earthquake event and to replicate it experimentally, the typical medium-rise building structure designed in the previous section was subjected to both horizontal components of the Kaikoura earthquake recorded at the base of the BNZ building, located in Wellington. Both the North-South and East-West earthquake record components are shown in figure 6, at the top and bottom respectively.

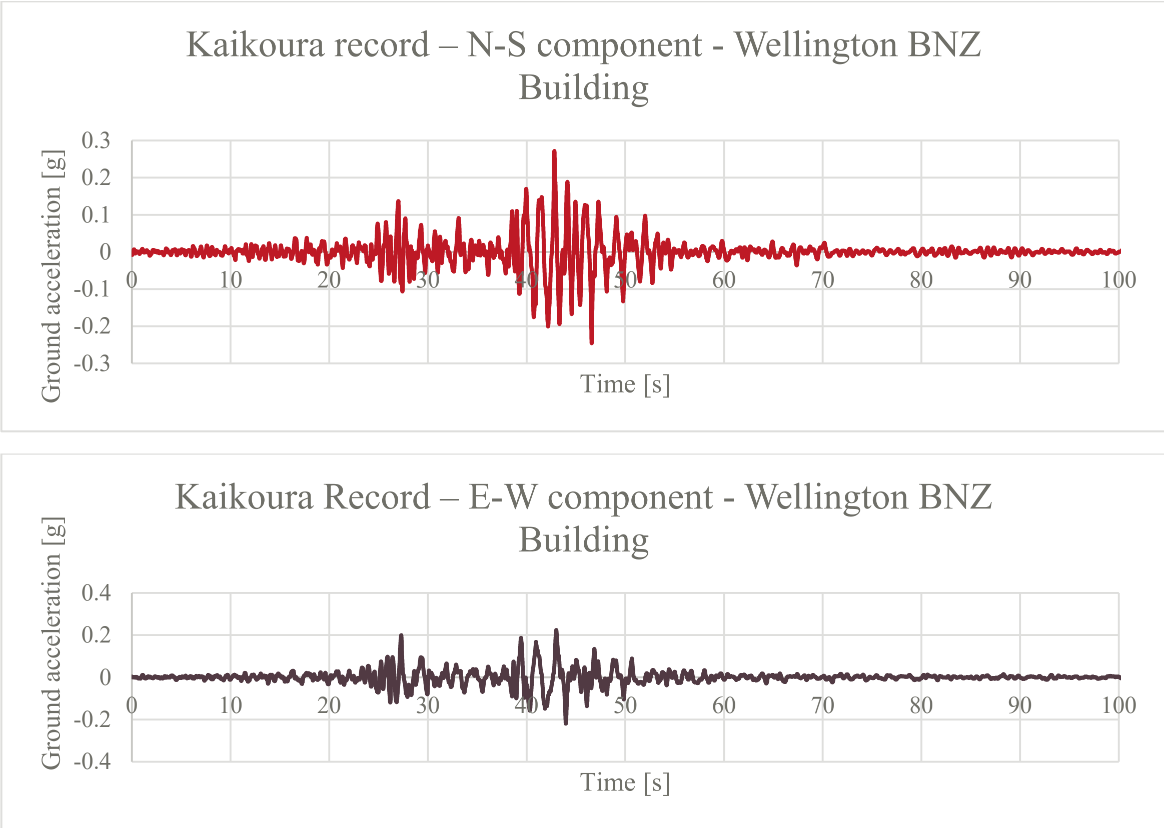
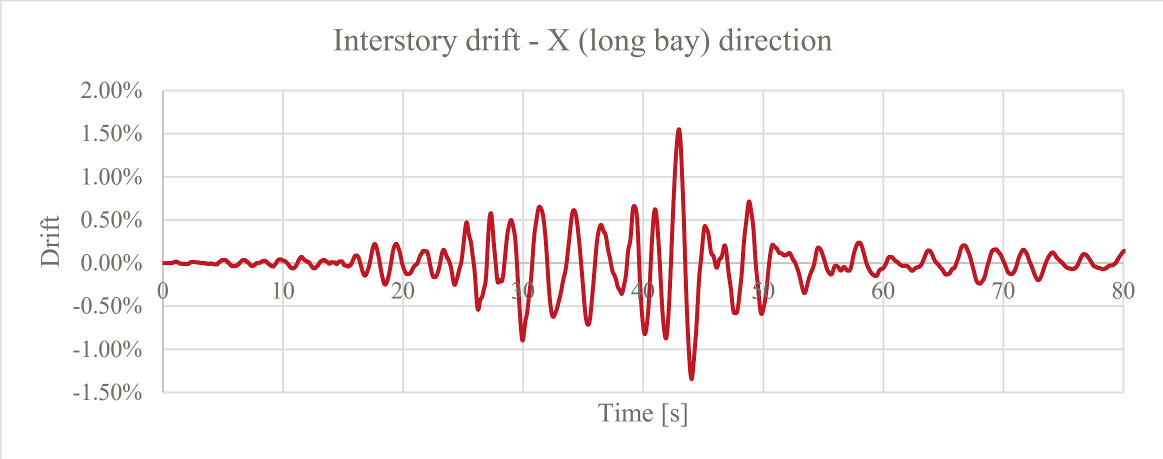


Figure 11: Kaikoura earthquake ground motions recorded at the BNZ building in Wellington; N-S component (top) and E-W component (bottom)

2.2.3 Analysis results

The main results of interest from the NLTH analyses are the interstory-drift at the level of the building where the test sub-assembly was supposedly located. Figure 12 presents the storey drift at the 3rd storey of the building for the two orthogonal directions as a function of time. Observe that for the longitudinal response direction the peak storey drift was estimated to be just over 1.5%. This would appear to align broadly with the peak response of other buildings subjected to the Kaikoura earthquake in Wellington. Figure 13 instead presents the combined X & Y drift response at the third storey.



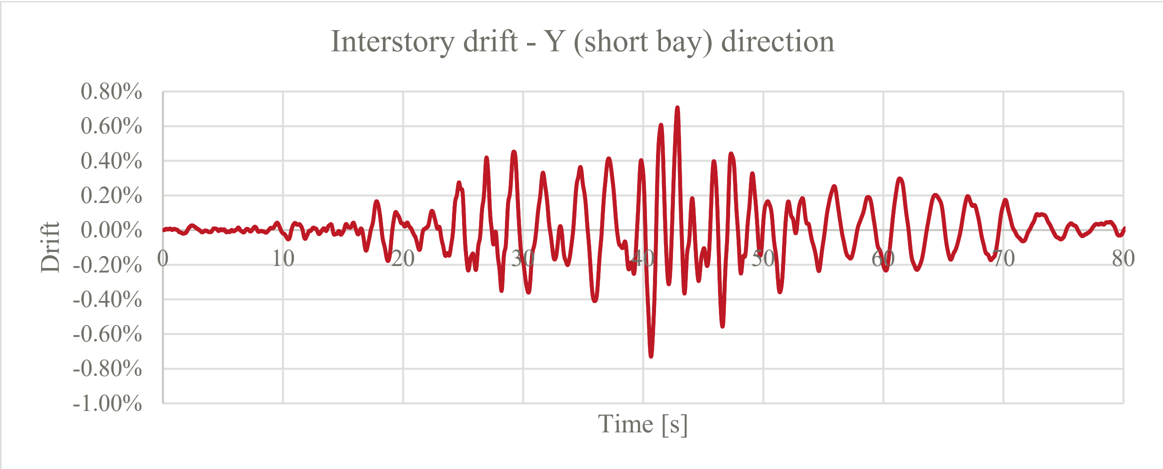


Figure 12: Inter-story drift time history at level 3, X (top) and Y (bottom) directions

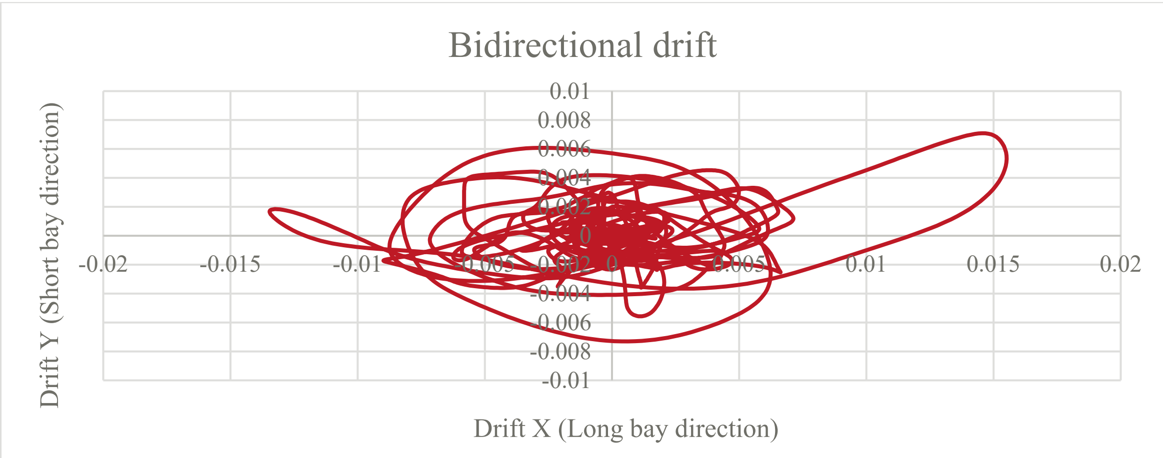
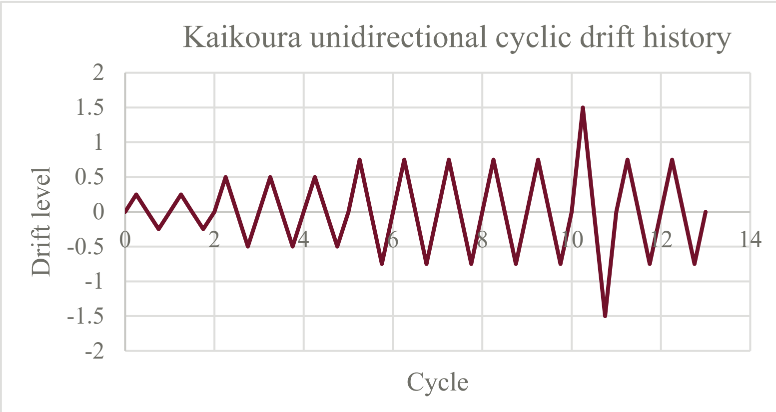


Figure 13: Inter-story drift time history at level 3

2.3 Interpreted loading protocol for the Recast floors experimental testing

The unidirectional response for the two horizontal directions shown in Figure 12, and the bidirectional response shown in Figure 13, have been modified to obtain a simpler and more regular loading protocol.

Based on the inter-story drift displacement obtained, it was decided to consider 2 cycles at 0.25%, 3 cycles at 0.50%, 5 cycles at 0.75%, 1 cycle at 1.50%, and 2 cycles at 0.75%. The test also included 2 preliminary cycles at 0.1% to check all the instrumentation was working properly.



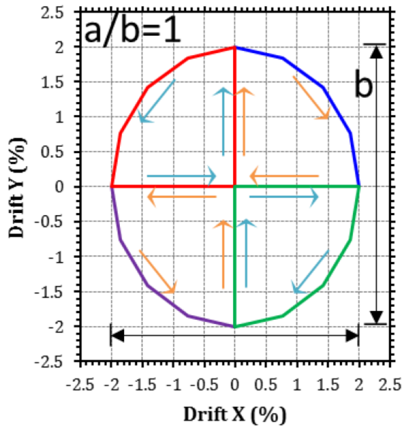


Figure 14: Kaikoura unidirectional loading protocol and orbital pattern assumed.

Each of the cycles presented in the plot on the left side of Figure 14 was applied according to the bidirectional loading protocol presented on the right side of Figure 14, Raza et al. 2019.

After application of the Kaikoura loading protocol The Recast frame was subjected to a standard progressive loading protocol that consisted of 2 cycles at 1.5%, two cycles at 2.0%, two cycles at 2.5%, and two cycles at 3.0%. At the end of the Kaikoura loading protocol and at the end of the progressive loading protocol the frame was also subjected to deformations similar to a shear-type deformed shape in plan, termed a rhomboid protocol.

3 LIMITATIONS OF EXISTING LOADING PROTOCOLS FOR BIDIRECTIONAL TESTING

Pseudo-static experimental tests are an important resource for researchers who intend to identify the likely seismic performance of structural systems. However, the dependency of the results on the loading protocol assumed could affect the experimental results obtained.

The loading protocol presented in this paper and conducted at the start of the first phase of the Recast project, was considered somewhat representative of the demands imposed on precast concrete floor systems by the Kaikoura earthquake in a typical building within the Wellington area. However, in general, the loading protocol should reflect the characteristics of the hazard that is typical for a region. To this extent, the use of hazard-consistent ground motions would be more desirable and specific characteristics of the earthquake records, such as amplitude/intensity of shaking, ground motion duration, pulse effects and soil type, would be considered as part of the loading definition.

The sensitivity of different possible failure mechanisms to the loading protocol assumed is also an important issue that researchers should consider when selecting a specific loading protocol. This aspect may be particularly relevant for bidirectional loading protocols. A bidirectional loading protocol that is characterized by equal displacement demand in both the directions of testing could be non-conservative for a specific failure mechanism with respect to a loading protocol that imposes more displacement demands in one direction than another. This is because the cracking and non-linear deformations that occur to demands in one direction may affect the loading and deformability in the orthogonal direction.

Further research is recommended to inform selection of the ratio (a/b) between the peak displacement demands in the two main orthogonal directions, considered by the likes of Raza et al. (2019) (see Figure 5). Research by Hong and Goda (2007) and Nievas and Sullivan (2017) has pointed out that the ratio will be dependent on the local seismic hazard and therefore definition of a suitable value of a/b for testing in New Zealand may need further research. Furthermore, the number of cycles of demand at different amplitudes, in the different testing directions, may also affect the capacity of a structure and hence should be considered further as part of the development of future loading protocols.

4 CONCLUSIONS

This paper presented an overview of the principal loading protocols that have been implemented in experimental tests to evaluate the seismic performance of structural system via quasi-static tests, for both unidirectional and bidirectional loading protocols.

The procedure adopted for determining the loading protocol used in the Recast project to evaluate the seismic performance of precast concrete floors under the Kaikoura earthquake was presented. The need for further development of existing loading protocols has also been identified, to be addressed in future research.

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