

Preliminary observations from biaxial testing of a two-storey, two-by-one bay, reinforced concrete slotted beam superassembly

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ABSTRACT: Displacement incompatibility between reinforced concrete moment frames and precast flooring systems has been shown experimentally, and in historical earthquakes, to be an area of concern. Plastic hinge formation necessitates beam damage and the resulting elongation of the beam reduces the seating length of the floor, exacerbates the floor damage and induces unanticipated force distributions in the system. In severe cases this can lead to collapse.

The slotted beam is a detail that protects the integrity of the floor diaphragm, respects the hierarchy of strengths intended by the designer and sustains less damage. The detail provides the same ductility and moment resistance as traditional details, whilst exhibiting improved structural performance. This is achieved with only a subtle change in the detailing and no increase in build cost.

This paper briefly presents the development of the slotted beam in reinforced concrete. The design and construction of a large scale reinforced concrete slotted beam superassembly is described. The experimental method used to undertake biaxial quasi-static testing is introduced. Preliminary observations from the experiment are presented. It is shown that the reinforced concrete slotted beam is a viable replacement for the traditional monolithic detail. Extremely promising structural performance and significantly reduced damage compared to monolithic reinforced concrete details is presented.

1 INTRODUCTION

1.1 Background

Seismic design requirements were introduced to New Zealand in 1935 (CAE 1999). Since this time and throughout subsequent revision of these requirements, reinforced concrete has remained a popular construction material (CAE 1999). Precast concrete construction gained popularity in the 1960's through the introduction of precast flooring systems. The 1980's saw an increase in the use of precast elements as part of the primary lateral load resisting system.

It has been shown through historical earthquakes and laboratory testing that well detailed traditional monolithic reinforced concrete structures perform well during earthquakes. Given the comparative lack of data on precast concrete, construction methods have evolved to primarily involve joining together precast elements to achieve comparable levels of performance to an equivalent monolithic system.

However, during recent earthquakes, such as Kobe and Christchurch, monolithic reinforced concrete structures have had to be demolished due to prohibitive reparation costs (Earthquake Engineering Research Institute 1995). The main contributors to this cost are residual drift and structural damage. Residual drift occurs when a building does not return to its original, plumb, position following an earthquake. The building needs to be righted to within acceptable limits because the lean of the building can impair lateral resistance to future events and also impose severe serviceability issues.

Structural damage with a monolithic reinforced concrete moment resisting frame primarily stems from plastic hinge zones. An example of a fully formed plastic hinge zone is shown in Figure 1 (a). In a monolithic structure the energy is dissipated through alternative yielding of the top and bottom longitudinal reinforcement as the loading reverses. This mechanism results in there being a difference in the neutral axis depths at the beam ends, this geometry results in beam elongation. Shear transfer through a plastic hinge zone is by way of an equivalent truss mechanism. The horizontal component of the diagonal shear strut causes tensile forces, and hence strains, to be larger than compressive. This accumulating tensile strain cause a further material contribution to beam elongation. The cumulative effect of combined geometric and material contributions to beam elongation is the potential to form an undesirable and unintended inelastic mechanism and tearing of the floor diaphragm. Floor diaphragm damage has been shown to inhibit lateral force transfer and in extreme cases cause floor collapse (Bull 2004; Matthews 2004). An example of hollow-core flooring collapse was observed at the Meadows Apartment car park structure following the 1994 Northridge earthquake, as shown in Figure 1 (b).



(a) Example of fully formed plastic hinge zone (Matthews 2004).



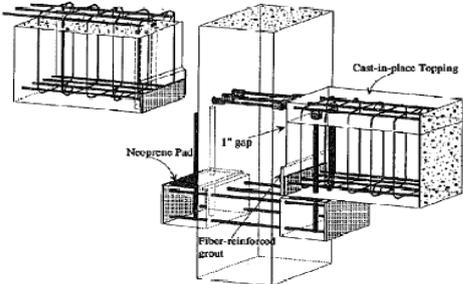
(b) Collapse of hollow-core flooring unit following 1994 Northridge earthquake (Norton, King et al. 1994).

Figure 1: Observed structural damage in experimental tests and historical earthquake.

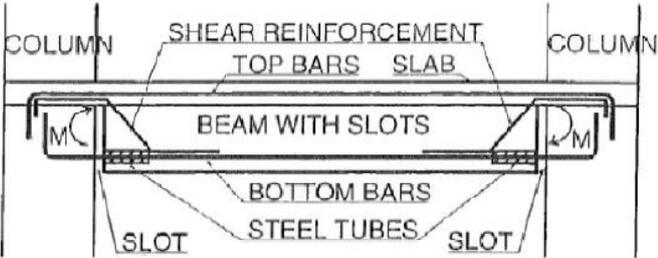
These deficiencies with current precast reinforced concrete design need to be rectified. Efforts to date have largely focussed on developing low damage connections using dry jointed ductile connections (Priestley 1996). Whilst these systems address connection damage they neglect floor and column damage caused by beam elongation.

1.2 Slotted beam development

The slotted beam is a solution which addresses these issues. The concept was first proposed during the PREcast Seismic Structural Systems (PRESSSS) research program in the form of the UT-GAP connection (Priestley 1996), shown in Figure 2 (a). This connection provided a 1” slot extending ¾ down the column face. This meant rotation occurred about the bottom of the beam, concentrating the plasticity in the top longitudinal reinforcement. The connection performed satisfactorily and was developed throughout the PRESSSS programme. Whilst this connection reduces beam elongation, it is likely to damage the floor diaphragm due to gap opening occurring at the top of the beam.



(a) UT-GAP connection developed during PRESSSS program (Palmieri, Saqan et al. 1996).



(b) Early Japanese reinforced concrete slotted beam (Ohkubo, Matsuoka et al. 1999).

Figure 2: Early slotted beam concepts.

The slotted beam solution for reinforced concrete was first proposed at a similar time in Japan. An early design of the reinforced concrete slotted beam is shown in Figure 2 (b). A slot extending approximately $\frac{3}{4}$ up the column face is provided which constrains rotation to occur about the top of the section for both positive and negative rotation. The top longitudinal reinforcement is stronger than the bottom to limit strain and hence cracks. The plasticity in the connection is limited to the bottom longitudinal reinforcement, which is debonded to reduce strain in these bars. Shear transfer is facilitated via diagonal hangers anchored into the columns.

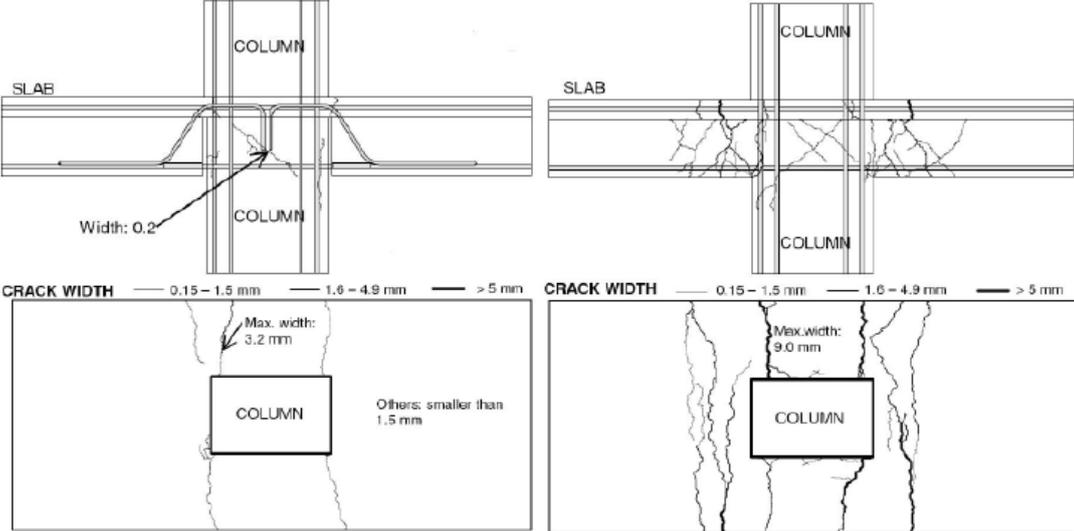


Figure 3: Damage to frame and in-situ floor for slotted (L) and monolithic (R) connection details (Ohkubo and Hamamoto 2004).

The rotation occurring about the top of the section at both ends of the beam drastically reduces the geometrical contribution to beam elongation. Furthermore, the reduction in cracking and the recovery of tensile strain reduces the material contribution to beam elongation. As a result, the beam elongation is approximately 10% that of an equivalent monolithic beam (Ohkubo and Hamamoto 2004; Au 2010). Subsequent research by Ohkubo and Hamamoto (2004) tested cruciform subassemblies with cast in-situ floor slabs. A benchmark monolithic connection was compared to a slotted to determine the differences in damage. The slotted beam displayed a stable response and resulted in significantly less damage to the frame and floor. This is shown in Figure 3.

Research on slotted beams at the University of Canterbury has built on the above research, both for precast systems and cast in-situ. Research by Amaris (2008) focussed on developing a low damage connection that was self-centring using post-tensioning and external dissipaters. Satisfactory performance was observed, but constructability issues were highlighted. Recent research by Au (2010) and Leslie (2010) has concentrated on investigating the slotted beam parametrically, analytically and experimentally. These investigations were conducted in parallel and were slightly different in their focus.

Leslie (2010) focussed on developing and experimentally validating a variety of precast or semi-precast concrete slotted beam details. This research showed that fabricated structural steel top hinges could deform excessively in shear, hastening buckling of the lower longitudinal reinforcement. It was found that high strength lower longitudinal reinforcement could reduce residual drifts.

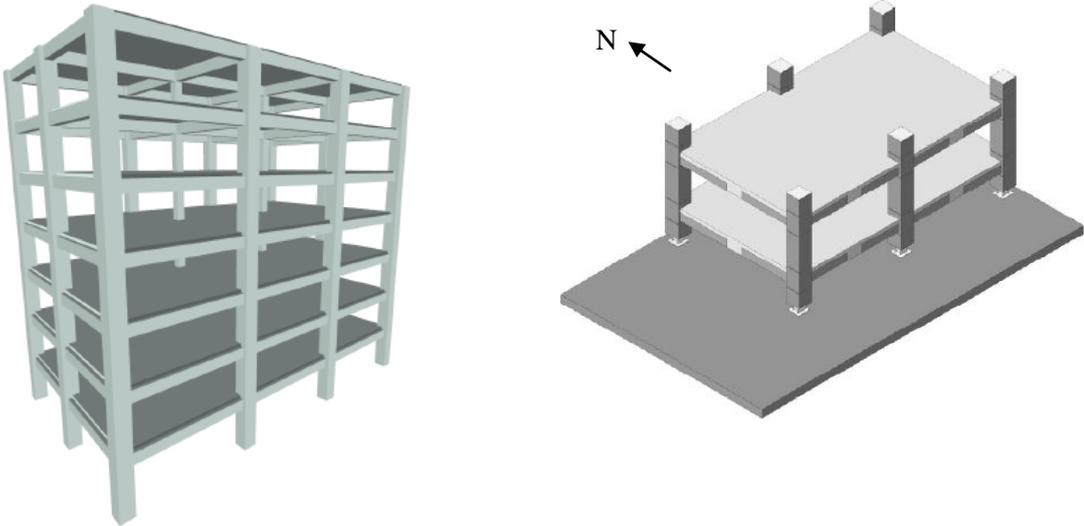
Au (2010) focussed on developing and testing an appropriate detail for a slotted reinforced concrete connection that can be used as a substitute for conventional monolithic reinforced concrete connection in New Zealand. An extensive theoretical investigation into slotted beam mechanics produced new design recommendations. Four cruciform subassemblies were tested experimentally, one benchmark monolithic and three slotted. Over the course of testing several details were improved to enhance performance, such as; restraint of buckling of debonded bars, beam torsion restraint, joint shear reinforcement and bottom longitudinal beam reinforcement bond requirements.

Recently, research by Byrne (2012) has investigated joint shear and bottom longitudinal reinforcement bond mechanics. A parametric investigation was undertaken and the results tested in two cruciform subassemblies. Very acceptable structural performance was observed in both.

2 SPECIMEN DESIGN

Research to date has focussed on the mechanics and connection behaviour of the slotted beam using small subassemblies. These types of specimens are purposely simplified in order to prevent the data being influenced by outside factors. This configuration lends itself well to trialling many details in a time and cost effective manner in order to refine design recommendations. However, to be able to fully evaluate the performance of a reinforced concrete slotted beam system the complex three-dimensional interactions between structural component needs to be assessed.

Specimen SA1 is a large scale three-dimensional reinforced concrete slotted beam superassembly designed to provide data on the interaction between structural elements in a realistic New Zealand building geometry. An oblique of the superassembly is shown in Figure 4 (b). It will also allow the development of connection details intended to improve robustness. It will serve to confirm whether the damage to the floor diaphragm is reduced, and to what extent, when the slotted beam detail is used. The project will also allow the practicality of the system to be assessed and serve as a showpiece to increase familiarity of the construction industry with this emerging detail.



(a) Prototype structure.

(b) Superassembly SA1 extracted from prototype.

Figure 4: Three-dimensional reinforced concrete slotted beam superassembly and origin.

The two-storey, two-by-one bay, superassembly was extracted from the first and second stories of the prototype building shown in Figure 4 (a). The specimen is scaled geometrically at 2/3 according to a 'practical real model' philosophy (Harris and Sabnis 1999) and has centreline bay lengths of 4.953m and 4.191m in the north-south and east-west direction respectively. This scale was chosen as it was the maximum size that could physically fit within the structural extension laboratory at the University of Canterbury. The floors on both stories are prestressed precast concrete units, with the first storey using hollow-core and the second dapped double-tee. Design of the specimen structure was undertaken according to NZS3101:2006 (Standard Association of New Zealand 2006). However, given that the Standard was not written with the intent of being applied to this type of structure, some aspects of the design were based on recommendations from recent research and first principles. As such, these types of structures lie outside of the current Standard. The specimen has been designed to closely replicate how a typical structure in New Zealand would be designed and constructed using the slotted beam configuration.

3 SPECIMEN CONSTRUCTION

Specimen SA1 was designed to be largely precast to reduce erection time and labour requirements. Furthermore, it was important to this project to assess the practicality of construction using the slotted beam system, especially when compared to traditional details. Hence, the manufacture of the precast units was undertaken by a reputable concrete precast company. The feedback from the precast company was invaluable and, on the whole, very positive. The issues encountered were often around forming the slot itself and tolerance, especially concerning the diagonal hanger bars and stirrups. The location and sealing of the unbonding steel tubes around the lower longitudinal reinforcement was sometimes an issue due to accessibility once in the forms. Employees commented that the job was challenging, but not as difficult as some other traditional details that they have worked on. The precast prestressed floor units were sourced from a local manufacturer and are no different to that used in a monolithic reinforced concrete structure. It can be concluded that the slotted beam detail can be effectively manufactured by reputable precast companies in a similar manner to traditional details. It is recommended that the engineer checks critical tolerances before casting.



(a) First floor precast components set out.



(b) First floor in-situ topping pour complete.



(c) Second floor precast components being grouted



(d) Completed specimen SA1.

Figure 5: Construction stages of reinforced concrete slotted beam superassembly SA1.

The specimen, being completely precast, was delivered in components and jointed together through grouting Drossbach tubes and mid-beam splices. The construction stages can be seen in Figure 5 (a) – (d). This method of construction enables rapid erection with a smaller workforce. However, care must be taken in assuring the quality of connections. The size of the precast components was dictated by the maximum size that could fit on a standard truck. For structures with different geometry other precast methodologies may be more effective.

The erection of this specimen took place during a seismically active period in Christchurch. As such, a lot of time, effort and cost were expended on the propping. This conservative approach was validated during the February 22nd seismic event, and following sequence of aftershocks. Only minor displacement of ungrouted precast components was observed and some minor cracking.

4 EXPERIMENTAL SETUP

Specimen SA1 was founded on universal joints to represent the points of contraflexure in the columns. An issue with slop was encountered with these universal joints. This was mitigated through shimming, however to avoid this issue true spherical universal joints are recommended. Loading was biaxial in order to impose a more realistic and demanding earthquake loading protocol. The force was applied through the frame ends at a constant force ratio of 2:1 between the top and bottom floors respectively. The protocol was quasi-static and followed a ‘cloverleaf’ displacement trace which conforms to ACI371.1-05 (ACI Committee 374 2005). The final experimental setup is shown in Figure 6 (a) and (b).



(a) South-East perspective.



(b) South-West perspective.

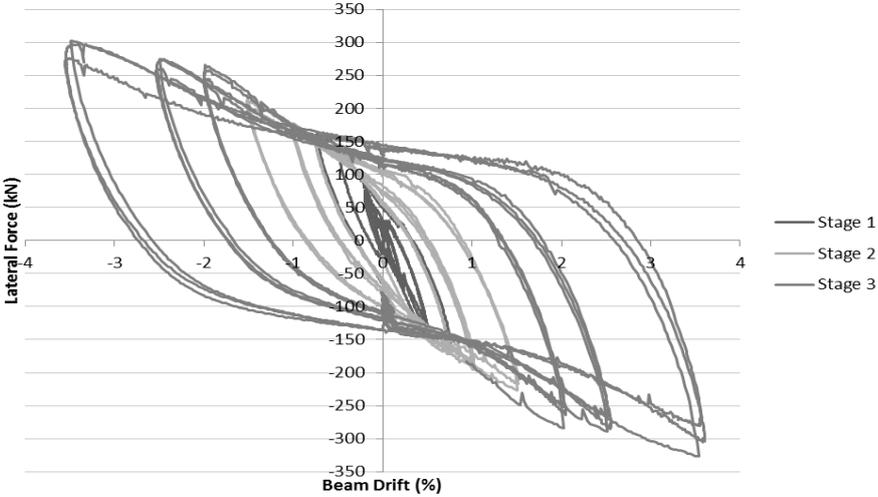
Figure 6: Reinforced concrete slotted beam superassembly SA1 experimental set up.

The forces required in this test were at the maximum of what is achievable given the current laboratory facilities. A full analysis of the structural extension laboratory strong floor was undertaken to assess capacity and safe working limits. Many issues were encountered controlling the five hydraulic rams displacing the specimen. A program to control the rams through the precise loading protocol was developed onsite. However, it was found that methods that had been applied to smaller and less complex specimens did not work effectively in this more complex, stiffer and stronger specimen. A consequence of this was interaction between the rams, both along the same axis and the orthogonal. This caused the ram forces to increase over numerous displacement increments until the maximum allowable force limits were reached. The continued development of the controller software, in conjunction with selective weakening, allowed this issue to be largely mitigated and was a significant outcome of this project. However, it will not be discussed in this paper.

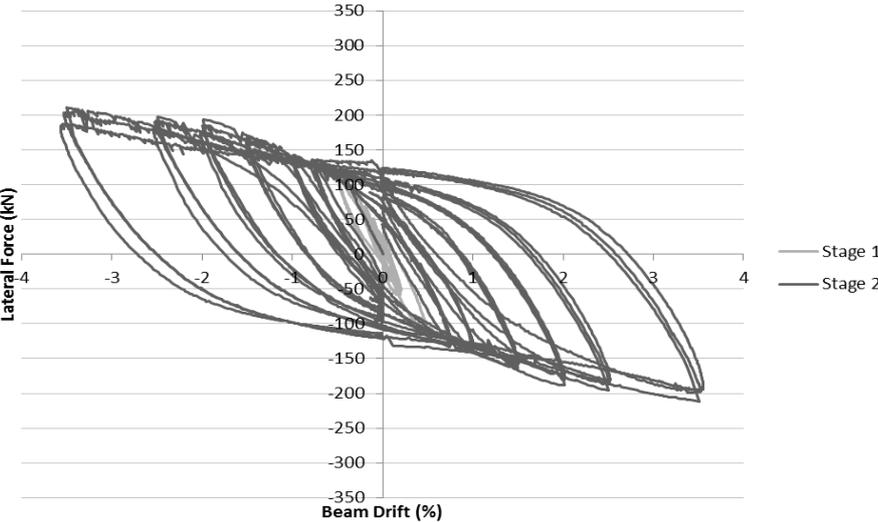
The specimen was extensively instrumented to capture all aspects of connection behaviour, influence on other structural arrangements and resulting deformation in the floor diaphragm. In total 587 strain, displacement and rotation channels were logged. The large number of logging boxes caused issues with supplied voltage and subsequently with the operation of the microchips. In addition, measurement of floor strain was undertaken using DEMountable Mechanical (DEMEC) strain gauges. These involved approximately 40,000 manual measurements.

5 PRELIMINARY OBSERVATIONS

In general, the overall performance of specimen SA1 was extremely promising. Figure 7 (a) and (b) present the global hysteretic response of the specimen in the east-west and north-south directions respectively. It can be seen that a stable response was observed out to 3.5% beam drift. High levels of hysteretic energy dissipation were observed. The overstrength in both directions was larger than anticipated based on previous experimental tests (Au 2010). In addition, the overstrength observed in the east-west direction was larger than that in the north-south. Detailed analysis of recorded data will reveal the cause of the high overstrength, and the discrepancy between the two directions. Stage 1, 2 and 3 in the plots refer to the aforementioned selective weakening undertaken to combat reaction frame interaction and extremely high levels of overstrength observed. This was undertaken in such a manner as not to influence the overall results, yet it will not be described in detail in this paper. The plots have been normalised to account for this. There was little difference in observed response between uniaxial and biaxial loading.



(a) East-West direction.

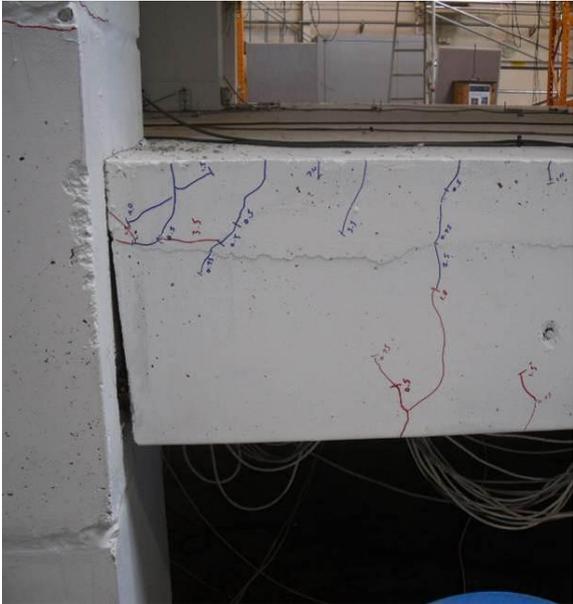


(b) North-South direction.

Figure 7: Global hysteretic response of superassembly SA1.

The damage sustained by specimen SA1 at ultimate limit state was far less than would be expected in a monolithic structure. The damage sustained at serviceability limit state would not require any repair. Recommendations by Priestley et. al. (2007) are used to define limit states. Figure 7 (a) and (b)

compare the damage to the beam end for specimen SA1 and a monolithic reinforced concrete detail at the ultimate limit state. It is clear that the slotted beam has suffered significantly less damage. With the exception of the primary crack through the top hinge, the cracks are typically less than 0.15mm. Strain penetration and cone-type pull out mechanism was observed in the lower longitudinal reinforcement. The full development of this damage coincided with the observed softening of response during the 2nd and 3rd cycles at 3.5% beam drift. The supplementary reinforcement welded to the lower longitudinal reinforcement through the interior connection has been effective in reducing the amount of strain penetration developed and increasing bond.



(a) Slotted beam end damage.



(b) Monolithic reinforced concrete plastic hinge damage (MacPherson 2005).



(c) Timber infill cracks, all less than 0.45mm.



(d) Timber infill cracks, approximately 8mm (Lindsay 2004).

Figure 7: Comparison of ultimate limit state damage in slotted specimen SA1 (L) and a conventional monolithic reinforced concrete structure (R).

Figure 7 (c) and (d) compare the damage to the hollow-core floor diaphragm for specimen SA1 and a monolithic reinforced concrete system at ultimate limit state. Again, it is clear that there is significantly less damage in the slotted beam system. The cracks in the infill are fewer and smaller. There is also less evidence of a bowstring effect being induced, which is due to the reduced beam elongation observed in the slotted beam. Due to the width of the columns large warping deformations are induced in the floor. These deformations were able to be accommodated by the infill and double-tee flange on the first and second stories respectively. Figure 8 (a) and (b) shows the damage observed to the hollow-core seating. The corners cracking completely through was typical, and also observed in structures following the February 22nd Christchurch aftershock. Due to the pragmatic seating length specified the spalled cover concrete did not pose a risk to gravity support. Cracks in the seating of the dapped double-tees were significantly less, and peaked at 0.45mm.



(a) Cracked end.



(b) Spalled seating.

Figure 8: Damage to hollow-core seating.

The next phase of this research program will involve the extraction of two subassemblies from superassembly SA1. These are exterior corner beam-column connections with precast prestressed floors. These will be tested to destruction to determine the residual capacity, which is a critical consideration when assessing a structure for future use. The subassemblies will then be retrofitted using external dampers to assess the viability for use in both retrofit, and new build applications.

This paper is not intended to be an in-depth description of the experimental program and interpretation of the collected data. Rather, it is a brief introduction to the research and statement of preliminary observations to inform the wider engineering community of the research being undertaken. Subsequent papers will describe, in detail, the experimental program, the reduced data and conclusions that can be drawn from it.

6 CONCLUSIONS

The experimental program described above has shown that the reinforced concrete slotted beam is a viable substitution for the monolithic detail. The detail can be manufactured accurately and economically by reputable precast companies. Extensive use of precast can reduce erection time and labour demand. Extremely promising structural performance was observed, with a stable response to 3.5% beam drift and high energy dissipation. The system displayed significantly reduced levels of damage to both the frame and floor diaphragm when compared to traditional monolithic details. Detailed analysis of the collected data will allow recommendations for practical design to be generated. The following phase of research will investigate the need for, and methods of, retrofit following a severe earthquake and assess the performance of replaceable dissipaters for new designs.

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