Towards a performance-based design of precast concrete diaphragms using jointed dissipative connectors: concept and feasibility study

R. Vides

UME Graduated School, IUSS Pavia, Italy

S. Pampanin

Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand

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ABSTRACT: Floor systems play a very critical role in the seismic response of a building as they are meant to resist and transfer internal forces (coming from the horizontal seismic demands) to the elements of the vertical lateral-force-resisting system(s) (LFRSs). However, the performance of diaphragms in recent earthquakes (damage beyond reparability levels, if not close to collapse) has raised concerns about some issues related to the effects of displacement incompatibilities between floors and LFRSs, as well as, in more general terms, to the overall design approach itself.

After an overview of the critical issues associated with precast concrete diaphragm behaviour, this paper investigates the feasibility of implementing dissipative jointed ductile connectors (JDCs) as connections between the floor system and the vertical LFRSs. The performance of topping and starter bars (T&SB) as a means of transferring shear forces from the floor system to the vertical LFRS, common practice in precast concrete diaphragms, is analysed. Due to beam elongation or other displacement incompatibility effects, which can cause cracking in the diaphragm, the shear friction contribution of the topping cannot be relied upon and the whole diaphragm action shear transfer mechanism should be carried out by the steel component. Alternatively, mechanical connectors at discrete locations can be reliably designed to transfer diaphragm forces, which could result into reduction of the response (in both acceleration and displacement) of non-structural elements supported by the structure.

1 INTRODUCTION

Many buildings have not performed as intended during recent earthquakes, leading to extensive damage in both structural and non-structural elements and, in the worst cases, to collapse and loss of lives. Particularly, floor systems, which play a very critical role in the seismic response of a building as they are meant to resist and transfer internal forces (coming from the horizontal seismic demands) to the elements of the vertical lateral-force-resisting system(s) (LFRS), have not behaved as expected, jeopardising the integrity of the whole structure whilst confirming the inadequate understanding of the actual diaphragm behaviour and the lack of robustness in the current design approaches.

Improvement, development and implementation of alternative design approaches and technologies, similar to those developed for low-damage structural systems (PRESSS Design Handbook, NZCS, 2010; Pampanin 2012) are highly needed in order to control the level of damage in diaphragms under expected (as well as unexpected) level of intensities. In general terms, the target should be to develop more robust performance-based seismic design approaches, which would eventually improve the confidence in the design of precast concrete diaphragms (and buildings in general).

In the first part of this paper, an overview of the critical issues associated with precast concrete diaphragm behaviour and current design approaches according to international standards and best practice is given. Then, some preliminary results of analytical studies aimed to develop a simplified performance-based methodology to design precast concrete diaphragms using dissipative jointed ductile connectors (JDC), which are mainly intended to *(i)* provide some degree of energy dissipation; *(ii)* protect diaphragms (capacity design approach) by limiting their seismic demands; and *(iii)* possibly deal with beam elongation issues, are presented. Finally, the influence of JDCs on floor acceleration and displacement demands (by means of floor spectra) to be used in the analysis/design of non-structural elements is analysed.

2 PRECAST CONCRETE DIAGPHAGMS: OVERVIEW

2.1 Critical issues associated with diaphragm behaviour

Load path. The transformation of horizontal seismic demands at each floor level into internal in-plane forces within the floor systems themselves is one of the key steps in the design of diaphragms. Floors systems are meant to provide diaphragm action by transferring such internal forces to the elements of the vertical LFRSs and by connecting those individual elements into a single vertical LFRS (*fib*, 2003). Thus, identifying the actual load paths within the diaphragms will reduce some of the uncertainties in the design process and make diaphragms perform as intended.

Diaphragm flexibility. Diaphragm flexibility has been proven to influence the dynamic behaviour of a building and its effects can be modelled (Fleischman and Farrow 2001). Structures modelled with flexible diaphragms can experience higher accelerations and displacements and have a longer fundamental period of vibration than structures modelled with rigid diaphragms. Additionally, diaphragm flexibility can produce large drifts on the gravity-load system (*fib* 2003).

Loss of support due to beam elongation. When a frame structure is subjected to earthquake-induced forces, once plastic hinges form in a beam and the beam undergoes large inelastic rotations, the beam grows in length (Fenwick and Megget 1993; Matthews 2004; Peng et al. 2011). This phenomenon is known as “beam elongation” and may cause the precast floor units supported by the same beam to lose support and, subsequently, partial or total collapse may occur.

Displacement incompatibility. Precast flooring units are normally designed to act as simply supported elements (ideally deforming in single curvature) even though they are tied to perimeter frames using topping and starter bars intending to transfer the inertial forces from the floor system to the vertical LFRS. In this case, the flooring units are forced by the adjacent beams to deform in double curvature, which causes a vertical displacement incompatibility that induces high shear forces along the interface of the first flooring unit and the perimeter beam (Matthews 2004; NZS 3101:2006).

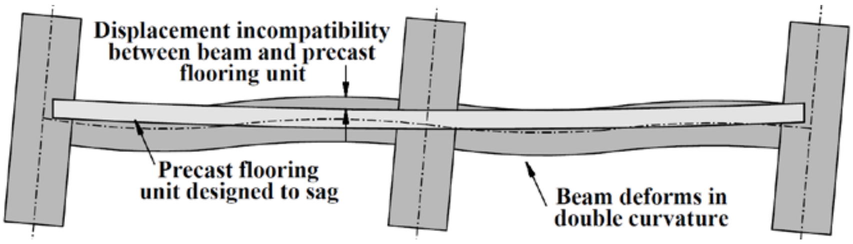

Figure 2.1. Displacement incompatibility between beam and precast flooring unit (after Matthews 2004).

Transfer forces. When using different vertical LFRS within a building, such as dual systems comprising of walls and frames, apart from the inertial forces, transfer forces are generated due to the incompatibility of the deformation pattern of the LFRS. Those forces may be higher than the inertia forces (Gardiner et al. 2008). Thus, transfer forces should be considered together with the inertia forces when analysing and predicting the behaviour of diaphragms.

2.2 Current design approaches

Current seismic designs of buildings concentrate on providing LFRSs capable of behaving safely during a seismic event. The capability of the floor systems to *(i)* spread and carry the out-of-plane gravity load to the gravity-load system (GLS); *(ii)* tie the different elements of the vertical LFRS and the GLS; and *(iii)* resist and transfer the earthquake-induced (as well as the wind-induced) lateral forces to the vertical LFRS, is implicitly considered in the design process. In such a design, providing an unterrupted load path and the use of capacity design principles, mainly intending elastic behaviour of diaphragms, has typically been the preferred approach .

Seismic demands in diaphragms are normally estimated using the Equivalent Lateral Force (ELF) method, even though it has been found to underestimate the demands, especially in lower levels (Rodriguez et al. 2002). Alternative methods to predict the demands in diaphragms have been proposed (modal response spectrum, first mode reduced (Rodriguez et al. 2002)). However, the ELF method is still used due to its simplicity and straightforwardness.

As regards the design methodologies, "strut-and-tie" models have traditionally been said to accurately predict the general behaviour of diaphragms, especially in squat rectangular configurations, in which the load paths within the diaphragms may be straightforward (*fib* 2003) and, alternatively, the "horizontal beam analogy" might be sufficient for design purposes. Nevertheless, such models may become complex when considering irregular floor plan configurations and/or openings within the floor systems, where load paths and force concentrations at corners and around openings are critical issues. Recently, Fleischman et al. (2013) proposed a new seismic design methodology for precast concrete diaphragms that considers force amplification and reinforcement overstrength factors, as well as the use of reinforcement with different degree of ductility and diaphragm flexibility limits. Figure 2.2 illustrates the design approach of the options offered in the methodology.

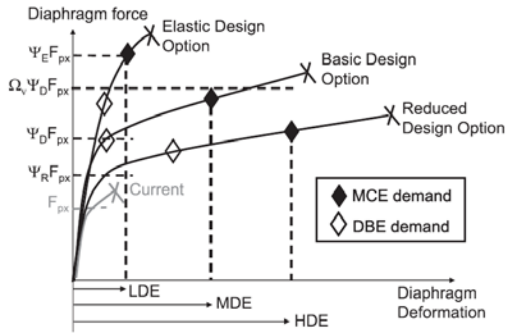

Figure 2.2. Precast diaphragm design approach (Fleischman et al. 2013).

2.3 Articulated flooring systems

Different solutions have been proposed in order to control and reduce damage to floor systems during major earthquakes. One of them refers to "articulated" floor systems, in which the floor system is partially detached from the supporting structure with appropriate connectors, while allowing for relative displacements between the floors system and the vertical LFRS and retaining the essential diaphragm action (PRESSS Design Handbook, NZCS, 2010). This solution was first implemented in the five-storey PRESSS building (Priestley et al. 1999) in the form of welded X-plate mechanical connectors (Fig. 2.3 (left)) and has continued to be developed over the years. Amaris et al. (2007) proposed a non-tearing floor solution in which the flooring unit is connected to the lateral beam of the vertical LFRS by sliders/shear mechanical connectors acting as shear keys when the floor moves (relatively) in the direction orthogonal to the beam and as sliders when the floor moves in the direction parallel to the beam. Figure 2.3 illustrates the aforementioned solutions.

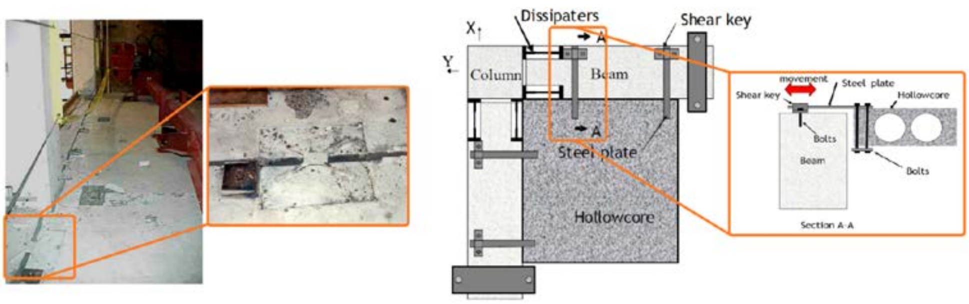

Figure 2.3. Articulated floor system solutions. Left: welded X-plate mechanical connectors (Priestley et al. 1999). Right: non-tearing floor solution (Amaris et al. 2007).

3 PERFORMANCE-BASED DESIGN OF PRECAST CONCRETE DIAPHRAGMS USING LOW DAMAGE SOLUTIONS: NEED AND KEY CONCEPTS

The damage scenarios observed during recent earthquakes has drawn attention to the need of higher seismic performance structures. Controlled (if not negligible) degree of damage in both structural and non-structural elements under expected (as well as unexpected) level of intensities is one of the most important (present and future) challenges in Earthquake Engineering. Floor systems are one of the elements that highly contribute to facing and rising to such challenges since they are intended to transfer forces to the vertical LFRSs. To do so, clear acceptance performance criteria as well as the use of effective and affordable solutions are needed.

Defining suitable limit/damage states of diaphragms is still an issue that requires further research. Significant effort has been made to estimate both seismic demands and capacity of diaphragms, as well as to develop rational design methodologies, yet there is a need for *(i)* better understanding of the actual behaviour of diaphragms under seismic events; *(ii)* development of more robust performance-based design approaches; and *(iii)* the use and/or improvement of low-damage solutions for floor-to-LFRS connections.

Protecting diaphragms (according to a capacity design approach) by limiting their seismic demands and providing some degree of energy dissipation are key concepts/considerations when intending to use low-damage solutions as connections between the floor system and the vertical LFRS. Bearing that in mind, some of the key aspects to consider in order to develop a low-damage seismic design approach for precast concrete diaphragms are: *(i)* seating /boundary conditions of the precast flooring units; *(ii)* different flooring systems; *(iii)* suitable locations of connectors; and *(iv)* the degree of energy dissipation and deformation capacity of the connectors (low to high ductility).

4 USE OF DISSIPATIVE CONNECTORS FOR FLOOR-TO-LFRS CONNECTIONS: PRELIMINARY RESULTS OF FEASIBILITY STUDY

4.1 Case study building

The analytical studies consider one of the 3-bay perimeter frames (longitudinal direction) of a 4-storey precast concrete case study building (Fig. 4.1) assumed to be designed and built using an “emulative” approach in Christchurch, New Zealand, (Z=0.3, IL2 according to NZS 1170.5:2004) on soil type D. The floor system consists of hollow-core precast flooring units (HC300) with a topping of 90 mm and starter bars. Seismic demands are estimated using a Direct Displacement-Based Design (DDBD) approach (Priestley et al. 2007). The drift limit (2%) and the elastic spectra are based on the New Zealand seismic standard (NZS 1170.5:2004). All the structural elements of the case study building are designed following a capacity design approach.

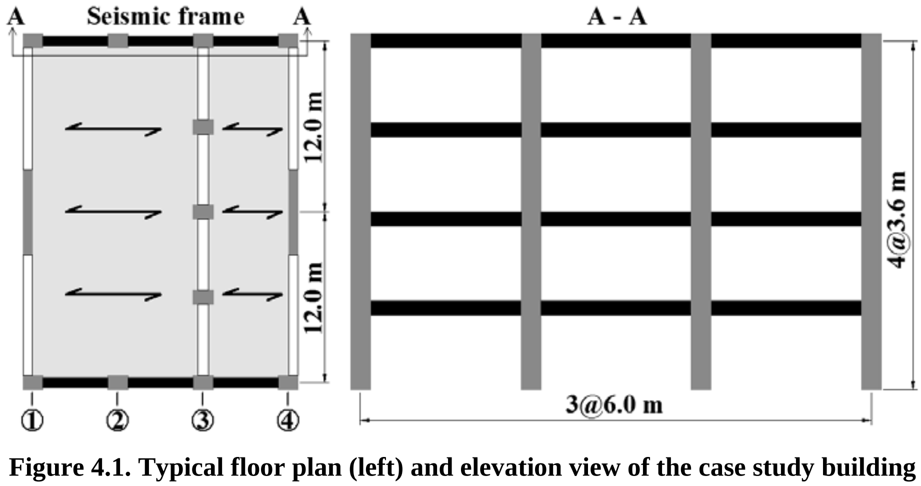

Figure 4.1. Typical floor plan (left) and elevation view of the case study building (modified after PRESSS Design Handbook, NZCS, 2010. Not to scale).

4.2 Numerical modelling considerations

Non-linear static (push-pull) and dynamic (time-history analyses) procedures are carried out using a lumped-plasticity approach in the program RUAUMOKO2D (Carr 2008) with seismic masses accordingly lumped at each node of the columns, beams and precast flooring units, respectively. Figure 4.2 shows the idealised 2-D numerical modelling: the elastic portion of the columns, beams, beam-column joints (panel zone) and floor system are modelled using Giberson elements; plastic hinge elements (Peng et al. 2011), capable of accounting for beam elongation, are used to simulate the (inelastic) expected damage in the elements; spring elements are used to model the slab seating condition (considered following the details provided in NZS 3101:2006) as well as the contribution of the topping and starter bars (T&SB): frictional resistance for the topping and from the dowel action for the starter bars. The model does not account for torsional effects on the beam (rotation about its longitudinal axis) as the floor is supposed to run parallel to the frame, nor for beam elongation in the orthogonal direction (as shear walls are assumed to take the seismic loading in the orthogonal direction and a gravity frame is present in grid 3).

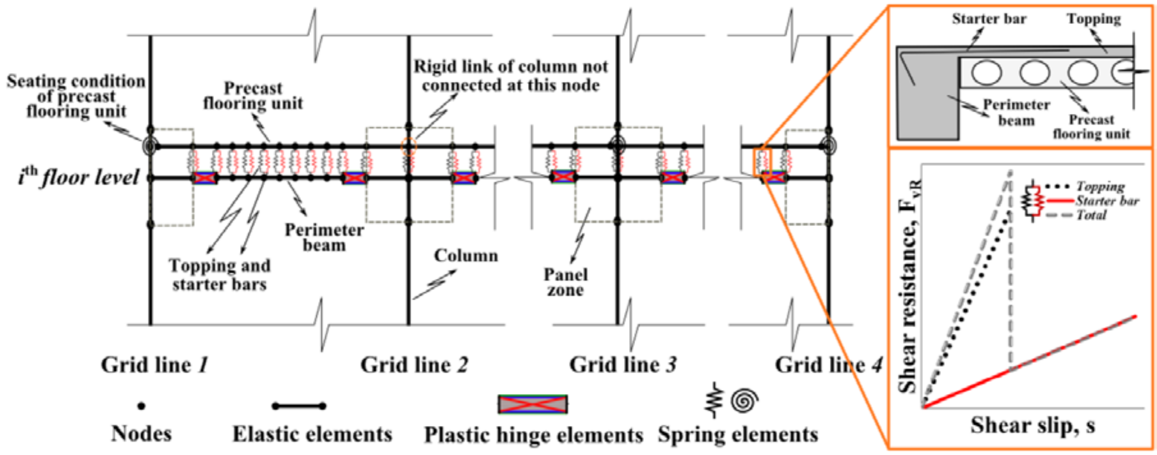

Figure 4.2. Modelling idealisation of floor-frame interaction due to vertical displacement incompatibility.

Dissipative jointed ductile connectors (JDCs) are also modelled using spring elements, initially accounting for in-plane shear. The properties of the connectors are chosen from the database reported by Ren and Naito (2013).

A set of 10 real spectrum-compatible accelerograms (representing 500-year-return-period motions for the ultimate limit state (ULS) condition for an IL2 building – 10% of probability of exceedance in 50 years) were selected for the non-linear time-history analyses (NLTHA). Figure 4.3 shows the scaled 5% damped elastic acceleration and displacement spectra of the accelerograms, compared with the design spectra. The set of records is characterised by an average magnitude of 6.7 and a distance from the epicentre of approximately 24 km. Details of the accelerogram set can be found in Vides (2015).

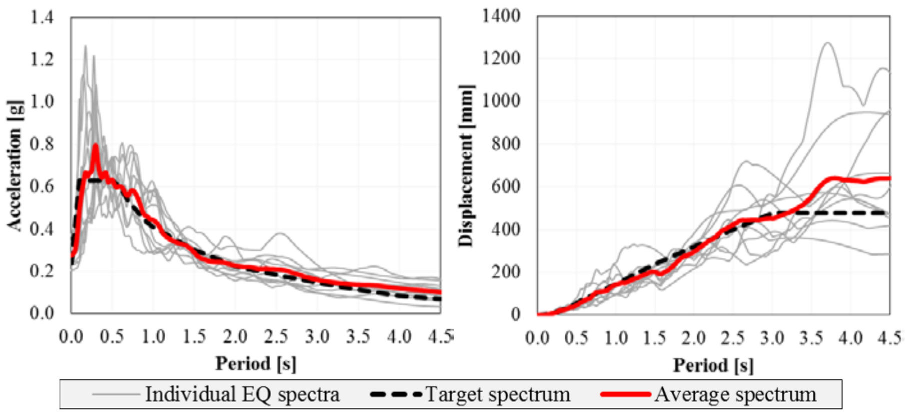

Figure 4.3. Elastic (5% damped) acceleration (left) and displacement (right) spectra of the accelerograms used for the NLTHA, compared with the NZS 1170.5:2004 design spectra.

4.3 Compromising of diaphragm action

Topping (via shear friction) and starter bars are normally relied upon to transfer shear forces from the floor systems to the vertical LFRS. However, once the capacity (strength) of the topping is exceeded (or compromised due to cracking induced by beam elongation effects in the orthogonal direction), the starter bars would be the only means to resist and transfer (through dowel action) the demands to the LFRS. When this occurs, the diaphragm action, as well as the integrity of the whole structure, is compromised. Figure 4.4 presents the normalised forces in the springs (at different states of applied drift) modelling the topping and starter bars (obtained from a displacement-controlled push-pull analysis) along the frame. These forces, which are calculated as the maximum demands in the springs divided by their respective capacity, represent the level of damage to the floor-to-LFRS connection (a normalised force equal to 1.0 means cracking for the topping and yielding for the starter bars). It is seen that the diaphragm action is compromised even before the building reaches its ultimate limit state (assumed to be reached at 2% drift) as the topping within regions near the columns starts to crack at +1.5% of applied drift; then the cracks extend along the interface between the beam and the topping as a “zipping effect”. This implicates that such zones of the topping are no longer able to transfer the diaphragms forces and these have to be redistributed into the starter bars (Figure 4.4 (middle)) in both the in-plane and out-of-plane direction (assumed to happen independently in this study). Such a redistribution appears to occur in the same way as the topping cracks: the bars near the already cracked zone appear to take the forces that the topping (in that zone) cannot withstand and transmit. However, after certain applied drift (say, +2.5%), some part of the steel component cannot resist and transfer the demands (Figure 4.4 (bottom): the failure of a starter bar is considered to happen when either the out-of-plane or the in-plane capacity is reached). In practical terms, similarly to the approach used for the shear contribution of concrete in plastic hinge zones (PHZs), the shear friction contribution from the topping should not be relied upon to transfer the diaphragm actions to the LFRS.

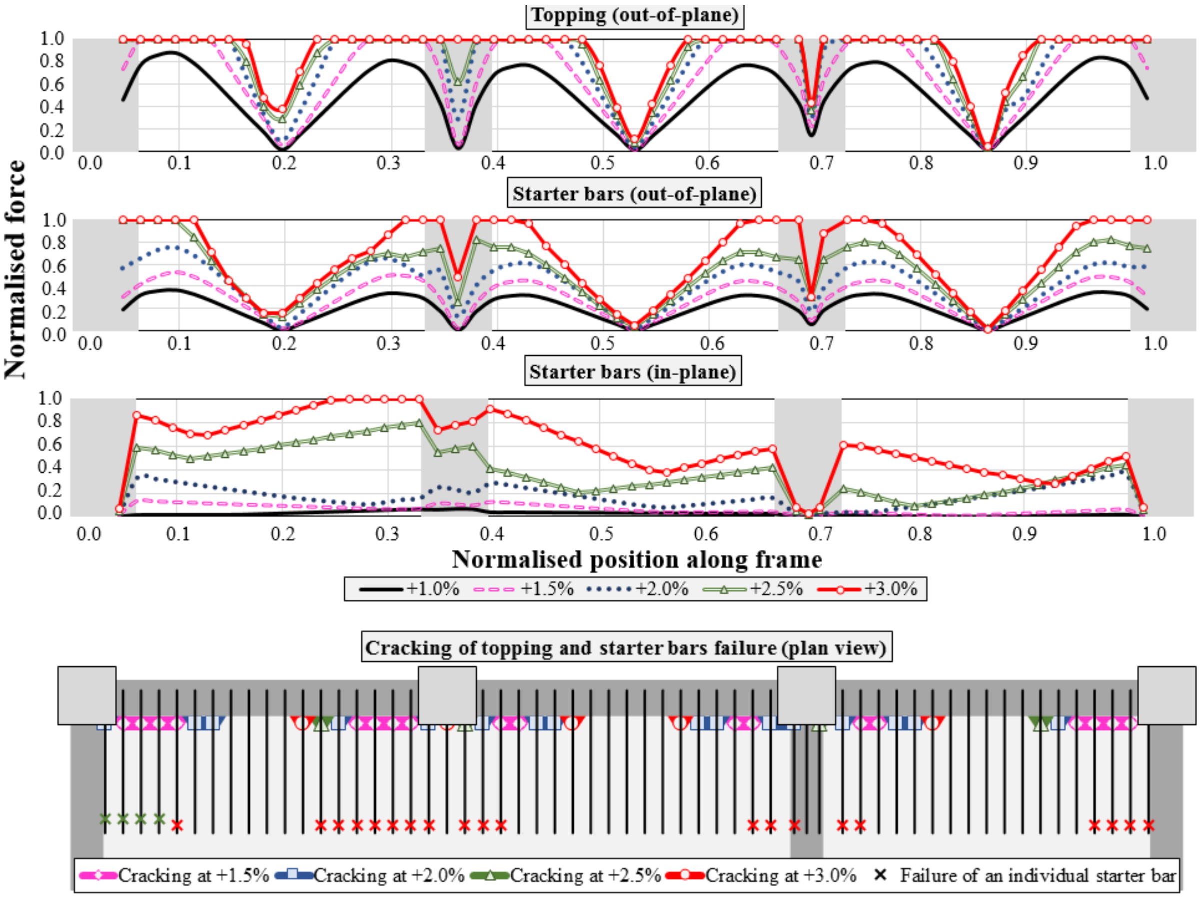

Figure 4.4. Normalised maximum forces in topping (top) and starter bars (middle) and cracking sequence of topping and starter bars failure (bottom) in the 1st floor level.

4.4 Vertical displacement incompatibility profiles and beam elongation: location of connectors

By introducing JDCs at discrete locations, possibly where displacement incompatibility effects are minimum, perimeter beams and precast flooring units would not only deform freely, but also a more reliable way to transfer forces from the floor system to the vertical LFRS is provided. Figure 4.5 shows the envelope of the Vertical Displacement Incompatibility (VDI), the predicted elongation of the beams (in the PHZ adjacent to grid line 1) and their corresponding axial force variation (obtained from a displacement-controlled push-pull analysis). Note that, in this case study structure, the pattern of the VDI is mainly the same at all the floor levels, having their maxima next to the columns and decreasing towards the middle of each span, where the minima are reached. Minimum values are also observed at the centre of the columns (on the frontal face, orthogonal direction). This pattern is the same as that found by Taylor, (2004), who analysed a subassembly of a frame system (changing certain geometrical parameters and slab seating condition) and introduced the concept of shape functions, which refers to the pattern that the envelope of the VDI follows. With that concept in mind and referring to Figure 4.5 (left), ideal location for JDCs (Fig. 4.6) in this specific case study building, would be within the central zone of each span and at the face of the columns. The latter possibility might not be practical as plastic hinges would be expected to develop just next to the beam-column junctions. However, provided adequate protection is given as close as possible to the PHZs, such a possibility could become in a suitable location for the JDCs. In this context, JDCs may also be designed to account for any possible issue related to loss of support due to beam elongation, not only in the longitudinal direction, but also in the transverse direction (even though the latter is not analysed in this study). It is worth mentioning that the elongation of the beams (up to 15 mm, which corresponds to around 3% of the total beam depth) at their ends (Fig. 4.5 (middle)), in this case study structure, was higher at intermediate floor levels as their corresponding axial load variation (Fig. 4.5 (right)) was lower than in the beams of the first and top floor levels.

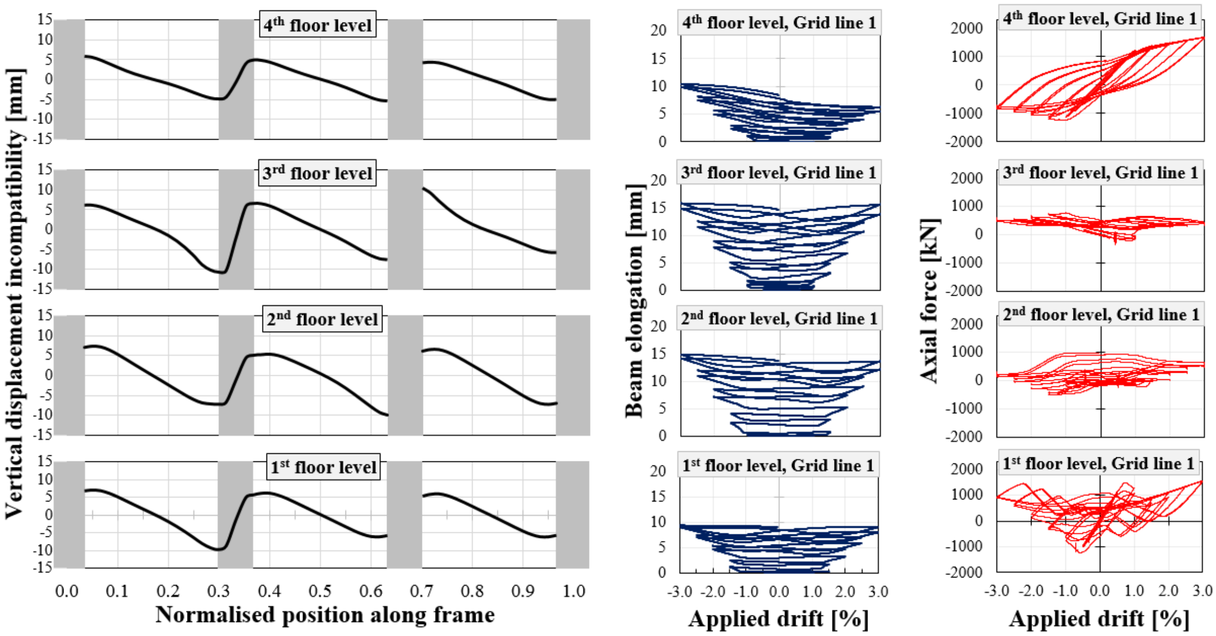

Figure 4.5. VDI (left), beam elongation (middle) and axial load variation (right).

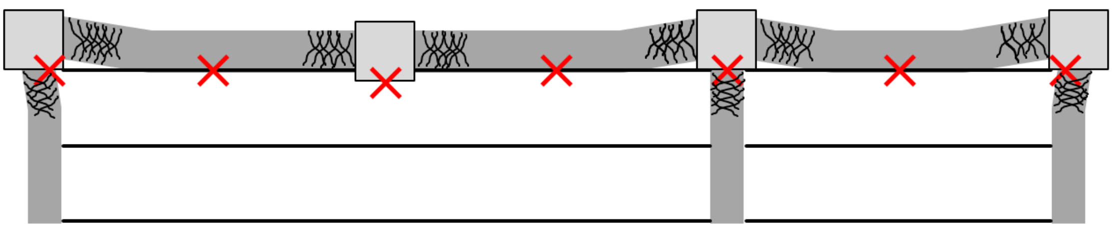

Figure 4.6. Ideal location of JDCs.

4.5 Energy dissipation

By analysing the energy delivered by an earthquake to the structure and how it consumes/stores such energy, the amount of dissipated energy by the JDCs can be estimated. Figure 4.6 shows the energy response of the case building with and without JDCs. It can be observed that the amount of viscous damped energy is nearly the same whether JDCs are used or not. Nevertheless, the amount of energy dissipated by damage to the structure (hysteretic energy) when using JDCs is reduced by nearly 10%, which is mainly consumed by the JDCs. Additionally, the total input energy slightly decreases when using JDCs. It may be due to the change of stiffness of the building when introducing JDCs and, consequently, in how it responds to the ground motion. Furthermore, JDCs can act as fuses, according to capacity design principles, and limit the higher mode effects transferable to the main LFRS.

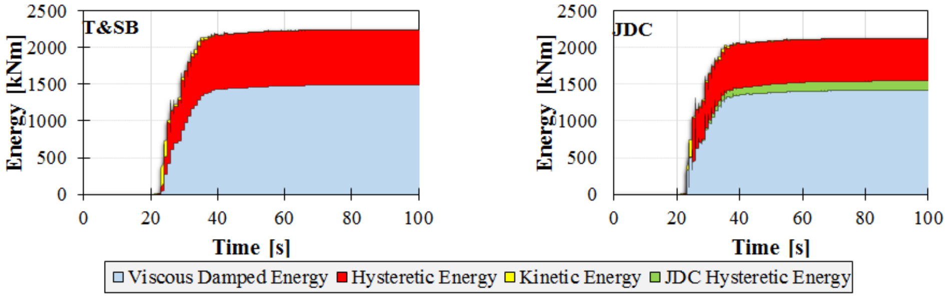

Figure 4.7. Energy response for the building with topping and starter bars (left) and building with dissipative connectors (right) for Iwate Japan (2008) ground motion record.

5 FLOOR DISPLACEMENT AND ACCELERATION DEMANDS IN NON-STRUCTURAL ELEMENTS SUPPORTED BY THE STRUCTURE

The performance of non-structural elements, contents and equipment within buildings during recent earthquakes has highlighted that the response of such elements is as much as important as the building's itself. One of the most popular methods to predict such a response is the Floor Response Spectrum (FRS) method, in which accelerations at each floor level are estimated from time-history analyses and then response spectra are calculated (Filiatrault and Sullivan 2014). Figure 5.1 shows the mean floor acceleration and displacement response spectra (obtained by means of the aforementioned method) of the top floor, as well as the mean plus one standard deviation of the floor acceleration amplification profile along height with and without JDCs. It can be seen that the use of JDCs, in this specific case, does not appear to have any significant influence on the response of non-structural elements (supported at such a floor level) that are "tuned" with the building (their fundamental period of vibration are close to the period associated to the first mode of vibration of the building, T_1 = 0.99 s). However, an important reduction in the response (approximately 30% in acceleration and around 12% in displacement) is observed at the period associated to the second mode of vibration of the building (T_2 = 0.29 s). In contrast, the response of elements having fundamental periods of vibration longer than the fundamental period of vibration of the building appears to slightly increase, in both acceleration and displacement.

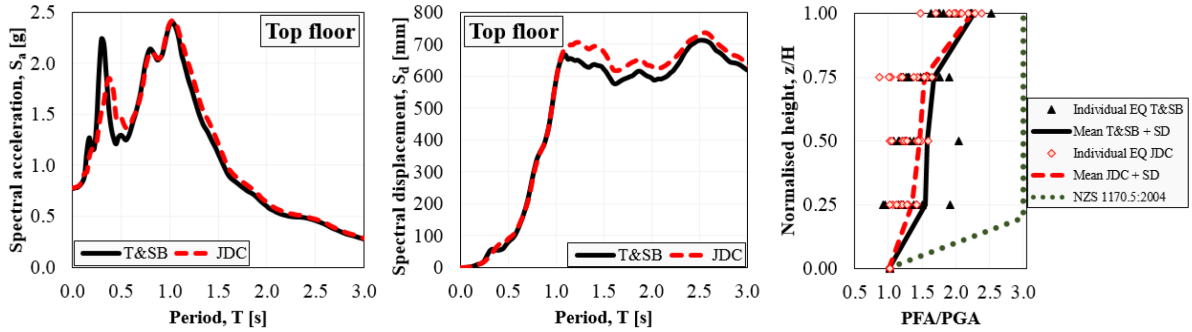

Figure 5.1. Elastic (5% damped) mean floor acceleration (left) and displacement (middle) response spectra of the top floor level and amplification of floor acceleration with height (right).

In terms of amplification of acceleration along the height (Figure 5.1 (right)), in this specific case study building, the use of JDCs appears to have some influence on the amplification profile when compared with the response of the building without JDCs, especially in lower and intermediate floor levels, where the amplification is reduced. Additionally, when comparing such a profile with that provided in NZS 1170.5:2004 (SNZ, 2004), which refers to a floor height coefficient (C_{Hi}) defined by Eq. (1) to (3), it is observed that the latter profile, even though works as an envelope, may be considerably conservative and significantly underestimates the acceleration amplification, especially at lower floor levels.

$$C_{Hi} = \left(1 + \frac{h_i}{6}\right) \qquad \text{for all } h_i < 12\text{ m} \tag{1}$$

$$C_{Hi} = \left(1 + 10\frac{h_i}{h_n}\right) \qquad \text{for all } h_i < 0.2h_n \tag{2}$$

$$C_{Hi} = 3.0 \qquad \text{for all } h_i \geq 0.2h_n \tag{3}$$

where h_i = the height of the attachment of the part; h_n = the height from the base of the structure to the uppermost seismic weight or mass.

6 CONCLUSIONS

Preliminary results of analytical studies aimed to develop a simplified performance-based methodology to design precast concrete diaphragms using dissipative jointed ductile connectors were presented. The use of both topping and starter bars, common practice in precast concrete diaphragms, was found to transfer shear forces from the floor system to the vertical LFRS. As the shear friction contribution of the topping cannot be relied upon (beam elongation or other displacement incompatibility effects that can cause cracking in the diaphragm), the whole transfer mechanism should be carried out by the steel component. Alternative to traditional starter bars, mechanical connectors can be specifically and reliably designed to transfer diaphragm forces, while accommodating the vertical and horizontal displacement incompatibility demands between the floor and the LFRS. Furthermore, such elements can act as fuses, according to capacity design principles, and limit the higher mode effects transferable to the main LFRS. In such a context, the paper has investigated the feasibility of introducing Jointed Ductile Connectors (JDCs) at discrete locations, based upon minimum Vertical Displacement Incompatibility and possible issues related to beam elongation. JDCs can also contribute to reduce the total hysteretic energy demands in the structure by means of the additional damping they can provide to the system. The use of JDCs for floor-to-LFRS connections could result into reduction of the response (both in acceleration and displacement) of non-structural elements (supported by the structure) having fundamental periods of vibration close to the period associated to the second mode of vibration of the structure. Based on the limited numerical investigation carried out in this study, with further work under going, the use of JDCs appears to have some influence on the acceleration amplification profile with height, reducing it at intermediate and lower floor levels. Protecting diaphragms (according to capacity design principles) is one of the key considerations/concepts to bear in mind when using low-damage solutions, such as JDCs, as connections between the floor system and the vertical LFRS.

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