Invited paper

Emerging Solutions for High Seismic Performance of Precast/Prestressed Concrete Buildings

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Abstract

Major advances have been observed in the last decade in seismic engineering with further refinements of performance-based seismic design philosophies and definition of corresponding compliance criteria. Following the worldwide recognized expectation and ideal aim to provide a modern society with high seismic performance structures, able to sustain a design level earthquake with limited or negligible damage, emerging solutions have been developed for high-performance, still cost-effective, seismic resisting systems, based on adequate combination of traditional materials and available technology. In this paper, an overview of recent developments and on-going research on precast concrete buildings with jointed ductile connections, relying on the use of unbonded post-tensioned tendons with self-centering capabilities, is given. A critical discussion on the conceptual behavior, design criteria and modeling aspects is carried out along with an update on current trends in major international seismic code provisions to incorporate these emerging systems. Examples of existing on site applications based on a recently developed cable-stayed and suspended solution for frame systems are provided as further confirmation of the easy constructability and speed of erection of the overall system.

1. Introduction

Significant advances have been accomplished in the last decade in the seismic protection of structures, based on the introduction and refinement of innovative design approaches. In particular, the rationalization of already known conceptual schemes based on the familiar Limit State Design approach, widely adopted for gravity load design, into more comprehensive Performance-Based Design philosophies represents a significant shift in the conceptual design philosophy. A broad consensus between public, politicians and engineering communities seems to be achieved when promoting the emerging opinion that the excessively severe socio-economical losses due to earthquake events, as still observed in recent years in seismic-prone countries, should be nowadays considered unacceptable, at least for “well-developed” modern countries.

It could in fact be argued (Bertero 1997) that the rapid increase in population, urbanization and economical development of our urban areas would naturally result into a generally higher seismic risk, defined as “the probability that social and/or economical consequences of earthquake events will equal or exceed specific values at a site, at various sites, or in an area during a specific exposure time”. Even though the seismicity remains constant, the implications of business interruption, i.e. downtime, due to damage to the built environment are continuously increasing and should be assigned an ade-

quate relevance in the whole picture of Seismic Risk, typically also defined as combination of Seismic Hazard and Vulnerability.

As a result, more emphasis needs to be given to a damage-control design approach, after having assured that life safety and the collapse of the structure are under control (in probabilistic terms).

In this contribution, an overview of recently developed technological solutions for precast/prestressed concrete buildings, capable to significantly reduce the expected damage after a moderate-to-strong earthquake event, is given. Major aspects related to design criteria within a performance-based design philosophy, recent trends in code provisions, as well as modeling aspects will be discussed based on completed as well as on-going research. Example of on site-applications will be given highlighting main constructability advantages and issues.

2. Definition of performance objectives, levels and acceptance criteria: a critical revision

In response to a recognized urgent need to design, construct and maintain facilities with better damage control, an unprecedented effort has been dedicated in the last decade to the preparation of a platform for ad-hoc guidelines involving the whole building process, from the concept and design to the construction aspects. In the document prepared by the SEAOC Vision 2000 Committee (1995), Performance Based Seismic Engineering (PBSE) has been given a comprehensive definition, as *consisting of a set of engineering procedures for design and construction of structures to achieve pre-*

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dictable levels of performance in response to specified levels of earthquake, within definable levels of reliability and interim recommendations have been provided to actuate it. Within this proposed framework, expected or desired performance levels are coupled with levels of seismic hazard by performance design objectives as illustrated by the Performance Design Objective Matrix shown in Fig. 1.

Performance levels are expression of the maximum desired (acceptable) extent of damage under a given level of seismic ground motion, thus representing losses and repairing costs due to either structural and non-structural damage. As a further and fundamental step in the development of practical PB-SE guidelines, the actual condition of the building as a whole should be expressed not only through qualitative terms, intended to be meaningful to the general public, using general terminology and concepts describing the status of the facility (i.e. Fully Operational, Operational, Life Safety and Near Collapse) but also, more importantly, through appropriate technically-sound engineering terms and parameters, able to assess the extent of damage (varying from negligible to minor, moderate and severe) for the single structural or non-structural elements as well as of the whole system.

The choice of appropriate engineering parameter(s), or damage indicator(s)/index(es), able to uniquely characterize the status of the structure after the earthquake, as well as the definition of appropriate values for lower and upper bounds of each performance level, represents the most critical and controversial phase of a reliable Performance-Based Design or Assessment Approach.

Recent developments in performance-based design and assessment concepts (Pampanin et al. 2002; Christopoulos and Pampanin 2004) have highlighted the limitations and inconsistencies related to current PBSE approaches, whereby the performance of a structure is typically assessed using one or multiple structural re-

sponse indices, related to maximum deformation (i.e. interstorey drift or ductility) and/or cumulative inelastic energy absorbed during the earthquake. The role of residual (permanent) deformations, typically sustained by a structure after a seismic event, even when designed according to current codes, has instead being emphasized as a major additional and complementary damage indicator. As noted by the authors, residual deformations can result in the partial or total loss of a building if static incipient collapse is reached, the structure appears unsafe to occupants or if the response of the system to a subsequent earthquake is impaired by the new at rest position of the structure. Furthermore, they can also result in increased cost of repair or replacement of non-structural elements as the new at rest position of the building is altered. These aspects have not been properly reflected in current performance design and assessment approaches.

To gap this apparent discrepancy between the real final state of a structure and current performance evaluation criteria, the authors proposed a framework for a more comprehensive performance-based seismic design and assessment approach. Residual local and global deformations of structures are explicitly taken into account, by introducing a residual deformation damage index (RDDI) as a complementary indicator of damage and by adopting a 3-dimensional performance-based matrix where, for a given seismic intensity, Performance Levels (PL_i) are represented by 2-D domains defined by the combination of maximum deformations (or displacements) and residual deformations (displacements) parameters (Fig. 2). Performance Objectives can be visualized connecting different PL_i domains belonging to different intensity levels.

A direct displacement-based design approach which includes an explicit consideration on the expected residual deformations has also been implemented (Christopoulos and Pampanin 2004).

Fig. 1. Seismic Performance Design Objective Matrix (SEAOC Vision 2000 1995).

Fig. 2 Framework for performance based design and assessment approach including residual deformations: RDDI index and performance matrix (Pampanin et al. 2002).

A first attempt to introduce the residual deformation/drift as a complementary parameter in a design guidelines or code provisions is found in the 1996 Japanese seismic design specifications for highway bridges, which, as reported by Kawashima (1997), imposes an additional design check for important bridges: residual displacements, computed as a function of expected ductility and post yielding stiffness coefficient, are required to be smaller than 1% of the bridge height.

Further requirements to limit residual deformations can be found in the recent draft guidelines for performance evaluation of Earthquake Resistant reinforced concrete buildings prepared by the Architectural Institute of Japan (AIJ 2004), where limits on residual crack widths are indicated and associated to ranges of maximum drift/ductility and damage level.

3. Alternative seismic design philosophies for precast/prestressed concrete buildings

Recognizing the economic disadvantages of designing buildings to withstand earthquakes elastically as well as the correlated disastrous consequences after an earthquake event with an higher-than-expected intensity (as observed with the Great Hanshin event, Kobe 1995), current seismic design philosophies favour the design of ductile structural systems able to undergo inelastic reverse cycles while sustaining their structural integrity,

According to the aforementioned original PBSE con-

cepts, different levels of structural damage and, consequently, repairing costs shall thus be expected and, depending on the seismic intensity, typically accepted as unavoidable result of the inelastic behavior.

A revolutionary alternative design approach has been achieved by the recent solutions developed under the U.S. PRESSS (PREcast Seismic Structural System) program coordinated by the University of California, San Diego (Priestley 1991, 1996; Priestley et al. 1999) for precast concrete buildings in seismic regions with the introduction of “dry” jointed ductile systems, alternative to traditional emulation of cast-in-place solutions and based on the use of unbonded post-tensioning techniques. As a result, extremely efficient structural systems are obtained, which can undergo inelastic displacements similar to their traditional counterparts, while limiting the damage to the structural system and assuring full re-centering capability. A damage control limit state can thus be achieved according to either the traditional or the more recent definitions of performance levels, leading to an intrinsically high-seismic-performance system almost regardless of the seismic intensity.

3.1 Emulation of cast-in-place concrete approach

Several alternative solutions to provide moment-resisting connections between precast elements for seismic resistance have been studied and developed in literature (Watanabe 2000; Park 2002; fib 2003) mostly relying on cast-in-place techniques to provide equivalent

“monolithic” connections (*i.e.* connections with equivalent strength and toughness to their cast-in-place counterparts).

The intrinsic and well-recognized advantages of precast construction, namely quality control, construction speed and costs, are thus greatly reduced. In typical emulation of cast-in-place concrete solutions, as for example adopted in New Zealand and Japan construction practice (**Fig. 3**), the connections can be either localized within the beam-column joint with partial or total casting-in-place of concrete, or in the middle of the structural member, which does not necessarily correspond to a unique prefabricated segment, as typical of cruciform (or tee-shaped) beam-column units.

Nonetheless, due to their economic inconvenience and construction complexity, such systems have not been widely adopted, particularly in the United States and in Mediterranean seismic-prone countries (Sanpaulesi 1995, **Fig. 4**).

3.2 Jointed ductile and hybrid systems

In dry jointed ductile solutions, opposite to wet and strong connection solutions, precast elements are jointed together through unbonded post-tensioning tendons/strands or bars. The inelastic demand is accommodated within the connection itself (beam-column, column to foundation or wall-to-foundation critical interface), through the opening and closing of an existing gap (rocking motion) while reduced level of damage, when compared to equivalent cast-in-place solutions, is expected in the structural precast elements, which are basically maintained in the elastic range. Moreover, the self-centering contribution due to the unbonded tendons can lead to negligible residual deformations/displacements, which, as mentioned, should be adequately considered as a complementary damage indicator within a performance-based design or assessment procedure (Pampanin et al. 2002).

A particularly promising and efficient solution within the family of jointed ductile connections is given by the

Fig. 3 Typical arrangements of precast units in the emulation of cast-in-place approach used in Japan and New Zealand (fib, 2003).

“hybrid” systems (Stanton et al. 1997), where self-centering and energy dissipating properties are combined through the use of unbonded post-tensioning tendons/bars and longitudinal non-prestressed (mild) steel or additional external dissipation devices (**Fig. 5**).

A sort of “controlled rocking” motion of the beam or wall panel occurs, while the relative ratio of moment contribution between post-tensioning and mild steel governs the so-called “flag-shape” hysteresis behaviour (**Fig. 6**).

4. Design criteria

Provided an adequate amount of energy dissipation capacity is given to the system, the seismic behaviour of hybrid systems (whose concept has been recently and successfully extended to steel moment resisting frames (Christopoulos et al. 2002b) and bridge systems (Mander and Chen 1997; Hewes and Priestley 2001; Palermo 2004, 2005)) has been proved to be at least as satisfactory as that of equivalent monolithic solutions (Pam-

Fig. 4 Technical solutions developed in Italy according to the emulation approach.

Fig. 5 Jointed precast "hybrid" frame and wall systems developed in the PRESSS-Program (Priestley et al. 1999; fib 2003).

panin et al. 2000, Christopoulos et al. 2002a), due to similar maximum displacements and negligible residual deformations.

Depending on the moment contribution ratio between self-centering and dissipating contribution, a wide range of hybrid solutions can be obtained, with upper and lower bounds being given respectively, by an unbonded post-tensioned solution (with or without additional axial load), with full re-centering capability (described by a Non Linear Elastic, NLE, behavior) and a Tension-Compression Yielding System, TCY, (Priestley 1996), with an hysteretic behavior similar to an emulative concrete system (i.e. stiffness degrading Takeda rule). The properties of the flag-shape hysteresis would vary accordingly (**Figures 7 and 10**). The static (maximum feasible) residual deformation and the equivalent viscous damping evaluated from the hysteretic rule can be adopted as main design or assessment parameters. Simplified design charts as those shown in **Fig. 7** (referring to a combination of a NLE and a degrading-stiffness

Takeda rule) can be used to define an adequate ratio $\lambda = M_{pt} / M_s$ in a preliminary design phase in order to satisfy the desired requirements. A full re-centering capacity can be achieved by selecting an appropriate moment contribution ratio $\lambda \geq \alpha_0$, being α_0 the expected material overstrength for the non-prestressed steel reinforcement or the energy dissipation devices.

As a result, the initial prestress in the tendon should have a lower limit to guarantee the desired recentering contribution at a target drift level. Additionally, if coulomb friction due to the post-tensioning is relied upon for partial shear transfer at the beam-column interface, a minimum prestress level should be guaranteed at any time to sustain it. On the other hand, an upper bound of the initial prestress has to be respected to maintain the tendons in the elastic range for the target interstorey drift level.

Dimension-less tables and design charts related to different section shapes and reinforcement layouts have been provided by Palermo (2004).

Fig. 6 Idealized flag-shape hysteretic rule for a hybrid system (fib, 2003).

Fig. 7 Influence of the moment contribution ratio λ between prestressed and non-prestressed steel on a) the hysteresis shape and on b) the key parameters of a hybrid system. Example of design charts in terms of equivalent viscous damping and residual displacement for a given ductility level (Pampanin 2000; fib 2003; DZ3101 2005).

4.1 Force-based or displacement-based design approach

Either a force-based or a displacement based design procedure can be adopted for the design of jointed ductile precast concrete systems. Limits and drawbacks of traditional force-based design approaches have been well recognized and critically discussed in literature (Priestley 1998). Moreover, a displacement-based design procedure would more naturally capture and control

the peculiar rocking behavior of these systems. According to a “flexible” design approach proposed by Pampanin (2000), the self-centering and energy dissipation contributions of a hybrid system, are recognized as key design parameters (identified with the symbols ψ and ξ respectively) and can be adequately selected while maintaining a given moment capacity. A first framework for a Direct Displacement Based design procedure for hybrid systems was proposed by Pampanin (2000) based

on the following modifications and integrations:

- adoption of Residual Displacement R_Δ as a secondary target parameter in addition to the target Design Displacement Δ_d (from Design Drift θ_d);
- definition of an adequate combination of energy dissipation and self-centering capability of the equivalent S.D.O.F. system to respect both the requirements, by means of appropriate inelastic spectra;
- evaluation of the appropriate ratio of PT steel/mild steel moment contribution ratio for the individual connection detailing, for a given design base shear and internal forces distribution, by means of design charts similar to those shown in Fig. 7

Figure 8 shows a flow-chart of the proposed DBD design for hybrid systems: the original DDBD design procedure (Priestley 1998) is basically shown on the left side and integrated with the introduction of Residual Displacement Spectra and residual-related compliance criteria.

A more comprehensive displacement based design procedure for precast concrete jointed systems including design examples has been recently provided by Priestley (2004).

When using a force-based design approach, as typically adopted in major seismic code provisions, appropriate values for the reduction factor R (or for the be-

DBD PROCEDURE

Fig. 8 Framework for a Displacement Based Design procedure for hybrid system as proposed by Pampanin (2000).

havior factor q as defined in the Eurocode 8) shall be defined. As mentioned, provided an adequate amount of hysteresis damping is given to the flag-shape rule, the performance of a hybrid system is expected to be at least as satisfactory as that of an equivalent monolithic system. Similar values for the reduction factors can thus be suggested to be adopted (Pampanin 2000). In more details, the reduction or behavior factor could be evaluated by interpolating between the value given to a monolithic system (i.e. no post-tensioned tendons) or a fully prestressed system (i.e. no mild steel), depending on the amount of hysteretic damping of the hybrid system (NZS3101 2005).

4.2 Modeling issues and alternative approaches

An overview of the main issues related to the analytical modeling of these systems has been given by Pampanin and Nishiyama (2002) and reported by fib (2003).

At a local level, when dealing with unbonded post-tensioned tendons, partially ungrouted longitudinal mild steel bars, or combination of the above, relatively substantial modifications are required when compared to a “fully bonded” case (i.e. monolithic cast-in-situ systems). In the critical section, the assumption of strain compatibility between steel and concrete, typically required for a section analysis approach, is violated. As a result, traditional section analysis methods, adopted to design/assess monolithic bonded prestressed concrete members, can not be directly applied. A procedure for the definition of moment-rotation curve for connections with unbonded reinforcements which violates section strain compatibility assumption was presented by Pampanin et al. 2001. Based on a member compatibility concept, the method relies on an analogy with equivalent cast-in-place solutions, named “Monolithic-Beam-Analogy” (MBA). Further refinements to the procedure have been given by Palermo (2004).

Within the same literature contributions, an overview of alternative modeling approaches at different level of complexity was also presented: 3-D finite elements

models (FEM), fiber elements, multi-spring macro-models and lumped plasticity approach. Particular emphasis has been given to the definition and refinement of simplified methods, based on a section analysis approach, which may be suggested as a viable tool for reliable predictions of the seismic response of subassemblies or of the whole systems. Investigations on the efficiency of simplified approaches to predict the response of hybrid systems based on further analytical-experimental comparisons have been also recently presented by Palermo et al. 2005.

At a global level, other issues related to beam elongation effects, to diaphragm flexibility and inelastic behavior as well as to displacement incompatibility between floor and lateral-load resisting systems (either frame of walls), indeed not peculiar to precast/prestressed systems but also expected in cast-in-place solutions, should be appropriately addressed (fib 2003; NZS3101 2005).

According to the proposed lumped plasticity approach, the cyclic behaviour of a hybrid system can be simply modeled with two rotational springs in parallel with appropriate hysteresis rules, i.e. NLE for the self-centering moment contribution of the unbonded tendons M_{pt} (plus axial load M_s) and an appropriate dissipative rule (i.e. Elasto-Plastic, Takeda, Friction or Viscous-Elastic) to represent the moment contribution of longitudinal mild steel or of alternative typologies of energy dissipation devices, M_s .

$$M(\theta) = M_{PT}(\theta) + M_s(\theta) \quad (1)$$

5. Development of a cable-stayed and suspended solution for jointed precast concrete frames

Based on similar concepts developed for jointed ductile systems, a particularly efficient connection solution and construction system, named “Brooklyn” for the peculiar-

Fig. 9 Modeling of an hybrid connections using a lumped plasticity approach: rotational springs in parallel (Pampanin et al. 1999; 2001).

Fig. 10 Alternative Flag/shape hysteresis rule as combination of re-centering (Non Linear Elastic) and dissipative contributions (Pampanin, 2000).

Fig. 11 Alternative solutions for the Brooklyn Systems (proprietary solution, B.S. Italia s.r.l. Bergamo, Italy) : a) cable stayed b) suspended.

ity of incorporating the structural concept and efficiency of cable-stayed or suspended bridges within the skeleton of a typical multi-storey building, has been developed in Italy after comprehensive research investigations started in 1998 and integration with experience from on site applications (Pagani, 2001, Pampanin et al. 2004).

In the suspended version of the system (Fig. 11 right side), continuous post-tensioned tendons, anchored at the exterior columns of the frame, supply, through an appropriate longitudinal profile, the desired moment resistance at the critical sections under combined gravity and lateral loads as well as an adequate uniformly dis-

tributed upward load along the beam axis, according to a load balancing concept.

Alternatively, for building with short-to-medium span length, a cable-stayed solution based on inclined anchored bars with or without initial prestress can be adopted (Fig. 11 left side). In this case, since inclined bars are very sensitive to losses of prestress due their relative short length as well as geometrical imperfections (i.e. alignment of anchorage and/or prestressing jack with bars) they can be more efficiently used as non prestressed elastic additional restraints.

Initially conceived for gravity-dominated frame solu-

tions (low-to moderate seismicity regions), the Brooklyn system has been recently developed for high-seismic applications merging the characteristics and major advantages of hybrid jointed ductile system, following the PRESSS-Technology, with the peculiarities of the emulating-bridge systems. Preliminary experimental validations based on quasi-static cyclic tests on PRESSS-Brooklyn hybrid beam-column joint exterior subassemblies, carried out at the University of Canterbury as part of an on-going experimental test campaign for the development of alternative precast hybrid solutions, will be briefly summarized in the following paragraphs. An overview of practical on site applications of the system will be also given, consisting, at the present time, of ten existing buildings (completed, plus few more under design or construction) in regions of low seismicity in Italy.

Figure 12 Torsion issues in an hybrid connection with mild steel and friction due to unbonded tendons as shear transfer mechanism (PRESSS Five Storey Building, (Priestley et al. 1999; Pampanin et al. 1999)).

5.1 Key features of alternative hybrid systems

The continuous and rapid development of jointed ductile connections for seismic resisting systems have resulted to the validation of a wide range of alternative arrangements, under the general umbrella of “hybrid” systems, currently available to designers and contractor for practical applications based on a case-by-case (cost-benefit) evaluation.

As a further advantage, being these solutions based on same basic original concepts, similar general design criteria, modeling assumption and analytical tools can be adopted with minor appropriate modifications.

In addition to the design parameter λ , i.e. the moment contribution ratio, main key features differentiating alternative solutions for hybrid systems for seismic resisting frames can be summarized as follows:

- *Shear transfer mechanism*: friction due to the post-tensioned tendons contribution, dowel actions in the mild steel, shear key, metallic horizontal or cable-stayed corbel/bracket or combination of the above, represent alternative transfer mechanisms for shear forces at the critical section interface. In addition, the possible presence of a (fiber reinforced) grout pad at the interface should be considered a distinguishing parameter, being used to improve the shear friction as well as to accommodate the construction tolerances. Ideally, the mechanism adopted to carry the design level shear at the interface should also be able to account for torsional issues when present, i.e. due to the weight of an orthogonal slab (**Fig. 12**)
- *Sources of Energy Dissipation*: internal or external supplemental damping devices (**Fig. 13**), relying on metallic or other advanced materials (e.g. shape

Fig. 13 Alternative arrangements of hybrid beam-column joints with internal or external energy dissipations tested at the University of Canterbury.

memory alloys, visco-elastic systems), can lead to alternative type of hysteretic dissipation (elasto-plastic due to axial or flexural yielding, friction, visco-elastic, which leads to alternative flag-shape loops, **Fig. 10**) implemented within a passive or semi-active control approach.

- *Longitudinal profile of post-tensioned tendons:* straight or draped tendons/cables profiles or combination of the above (**Fig. 14**) can be adopted depending on the ratio between gravity and lateral loads effects, as a consequence of different level of seismicity (target design earthquake) as well as of the assigned role of the system during the seismic response (i.e. pure gravity-load carrying system, pure seismic resisting system or intermediate solutions).

It is worth noting that similar considerations on key parameters differentiating hybrid system can be appropriately extended to wall systems. In particular several types of either internal or external dissipation systems have been developed for either single or coupled walls (through various devices or rocking post-tensioned beams) (Priestley et al. 1999; Kurama and Shen 2004; Holden et al. 2003).

5.2 Use of permanent steel corbel/bracket

A key feature of the original version of jointed systems, as developed in the PRESSS-program and accepted in the ACI 318-05 code provisions (following the special provisions for Hybrid Moment Frames provided by the ACI T1.2-03 document (2003)), was to rely on pure

friction induced by the post/tensioning at the interface between beam and column for both gravity and lateral loading. As a consequence, multi-storey columns could be built without the permanent corbel typically found in precast concrete construction.

On the other side, conservative lower and upper limits on the initial prestressing should be respected, in order to, respectively, guarantee a minimum initial prestressed force to carry the factored gravity loads as well as avoid losses of prestress (thus shear carrying capacity) due to yielding of the tendons up to the drift level of 3.5%. The use of frictional joints can thus significantly affect the distribution of prestressing tendons, which cannot be fully exploited to counteract flexural effects, particularly in the case of gravity load dominated frames.

Furthermore, shear transfer mechanism based on pure friction are typically penalized (if not prohibited) by major design codes as well as by the common practice of design engineers. The recently revised NZ Concrete Code (NZS3101 2005, Appendix B), requires special supports to carry the shear due to factored gravity loads, while only the shear (or part of that) induced by the lateral loads can be assigned to the post/tensioning friction contribution at the interface.

A controversial argument can also be raised on the possible losses of prestressing due to beam-elongation effects in a multi/storey building.

In order to eliminate this shortcoming, the Brooklyn system was based on the introduction of a steel bracket/corbel (modified-Hercules), able to fully counteract the shear force transmitted by the beam to the column. In this way, the prestressing tendons have only to balance flexural stresses and large dimensions of the slab grid (i.e. 10 m x 12 m) can be achieved.

Fig. 14 Combination of draped and straight tendons profile (application of Brooklyn suspended solution, office building in Varese, Italy (Pampanin et al. 2004)).

Moreover, a steel corbel produced following a controlled process, typical of structural steel industry, can be regarded as a high-quality element, whose performance can be validated in advance by special and exhaustive laboratory tests.

By “hiding” it in the depth of the beam, architectural and aesthetic requirements can be also met.

Alternative versions of hidden steel corbel/brackets, either slotted or cable-stayed, developed and adopted in the Brooklyn Systems, are shown in Fig.15.

5.3 Development of a PRESSS-Brooklyn hybrid system

An extensive experimental campaign was carried out to investigate in more details the structural behaviour of the Brooklyn system at both local and global level as well as to calibrate simplified analytical models for de-

sign and analysis purposes.

In the first phase of the research program the efficiency and structural performance of the proposed solutions (either cable-stayed or suspended version) were experimentally validated through monotonic cyclic tests on six one storey one-bay full-scale frame systems under simulated gravity loads carried out at the Department of Structural Mechanics of the University of Pavia (Fig. 16). An overview of the first phase experimental tests has been given in Pampanin et al. (2004). More detailed information on the experimental program and results will be presented in further publications under preparation.

At a local level, independent shear tests on the steel corbel-to-column system were carried out at preliminary stages and consistently carried out during the evolutions of the alternative versions (i.e. slotted or cable-stayed).

Fig. 15 Alternative versions of hidden steel bracket: slotted or cable-stayed (Hercules systems, proprietary of B.S. Italia srl).

Fig. 16 Test set-up (beam length not in scale) and experimental deformed shape of suspended solution frame.

The evolution towards a solution for high-seismicity has been developed by merging the know how of the PRESSS and Brooklyn System research outcomes and on-site applications. A comprehensive series of experimental investigations on beam-column joint subassemblies and frame systems implementing different aforementioned key features of hybrid systems (shear transfer mechanism, source of energy dissipation, tendon profile) are being carried out at the University of Canterbury.

Figure 17 shows the test set-up of an exterior beam-column joint with a draped tendon configuration, a hidden shear key and external energy dissipation devices, consisting on deformed bars machined down to devel-

oped a fuse and inserted in grouted metallic cylinders used as anti-buckling restrainers. Adequate protection of the concrete compression zone was achieved by using light steel angles at the top and bottom corners of the beam.

Preliminary results on quasi-static tests on the 2-D exterior beam-column subassemblies with alternative arrangements confirmed the efficiency of the PRESSS-Brooklyn configuration. As shown in **Fig. 18**, a stable hysteresis flag-shape hysteresis behavior was observed, showing an adequate amount of energy dissipation as well as full-recentering capability. The asymmetric behavior in terms of strength is due to the non-central posi-

Fig. 17 PRESSS-Brooklyn hybrid beam-column subassembly: test-set-up and details of the dissipation devices.

Fig. 18 PRESSS-Brooklyn hybrid system: gap-opening at 3% of drift level and hysteresis loop.

tion of the cable within the section.

No evident loss of stiffness occurred thanks to the protection of the concrete edge corners. No damage occurred up to design drift in the structural elements, as expected by a properly-designed jointed ductile connection.

6. On site applications

Several on site applications on precast jointed ductile systems, adopting PRESS-type technology have been implemented in different seismic-prone countries around the world including U.S., Europe, South America, Japan, and New Zealand. One of the first and most glamorous application of hybrid systems in high seismic regions was given by the Paramount Building in San Francisco (Fig. 19), consisting on a 39-storey apartment building and representing the higher precast concrete structure in a high seismic zone (Englerkirk 2002).

First application presented in literature on the use of hybrid coupled wall systems, in addition to frame systems, is given by the Cala Building in the Dominican Republic (Stanton et al. 2003). Given the evident structural efficiency and cost-effectiveness of these systems (e.g. high speed of erection) as well as the flexibility in the architectural features typical of precast concrete, several applications of the Brooklyn System has also been implemented in Italy, based on either the cable stayed or suspended solutions. Ten buildings, with different use (commercial, offices, exposition, industrial,

hospital), plan configurations, beam and floor span length as well as storey height (up to six), have been currently designed and constructed in region of low seismicity (gravity-load dominated frames). Brief description of on-site applications has been given in Pagan (2002) and Pampanin et al. (2004).

Good level of flexibility in the structural configuration was achieved, allowing to meet complex and articulated architectural requirements (i.e. Fig. 20). In particular the presence of inclined bars or continuous cables can allow to significantly reduce the depth of the structural beams, leading to more desired aesthetic solutions.

As mentioned, when adopting suspended solutions, a combination of straight and draped tendon profiles can be used within the same frame systems, which follow the bending moment diagram due to gravity loads and run the entire length of the frame to minimize the number of anchorages (Fig. 14).

The construction process showed to be extremely efficient, with beam column elements and floor units being quickly assembled into a modular building system (Figs. 21-23), without the need for temporary supports (thanks to the adoption of steel brackets) nor any casting of connections. Metallic complementary elements were also embedded at the beam edges to accommodate and lock the steel corbel. As a result, a non-invasive (well-“hidden”) beam-column connection, when compared to traditional solution relying on concrete corbels in the columns, was obtained.

Fig. 19 From theory to practice. 39-storey apartment building in San Francisco, Paramount Building (Englerkirk, 2002): rendering and construction site at 27/9/2000 .

Fig. 20 Plan view and elevation of the first application of the cable-stayed solution.

Fig. 21 Construction sequence for the Brooklyn cable stayed solution.

Fig. 22 Brooklyn cable-stayed solution: positioning, prestressing operation and patching of the inclined bars accommodations.

7. Conclusions

An overview of emerging solutions for precast concrete buildings has been given, with attention to both design methodology and construction technology. These recently developed high-seismic resisting systems, able to undergo inelastic deformation during a major seismic event with minor structural damage and re-centering capability, represent a major achievement in seismic engineering in the last decade and could be possibly considered a fundamental milestone in the historical

development in the field (**Fig. 24**). The conceptual innovation introduced by capacity design principles as part of design approach for ductile systems has in fact led in the mid-1970s to revolutionary implication in seismic design philosophy. Similarly, the development started in the early 1990s of ductile connections able to accommodate high inelastic demand without suffering extensive material damage appears to be a promising and critical step forward for the next generation of high-performance seismic-resisting systems based on the use of conventional material and techniques.

Fig. 23 Structural skeletons of buildings under construction adopting the Brooklyn suspended solution.

Fig. 24 Evolution of seismic resisting connections: performance of beam-column joints designed according to pre-1970 codes (shear damage in the joint); following capacity design principles as per the NZS3101:1995 (beam plastic hinge) and adopting hybrid jointed ductile connections as per NZS3101:2005 (controlled rocking system).

References

- ACI Committee 318, (2005). "Building Code Requirement for Structural Concrete (ACI 318-02 and 318-05) and commentary." American Concrete Institute, Farmington Hills, MI.
- ACI T1.2-03, (2003). "Innovation Task group 1 and collaborators, Special Hybrid moment frames composed of discretely jointed precast and post-tensioned concrete members (ACI T1.2-03) and commentary (ACI T1.2R-03)." American Concrete Institute Farmington Hills, MI.
- AIJ (2004). "Guidelines for performance evaluation of earthquake resistant reinforced concrete buildings (Draft)." Architectural Institute of Japan. (in Japanese)
- Bertero, V. (1997). "Performance-Based Seismic Engineering: a critical review of proposed guidelines." *Seismic Design Methodology for the Next Generation of Code*, Fajfar and Krawinkler Eds, Balkema, Rotterdam.
- Christopoulos, C., Filiatrault, A. and Folz, B. (2002a). "Seismic response of self-centering hysteresis SD & F Systems." *Earthquake Engineering and Structural Dynamics*, 31, 1131-1150.
- Christopoulos, C., Filiatrault, A., Uang, C. M. and Folz, B. (2002b). "Post-tensioned Energy Dissipating Connections for Moment Resisting Steel Frames." *ASCE Journal of Structural Engineering*, 128(9), 1111-1120.
- Christopoulos, C. and Pampanin S. (2004). "Towards

- performance-based design of MDOF structures with explicit consideration of residual deformations." *ISET Journal of Structural Engineering*, Special Issue on "Performance Based Seismic Design" (Guest Editor M.J.N. Priestley) 41(1), 440.
- Englerkirk, R. E. (2002). Design-construction of the paramount – a 39 story precast prestressed concrete apartment building, *PCI Journal*, 47(4), 56-71.
- fib, International Federation for Structural Concrete, (2003). "Seismic design of precast concrete building structures." Bulletin 27, Lausanne, 254 pp.
- Hewes, J. T. and Priestley, M. J. N. (2001). "Experimental testing of unbonded post-tensioned precast concrete segmental bridge columns." *Proc. of the 6th Caltrans Seismic Research Workshop Program*, Sacramento, California.
- Holden T., Restrepo J. and Mander J. B. (2003). "Seismic performance of precast reinforced and prestressed concrete walls." *Journal of Structural Engineering*, 129(3), 277-424.
- Kawashima, K. (1997). "The 1996 Japanese Seismic Design Specifications of Highway Bridges and the Performance Based Design." *Proceedings, Seismic Design Methodologies for the Next Generation of Codes*, Fajfar & Krawinkler Eds, Balkema, Rotterdam, 371-382.
- Kurama, Y. and Shen, Q. (2004). "Posttensioned hybrid coupled walls under lateral loads." *J. Structural Engineering*, 130(2), 297-309.
- Mander, J. B. and Chen, C. T. (1997). "Seismic resistance of bridge piers based on damage avoidance design." *Technical Report NCEER-97-0014* (National Centre for Earth. Eng. Research), State University of New York, Buffalo.
- NZS 3101. (2005). "Standards New Zealand, Appendix B: special provisions for the seismic design of ductile jointed precast concrete structural systems."
- Pagani, C. (2001). "Four is better than two – The principle of cable-stayed bridges applied to building beams." *Elite Journal*, 4, 50-69, 5, 42-57.
- Palermo, A. (2004). "The use of controlled rocking in the seismic design of bridges." Ph.D. Dissertation, Department of Structural Engineering, Technical University of Milan, Italy.
- Palermo, A., Pampanin, S. and Carr, A. (2005). "A efficiency of simplified alternative modeling approaches to predict the response of precast concrete hybrid systems." *Proceedings of the fib symposium "Keep Concrete Attractive"*, Budapest, 1083-1088.
- Palermo, A., Pampanin, S. and Calvi, G.M. (2005). "Concept and development of hybrid solutions for seismic-resistant bridge systems." *Journal of Earthquake Engineering*, (under publication)
- Pampanin S., Priestley, M. J. N. and Sritharan, S. (2000). "Passive energy dissipation and self-centering capabilities in precast ductile connections." *Proceedings of the Second European Conference on Structural Control*, ENPC, Champs-sur-Marne, France.
- Pampanin, S. (2000). "Alternative design philosophies and seismic response of precast concrete buildings." Ph.D. Dissertation, Department of Structural Engineering, Technical University of Milan, Italy.
- Pampanin, S., Priestley, M. J. N. and Sritharan, S. (2001). "Analytical modelling of the seismic behaviour of precast concrete frames designed with ductile connections." *Journal of Earthquake Engineering*, 5(3), 329-367.
- Pampanin, S. and Nishiyama, M. (2002). "Critical Issues in Modeling the seismic behavior of precast/ prestressed concrete connections/systems." *1st fib Congress*, Osaka.
- Pampanin, S., Christopoulos, C. and Priestley M. J. N. (2002). "Residual deformations in the performance-based seismic assessment of frame systems." *ROSE Research Report 2002/02*, European School on Advanced Studies on Reduction of Seismic Risk, Pavia, Italy.
- Pampanin, S., Pagani, C. and Zambelli, S. (2004). "Cable-stayed and suspended post-tensioned solutions for precast concrete frames." *The Brooklyn System; Proceedings of New Zealand Concrete Industry Conference*, Queenstown
- Park, R. (2002). "Seismic Design and Construction of Precast Concrete Buildings in New Zealand." *PCI Journal*, 47(5), 60-75.
- Priestley, M. J. N. (1991). "Overview of the PRESSS Research Programme." *PCI Journal*, 36(4), 50-57.
- Priestley (1996). "The PRESSS program current status and proposed plans for phase III." *PCI Journal*, 41(2), 22-40.
- Priestley, M. J. N. (1998). "Displacement-based approaches to rational limit states design of new structures." Keynote address of the *11th European Conference on Earthquake Engineering*, Paris, France.
- Priestley, M. J. N., Sritharan, S., Conley, J. R. and Pampanin, S. (1999). "Preliminary results and conclusions from the PRESSS five-storey precast concrete test building." *PCI Journal*, 44(6), 42-67.
- Priestley, M. J. N. (2002). "Direct displacement-based design of precast/prestressed concrete buildings." *PCI Journal*, 47(6), 66-78.
- Sanpaolesi, L. (1995). "Sperimentazione su Prototipi di Strutture Prefabbricate per Edilizia Civile in Zona Sismica." C.N.R. Progetto finalizzato Edilizia.
- SEAOC Vision 2000 Committee, (1995). "Performance-based seismic engineering." Structural Engineers Association of California, Sacramento, California.
- Stanton, J. F., Stone, W. C. and Cheok, G. S. (1997). "A hybrid reinforced precast frame for seismic regions." *PCI Journal*, 42(2), 20-32.
- Watanabe F. (2000). "Seismic design for prefabricated and prestressed concrete moment resisting frames." *Proceedings of the 46th PCI Annual Convention*, Orlando, Florida.