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FEASIBILITY STUDY OF LOW-DAMAGE TECHNOLOGY FOR HIGH-RISE PRECAST CONCRETE BUILDINGS

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Abstract: *The research investigates the benefits associated to the application of high-performance hybrid rocking connections for tall buildings. A comparison between conventional (cast-in-situ) monolithic system and a low-damage rocking dissipative system (PRESSS technology) has been carried out in terms of seismic performance and post-earthquake economic losses. The case study building consisted of an 18-storeys tower with a dual structural system designed for high seismic demand. A Direct Displacement Based Design procedure for frame-wall structures has been implemented and 2D analyses have been performed using lumped plasticity modelling (Ruaumoko 2D). After a calibration of the numerical models using non-linear static analyses (adaptive push-over and cyclic adaptive push-over) spectra compatible accelerograms have been selected to perform non-linear time history analyses. The results proved that PRESSS technology is capable of improving the seismic performance of tall buildings. The presence of post-tensioned unbonded tendons and/or bars into the structural elements in parallel with external dissipaters (Plug&Play) lead to negligible damages and to the absence of post-earthquake residual drifts. Finally, the efficiency of this technology has been further highlighted in terms of post-earthquake losses reduction, such as repair cost and downtime, through the estimation of the Probable Maximum Losses (PML) from an intensity-based calculation (FEMA P-58 methodology). Considering the relevance of non-structural elements in increasing the economic losses, an integrated solution with both low-damage structural members (PRESSS technology) and façade systems (unreinforced masonry infill walls) has been studied, demonstrating how this building configuration can substantially reduce the expected repair cost and business interruption for tall buildings.*

Introduction

High-rise buildings have great impact on the current society as well as on the urbanistic plan and economy of the cities. In the past these structural systems were generally designed as isolated cases and just for business purposes but, due to the fast worldwide spreading of this building solution, they became very useful for residential and commercial building use as well. For these reasons proper code-design methodologies must be developed for this structural typology, especially when these structural systems are built in a moderate-to-high seismic region. In fact, their post-earthquake damage may be substantial and associated with very high socio-economic losses can be estimated.

The seismic design of tall buildings is affected by a pronounced slenderness, higher-modes effect and low structural damping, while floor accelerations and displacements due to horizontal forces can be relevant. The adoption of typical structural connections designed referring to capacity design principles and targeting Life-Safety criteria might lead to significant direct and indirect economic losses after earthquakes, even for low-to-moderate seismic intensity levels.

With the aim of improving the seismic behaviour of such building typology and reducing the significant post-earthquake losses associated, new structural solutions can be implemented into the design, such as the rocking dissipative hybrid connections of the PRESSS (PREcast Seismic Structural System) technology. These innovative structural connections, composed by the combination of post-tensioned bars/tendons and external dissipater devices (Plug&Play), are able

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to improve the seismic design when compared with a traditional monolithic (cast-in-situ) connection. In fact, post-tensioned forces guarantee the re-centering of the structure while the external devices supply the required energy dissipation (Figure 1 – left). Thanks to this combined technology, a structural system with very limited post-earthquake damage and consequently reduced repair costs and business interruption can be designed.

Figure 1. Left: concept of low-damage system (fib 2003); Centre: five-storey PRESSS Building tested at University of San Diego (Priestley et al., 1999) Right: First multi-storey PRESSS-Building in New Zealand (Structural Engineers: Dunning Thornton Consultants; Cattanach and Pampanin, 2008).

The PRESSS technology, initially developed by Stanton et al. (1997) and Priestley et al. (1999) during the US PRESSS program at the University of San Diego in the 1990s (Figure 1 – centre) represents a cost-effective low-damage solution with very high seismic performance, characterized by reduced residual deformations after earthquakes. This low-damage technology can be efficiently implemented into a dual resisting system, where frame and wall work as components in series, which is also very convenient for the case of tall buildings (Abellán et al. (2012). In fact, the advantage of this frame-wall structure with traditional monolithic joints is to provide a better control of the inter-storey drift, due the stiffness of the wall compared to only frame structures, reducing the displacements at higher floors. Advantages can be also obtained in the modularity of the construction phases, increasing speed, workability and safety in work areas (Figure 1 – right).

Research motivation

As mentioned, due to the flexibility design of the PRESSS connections, this low-damage technology is very attractive for improving the design of tall buildings. Therefore, this research carries out a feasibility study of implementing this structural system for precast concrete high-rise buildings, as initially proposed by Palmieri and Pampanin (2011).

Referring to a specific case-study building, numerical analyses (push-over and time-history) have been implemented to compare a monolithic structural skeleton with the related low-damage system and the benefits and convenience of the innovative strategy is shown in terms of both seismic response and post-earthquake losses (repair costs and downtime).

Finally, taking into account the great percentage of post-earthquake damage related to non-structural components, low-damage solutions available from literature for these building elements are also introduced, obtaining a complete structural and non-structural integrated low-damage building configuration characterized by high seismic capabilities, negligible damage and very reduced post-earthquake losses.

Case-study

Building description

The case study building is an 18-storeys reinforced concrete tower with regularity in plan and elevation. The tower has plan dimension of 22.05 meters for both structural directions and an inter-storey height of 3m (Figure 2). The lateral loads resisting elements are two frame-wall systems in each direction. A 2-way spanning flat slab 0.25m thick is responsible for ensuring the floor diaphragm and is assumed to be stiff enough and properly connected to transfer the entire floor forces to the seismic-resistant systems. The building seismic mass is 736.0 tons per each floor, apart from the roof where a mass of 719.8 tons can be found.

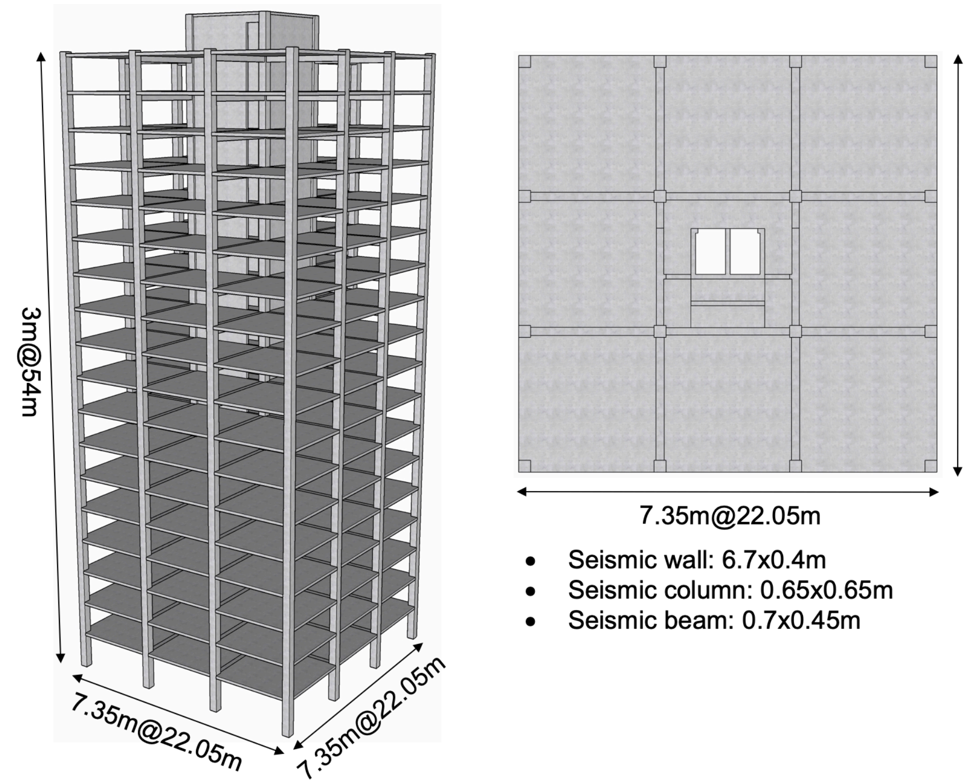

Figure 2. Left: 3D render of the case study building; Right: typical floor and dimensions of the structural elements.

This structural skeleton is “dressed” by external unreinforced masonry infill walls and different types of non-structural components are introduced (internal gypsum partitions, suspended ceilings, building services and contents) to be used for the subsequent loss-assessment investigation.

Design methodology

Based on this geometry and correlated gravity loads, two towers with different technologies have been further analyzed: a conventional building and a Low-Damage PRESSS building. Both structures have been designed following the principles of the Direct Displacement Based Design (DDBD) (Priestley et al. 2007, Pampanin et al. 2010) adapted for frame-wall systems (Abellán et al. 2012).

Considering two parallel systems for both structural directions, the design has been implemented assuming values for the following parameters:

1. Design Drift Limit, θ_d: 1.8%
2. Frame overturning-moment ratio, β_F: 40%
3. Re-Centering ratio of the system, λ_F: 1.25

The drift limit (θ_d) should be defined without exceeding the limit imposed by codes and for this reason it has been chosen a value around 1.8% as a result of an iterative calculation for both buildings. A frame overturning-moment ratio (β_F), representing the overturning moment contribution of the frame only system vs. the total (frame-wall), has been taken as 40%. Finally, a Re-Centering ratio of 1.25 has been selected as minimum value suggested by codes which means how the overturning-moment is distributed among the re-centering elements (tendons/bars) and energy dissipation devices.

The design of the two Tall Buildings has been implemented referring to a Maximum Credible Earthquake scenario corresponding to an event with 2500 years of return period. According to this investigation, a corner period (T_D) of 5.5s and a peak displacement ordinate (Δ_D) of 997.63mm have been estimated using the following equations:

$$T_D=1+2.5(M_w-5.7) \tag{1}$$

and

$$\Delta_D=C_s \cdot 10^{(M_w-3.2)}/r \tag{2}$$

where M_w is the Moment Magnitude, r the fault rapture distance in kilometre and C_s is a local soil factor. Referring to the case-study buildings, for M_w it has been chosen a value of 7.5 simulating a high seismic demand. Regarding the other coefficients, it has been considered a distance r of 20km from the fault, that represents an intermediate condition between near-fault and far-field conditions, while for C_s a unit value is taken to simulate a firm ground.

Taking into account both the seismic scenario and the expected relatively high fundamental periods, the elastic displacement response spectrum has been computed using the formula proposed by Faccioli et al. (2004) as showed in Figure 3.

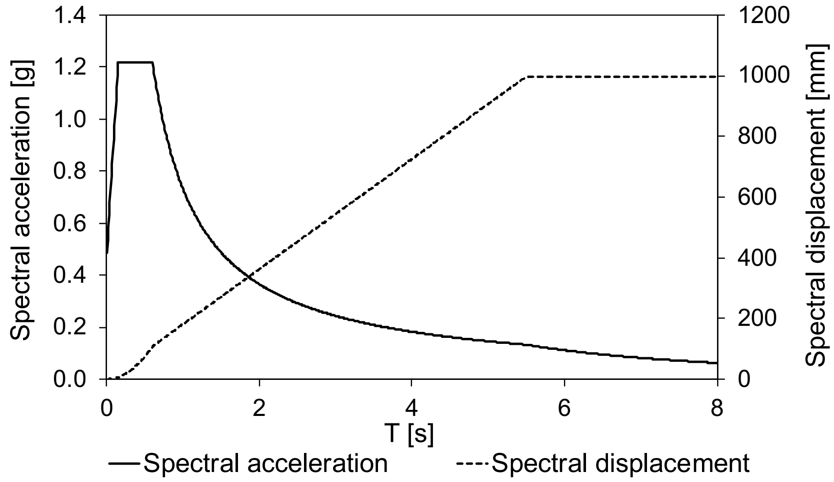

Figure 3. Elastic spectra from the formulation of Faccioli et al. (2004).

After the implementation of the DDBD procedure, the results in Table 1 have been determined.

Parameter	Monolithic Tower	PRESSS Tower
Contra-flexure Height, H_{cf} [m]	40.30	40.30
Effective Height, H_e [m]	38.30	38.30
SDOF Design Displacement, Δ_d [mm]	661.77	661.77
Effective Mass, m_e [tonn]	9377.50	9377.50
System Ductility, μ_{sys} [-]	3.79	3.79
System Damping, ξ_{sys} [%]	19.58	11.48
Effective period, T_e [s]	5.50	4.66
Total Overturning Moment, OTM_{tot} [kNm]	151867.40	216143.80
Total Base Shear, $V_{b,tot}$ [kN]	3961.40	5638.00

Table 1. Main DDBD parameters for the Frame-Wall system.

As highlighted in Table 1, both buildings have been designed having the same displacement shape, as shown in Figure 4, and consequently the same design displacement (Δ_D) and ductility (μ_{sys}). Instead, regarding the value of the System Damping (ξ_{sys}), since for the PRESSS tower the equation depends on the re-centering ratio of the system (λ_F), it is assumed to be less due to the high contribution of the elastic structural behavior.

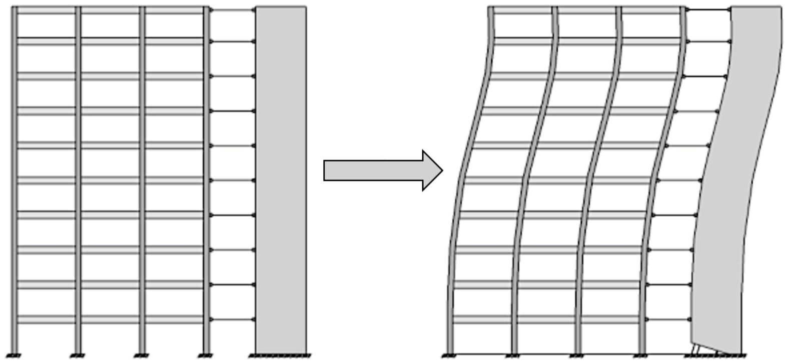

Figure 4. Deformed frame-wall system with hybrid rocking dissipative joints (Abellán et al. 2012).

Distributing the base shear throughout the structural system, both the monolithic and low-damage connections can be designed. Therefore, the steel reinforcement of the traditional structural members can be defined, while the properties of both the post-tensioned cables/tendons (type of cable/tendon, initial force) and the external dissipaters (diameter, internal fuse) are determined.

As example, Figure 5 presents the Moment-Rotation relationships obtained for the hybrid beams of each floor apart from the roof, designed considering a re-centering ratio (λ) of 1.25 (44% for the design of the Plug&Play dissipaters and 56% for the post-tensioned bar) and for the hybrid rocking wall, that is designed considering a re-centering ratio (λ) of 1.75 (36% for the Plug&Play dissipaters and 64% for the post-tensioned bar).

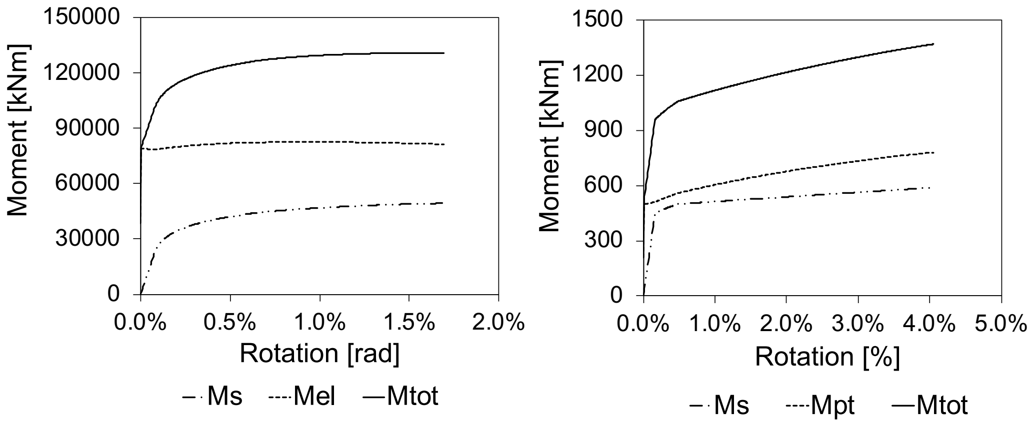

Figure 5. Moment-Rotation relationships of the hybrid connections. Left: hybrid beam-column connection; Right: hybrid wall-foundation connection.

Numerical Investigation

Numerical modelling of both monolithic and low-damage buildings has been implemented using the software *Ruaumoko2D* (Carr 2003), adopting a concentrated plasticity approach for the representation of the nodal regions where the inelastic behavior is expected.

The structural elements are modelled as elastic members linked together through springs, described by moment-rotation relationships and proper hysteresis rules. For the monolithic building, the springs represent plastic hinge regions (using Takeda hysteresis-rule) designed to develop a beam-side-sway mechanism for the frame system, while for the low-damage building two rotational springs are introduced at the end sections of the structural members to simulate the combined action of energy dissipation (using Ramberg-Osgood hysteresis rule) and re-centering (using multi-linear elastic hysteresis rule).

Non-linear static analyses

The numerical models have been initially validated performing non-linear static analyses: adaptive push-over and cyclic adaptive push-over better represent the change of structural stiffness. In fact, the load lateral pattern changes every step depending on mass, new effective frequency and displacement shape. Finally, the results obtained can help to understand the behaviour of the buildings before developing dynamic analyses. Figure 6 – right presents a comparison between the numerical pushover curves of both structural systems using non-linear static adaptive analysis.

As per design, the push-over curve results with same initial stiffness (from modal analysis: T_1= *2.35 s* for the monolithic skeleton and T_1= *2.40 s* for the hybrid skeleton) while the increasing of strength in the low-damage building is related to the elastic behavior of the post-tensioning cables. It can be also observed that numerical results confirm the assumption of the displacement shape at concept design level, that are imposed to be equal for both structural systems (Figure 6 – left).

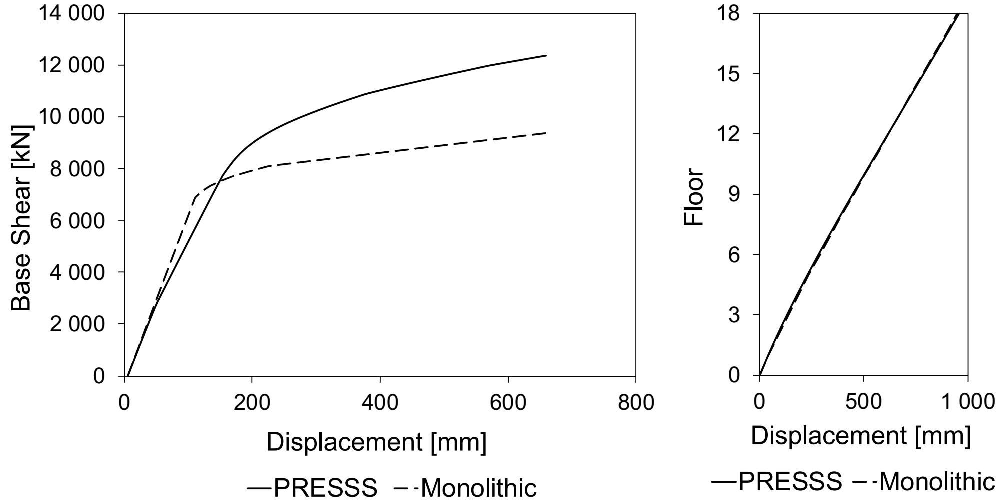

Figure 6. Non-linear static analyses. Left: comparison between pushover curves; Right: displacement shapes at the design level.

Figure 7 shows the numerical result of a push-pull analysis carried out for the low-damage tower with hybrid rocking dissipative connections. This typical cyclic structural behaviour called *Flag-Shape* is related to the combination of elastic post-tensioning actions and axial forces, that avoid residual displacements, and energy dissipation capabilities due to the external Plug&Play devices.

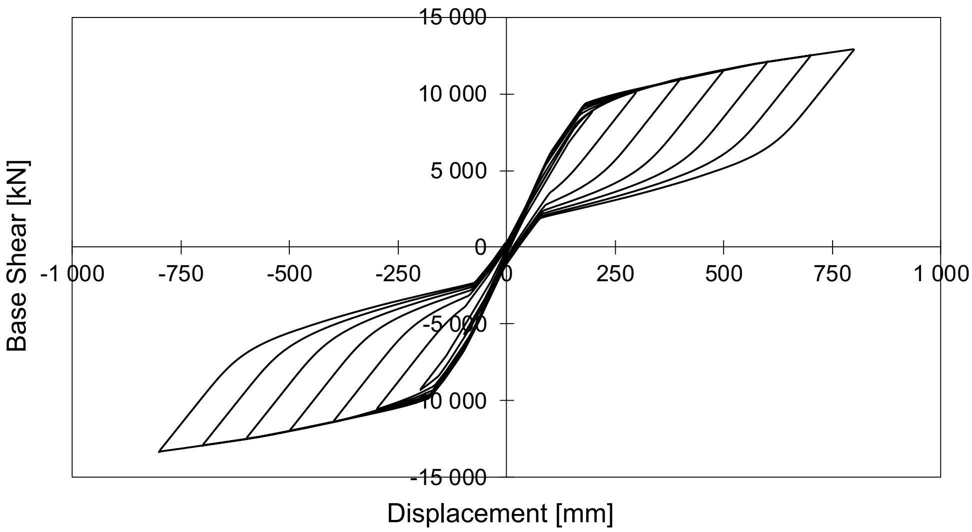

Figure 7. Adaptive cyclic push-over curve of low-damage building system.

Non-linear dynamic analyses

The seismic behaviour of both the monolithic and low-damage tall buildings has been compared in terms of floor accelerations, inter-storey drift ratios and residual drift carrying out non-linear time-history analyses.

Seven non-scaled spectrum-compatible accelerograms have been selected based on magnitude from the European Strong Motion database using REXEL.DISP software (Smerzini et al. 2013). A comparison between the Average Spectra and Design spectra is showed in Figure 8, where it can be observed a maximum spectral difference of 20% until the corner period of 5.5s. These records are finally considered for the numerical investigation.

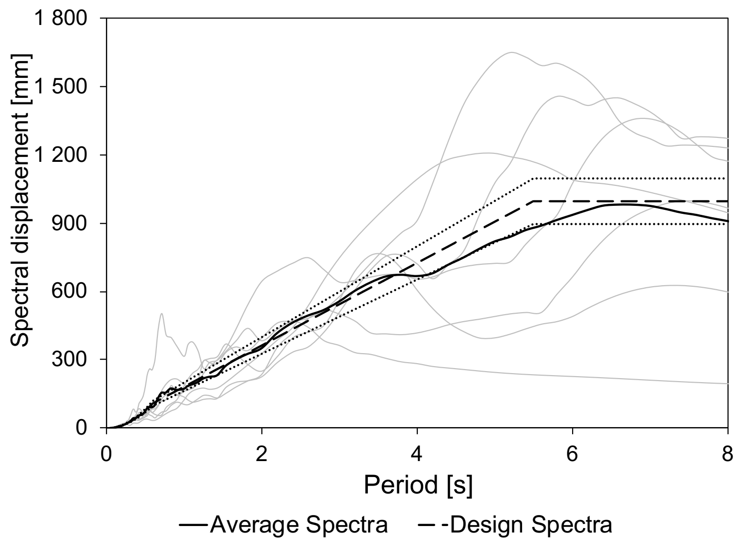

Figure 8. Selected ground motions: average and design spectra.

The results from the time-history analyses are presented in Figure 9 for both buildings' primary system without including the impact of infill in this preliminary study.

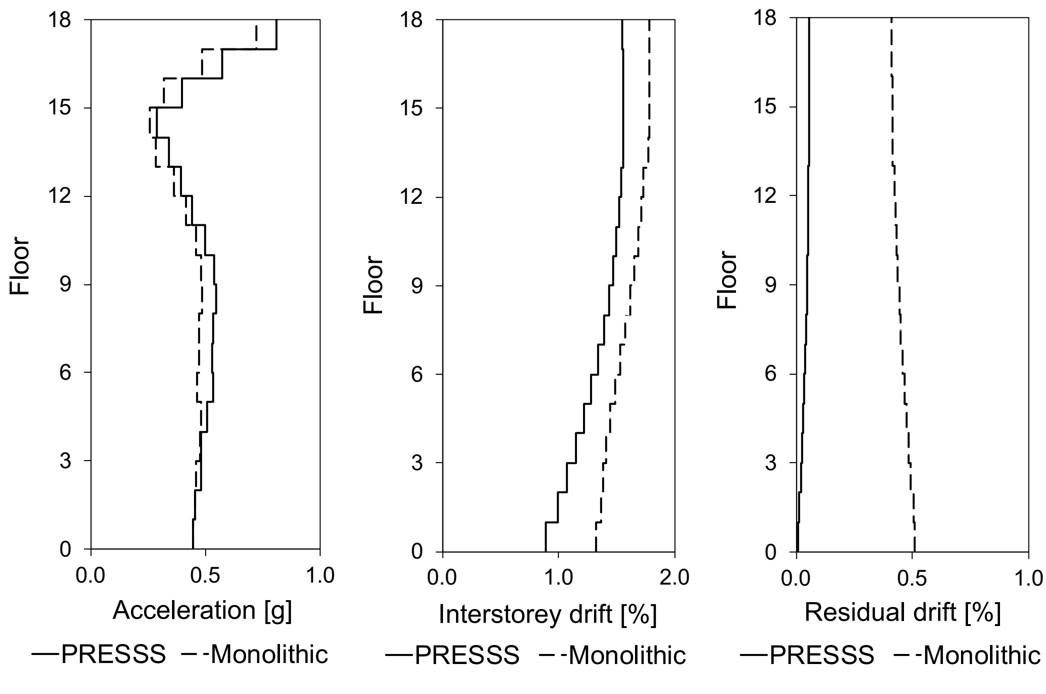

Figure 9. Comparison between monolithic and low-damage buildings. Left: peak floor accelerations; Centre: inter-storey drift ratios; Right: residual drift ratios.

From Figures 9 the following considerations can be highlighted:

1. Peak floor accelerations: the low-damage system generates higher accelerations, due to the action of the post-tensioned cables/bars and due to the post-yielding tangent stiffness slope, as previously observed from the numerical static analysis. For both building typologies, an increase of this demand parameter is observed at the upper storeys due

to higher mode effects. This increasing demand may lead to higher damage related to acceleration-sensitive components.

2. The inter-storey drift ratios are greater for the monolithic building when compared to the hybrid structure. This is justified by the lower post-yielding stiffness associated to the low-damage building, as noticed from the push-over curves. The results obtained in terms of drift are also coherent with the design procedure implemented, because none value is greater that the design level drift of 1.8%.
3. Residual drifts: it can be observed how the implementation of this innovative technology is able to highly reduce the residual deformations expected after earthquakes thanks to the re-centering capability associated to the post-tension and axial load. The residual displacement and drift are very important damage indicators that are related to the partial or total loss of structural safety after earthquakes and can produce substantial increase of the socio-economic losses.

Loss assessment analysis

The loss assessment investigation is implemented referring to the probabilistic methodology proposed in the FEMA P-58 (2012), that allows the estimation of either the repair costs or the repair time, while the business interruption is determined introducing the delays due to "impeding factors" and utility disruption according to the procedure presented by Almufti and Willford (2013).

Fragility curves of building components

Input data for the intensity-based loss assessment are the predicted accelerations and drift ratios as well as the fragility functions of the structural and non-structural elements. Therefore, the potential damage states of all the building components must be defined.

Fragility data for the traditional monolithic structural members can be determined from the FEMA P-58 database, while equivalent fragility functions must be defined for the hybrid connections. Considering the only damage state of collapse of the external dissipaters, from the moment-rotation section analyses the median value of connection drift to be used for the construction of the fragility curves are obtained. For the consequence functions, these are assumed referring to the ones of the monolithic connections, also if this assumption is conservative because the repair costs and time associated to the substitution of the external dissipaters can be less.

For the external unreinforced masonry walls, the fragility and consequence functions are defined from the data available in Cardone and Perrone 2015. For such type of non-structural system, equivalent fragility curves are built for a corresponding low-damage solution. In fact, to further highlight the convenience of implementing low-damage solutions, both the traditional monolithic walls and the damage-resistant rocking walls suggested by Tasligedik and Pampanin (2016) are considered. The fragility specifications of the innovative system are determined from the experimental results carried out at the University of Canterbury, where it has been proved how this system can remain serviceable even at 2.0 - 2.5% drift.

Finally, for the other non-structural systems introduced in the analysis (partitions, ceilings, building services/contents), the fragility specifications are obtained from FEMA P-58 database.

Loss estimation

The intensity-based analyses are performed considering that the cost of the low-damage technology is 10% higher than the benchmark cost of the monolithic building while the replacement time is 25% lower.

Considering the Probable Maximum Loss (PML) as performance measure, as suggested by Nuzzo et al. 2018, representing the probable repair cost induced by a specific earthquake intensity, the results from the loss investigation are shown in Figure 10 and expressed as the probability of exceeding a certain level of loss given a seismic intensity and the repair cost that is expressed as percentage of the replacement cost.

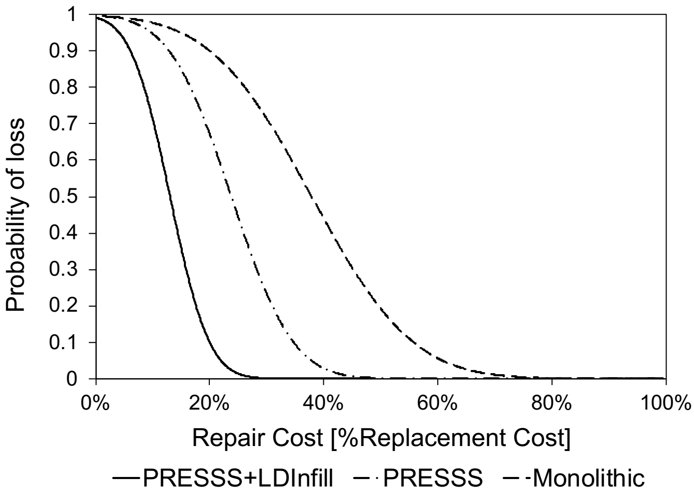

Figure 10. Comparison of alternative solutions in terms of Probable Maximum Loss (PML) curve.

The previous graph highlights the greater benefits related to the implementation of low-damage technologies for Tall Buildings. It can be observed how the probable maximum expected loss is respectively equal to 30%, 50% and 80% for the case of integrated low-damage system (low damage masonry infill walls and PRESSS structure), PRESSS structure and monolithic structure, consequently it can also be observed how the damage-mitigation systems reduce substantially the expected repair costs (for example, at a 30% of repair cost, the probability of exceeding this value is respectively around 0%, 25% and 70%).

The convenience of implementing low-damage technologies for tall buildings is evident from Figure 11 where a comparison between the building configurations in term of repair costs and downtime is highlighted.

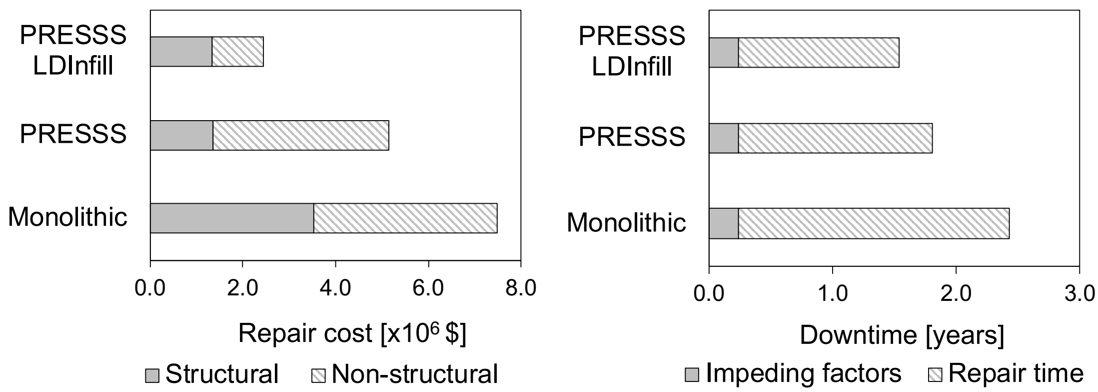

Figure 11. Post-earthquake losses (repair cost and downtime) for the different building systems.

Referring to the repair costs determined from the intensity-based analysis performed using the Performance Assessment Calculation Tool (PACT) of FEMA P-58 (2012), it can be observed how the introduction of the sole hybrid connections reduces the repair cost of the benchmark monolithic structure by 30%, while adding low damage external masonry walls this reduction increase to around 65%. Concerning the downtime, estimated considering both the results from the PACT software and the methodology proposed by Almufti and Willford (2013) and referring to the ULS condition, a reduction of 25% and 35% are obtained for respectively the case of PRESSS structure and integrated low-damage building.

Conclusions

This research investigates the implementation of low-damage PRESSS technology in tall buildings. The final aim is to provide appreciable evidences on the socio-economic benefits of implementing these solutions for the specific type of building.

The results of the study case highlight how the application of hybrid connections in the structural skeleton lead to high benefits in terms of increasing the seismic performance as well as reducing the consequence losses after earthquakes. Notwithstanding the comparison made considering a monolithic (cast-in-situ) tall building with a quite high seismic performance as, in this specific study, it is characterized by a Dual System structure and it has been designed according to DDBD procedure, the convenience of implementing low-damage systems is evident. The low-damage system has lower damage than the one of the corresponding monolithic building at the same drift level and the repair costs are mostly related to the need to substitute the damaged external dissipaters, while the re-centering effect of the post-tensioned tendons also reduces the residual inter-storey drift. Finally, the research proves how significant savings for both repair costs and downtime can be obtained introducing low-damage facades, that is damage-mitigation infill walls for the analysed building configuration.

However, more refined results can be determined implementing 3D numerical models, while for the current research 2D numerical investigations were carried out. Further investigations are also required to define the losses related to other seismic intensities, especially for low-intensity levels for which the application of low-damage technologies can be very effective.

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