CABLE-STAYED AND SUSPENDED POST-TENSIONED SOLUTIONS FOR PRECAST CONCRETE FRAMES: THE BROOKLYN SYSTEM

Stefano Pampanin[1], Claudio Pagani[2], Sergio Zambelli[3]

SUMMARY

Alternative solutions for precast concrete buildings have been recently developed under the U.S. PRESSS program and successfully adopted with practical applications in seismic regions worldwide. Jointed ductile “dry” connections, obtained through unbonded post-tensioning techniques, have been proved to provide extremely efficient and damage-resistant systems for the next generation of buildings.
In this contribution, an extension of these emerging solutions for gravity-load-dominated frame buildings is presented, being named “Brooklyn” system for the peculiarity of incorporating the structural efficiency of a cable-stayed or suspended bridge systems within a multi-storey buildings. An overview of the conceptual definition, development, experimental validations on six full-scale one-storey frame systems will be given, including a description of the up-to-date practical applications on a series of buildings in regions of low seismicity. Proper modifications and validations are under development to accommodate high seismic demand.

RECENT DEVELOPMENTS IN PRECAST CONNECTIONS AND SYSTEMS

The use and development of precast concrete for multi-storey building structures have typically suffered, when compared to their cast-in-situ concrete counterparts, an intrinsic lack of redundancy in the main structural scheme, consisting of statically determined systems with beam simply supported on, or hinged to, cantilever columns. As a result, excessive dimensions of, or reinforcement ratio in, the structural members (both beam and columns) are adopted, due to the un-convenient distribution of internal moments in a pinned frame, in order to reduce the excessive deformability of the system (even more emphasized by the P-Δ effects), due to the inadequate structural scheme. Additional and architecturally invasive lateral load resisting solutions (i.e. typically braces) should thus be adopted.

Emulation of cast-in-place approach

Several alternative solutions to provide rigid connections between beam and columns have been studied and developed in literature ([1], [2]) mostly relying on cast-in-place techniques to provide equivalent “monolithic” connections. 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 solutions, as for example adopted in New Zealand and Japan construction practice, the connections can be either localized within the beam-column joint with partial or total casting-in-place of concrete (Fig. 1a), 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 (Fig. 1b).

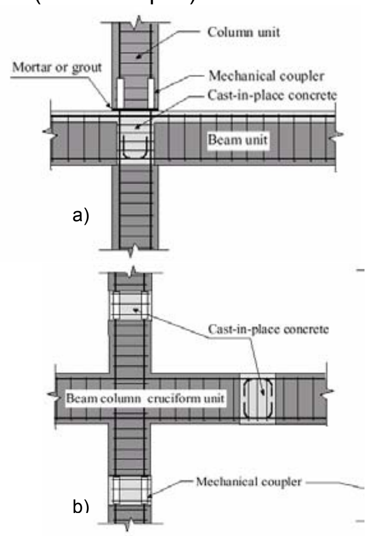

Fig. 1 - Typical arrangements of precast units in the emulation of cast-in-place approach ([1], [2])

Nonetheless, due to their economic inconvenience and construction complexity, such

[1] *Senior Lecturer, University of Canterbury, Christchurch, New Zealand*
[2] *Chief Engineer, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*
[3] *Architect and Principal, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*

systems have not been widely adopted, particularly in the United States and in Mediterranean seismic-prone countries ([3], Fig. 2).

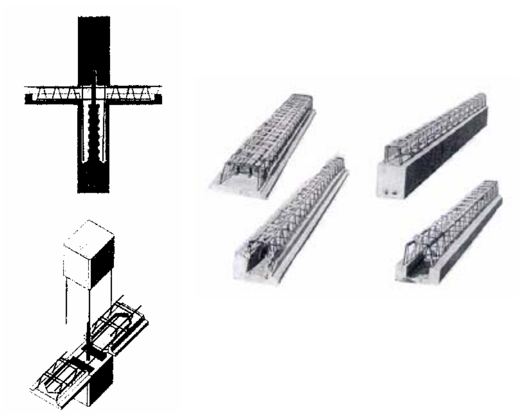

Fig. 2 – Technical solutions developed in Italy according to the emulation approach ([3]):

Jointed ductile and hybrid systems

Recent development in precast concrete solutions for seismic regions, carried out under the U.S. PRESSS research program in the 1990's ([4],[5]), have successfully underlined the efficiency of "dry" jointed ductile beam-column connections for moment resisting frames, alternative to the emulation of cast-in-place approach and based on post-tensioning techniques (Fig.3(

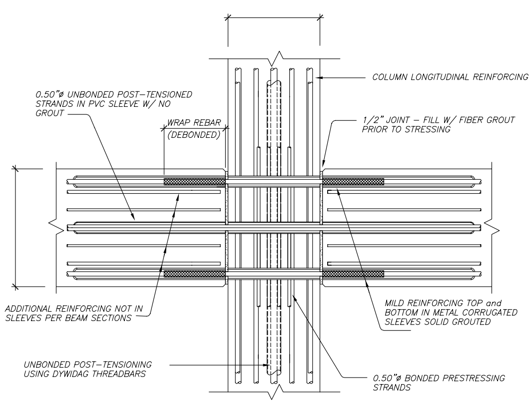

Fig. 3 – Jointed precast "hybrid" beam-column connection in the PRESSS program ([4],[5])

The inelastic demand is accommodated within the connection itself (beam-column, column to foundation or wall-to-foundation critical interface), through opening and closing of an existing gap (rocking motion). Reduced level of damage, when compared to equivalent cast-in-place solutions, is expected in the structural precast elements, when subjected to earthquake loading. In addition the self-centering contribution due to the unbonded tendons can lead to negligible residual deformations/displacement, which should be adequately considered as a complementary damage indicator within a performance-based design or assessment procedure [6]

Within the proposed solutions a particularly promising efficiency and high flexibility have been shown by the so-called hybrid systems (Figs. 3,4 [7}), where unbonded post-tensioning tendons/bars with self-centering properties are adequately combined with longitudinal mild steel (i.e. in frame systems) or additional dissipation devices (i.e. vertical connectors in jointed wall systems) which can provide an appreciable energy dissipation.

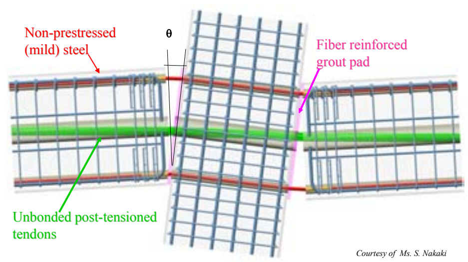

Fig. 4– Rocking mechanism of an hybrid connection under lateral loading connection ([4],[5])

The "Brooklyn system": the bridge in the building

Based on similar concepts, a peculiar connection solution and construction system (named "Brooklyn") has been studied and developed in Italy for gravity-load-dominated frame buildings. The natural evolution to accommodate higher seismic demand, based on the concept developed in the PRESSS program, is currently being under development and investigation and will be presented in future contributions.

The definition, design and development of this system started in the 1998 building on the existing recent developments in the area of precast solutions with the intuition of combining the structural concept and efficiency of cable-stayed or suspended bridges within the skeleton of a typical multi-storey building system ([8]).

Continuous post-tensioned tendons, anchored at the exterior columns of the frame, supply, through

[1] Senior Lecturer, University of Canterbury, Christchurch, New Zealand
[2] Chief Engineer, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy
[3]Architect and Principal, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy

an appropriate longitudinal profile, an adequate moment resistance at the critical sections under combined gravity and low-to-moderate lateral loads. (i.e. beam mid-span and beam-column interface). Alternatively, for short-medium span length buildings, a cable-stayed solution (inclined anchored bars with or without initial prestress) can be adopted.

In the present contribution, the main issues related to the original concept, the structural behaviour as well as the design approach of the proposed system will be presented. The experimental results on monotonic cyclic tests on six full-scale one storey frame systems will be critically discussed, with particular attention to the suspended solution (unbonded post-tensioned tendons). In conclusion, an overview of practical applications on site, consisting, at the current time, of ten existing buildings in regions of low seismicity in Italy, will be given.

SYSTEM BEHAVIOR AND DESIGN APPROACH

Use of steel corbel

A key feature of the original version of the jointed system, as developed in the PRESSS-program and accepted in the ACI 318-99and ACI 318-02 code provisions [9](following the special provisions for Hybrid Moment Frames provided by the ACI T1.2-XX document [10]), 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 column could be built without the permanent corbel typically found in precast concrete construction.

On the other hand, conservative lower and upper limits on the initial prestressing should be respected, respectively, to guarantee a minimum initial prestressed force to carry the factored gravity loads as well as to avoid losses of prestress (thus shear carrying capacity) due to yielding of the tendons up to a 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 frictions are typically penalized (if not prohibited) by major design codes as well as by the common practice of design engineers. The current draft of the NZS3101 Concrete Code, under revision, tends to require 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 has also been recently raised up on the possible losses of prestressing due to bream-elongation effects on a multi/storey building ([11], [12]) higher mode effects.

In order to eliminate this shortcoming, the Brooklyn system was based on the introduction of a steel corbel in the column, 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. Furthermore, the steel corbel, produced according to 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.

Inclined bars and draped tendons

According to this approach, the prestressing tendons should guarantee the transmission of bending moments at the beam-column interface and supply an adequate uniformly distributed upward load along the beam axis, according to the load balancing concept. Appropriate profile of the tendons can thus be defined to respect the static loading requirements.

On the contrary, when adopting straight inclined bars their efficiency is reduced, as the corresponding equivalent loads only consist of forces at the end anchorages. Furthermore, due to their limited length, inclined bars are very sensitive to losses of prestress due to geometrical imperfections (i.e. alignment of anchorage and/or prestressing jack with bars). For this reason inclined bars can be more efficiently used as non prestressed elastic additional restraints.

On the basis of the aforementioned main design concepts the two following Brooklyn systems were conceived (Fig. 5):

- Cable Stayed Solution including prestressed or not prestressed inclined bars, intended for small-medium span-length buildings.
- Suspended Solution, including post-tensioned curved tendons, intended for medium-large span length buildings.
-

According to a Performance-Based (or Limit State) design approach, where different performance level or limit state are accepted depending (for a given structural "importance") on the expected

[1] Senior Lecturer, University of Canterbury, Christchurch, New Zealand
[2] Chief Engineer, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy
[3]Architect and Principal, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy

intensity of the input loads, the Brooklyn Suspended System can be designed in order to either guarantee no tensile stress at the beam-column joint section or, alternatively, allowing for a gap opening with rocking motion of the beam at the interface with the column.

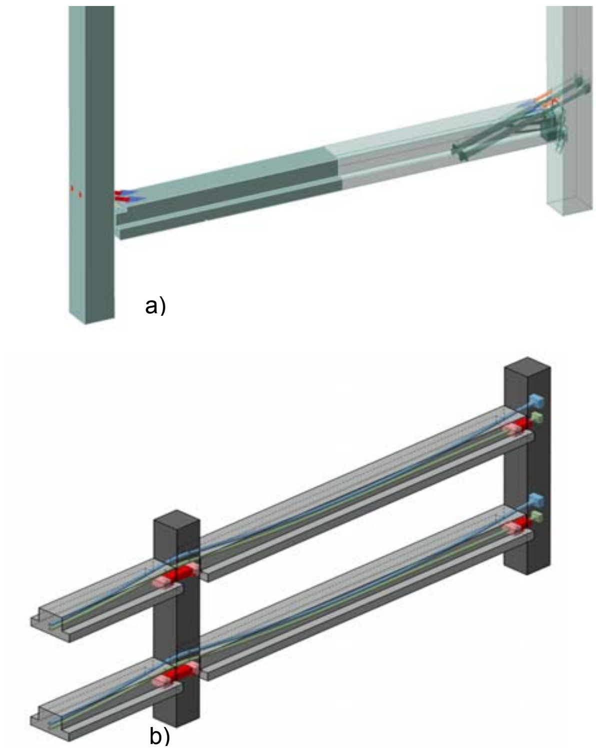

Fig. 5 – Alternative solutions for the Brooklyn systems: a) cable stayed b) suspended

In the first case, a complete monolithic linear behaviour of the joint is thus guaranteed in the service stage This design approach can be referred as Integral Prestressing (IP). However, taking into account that the shear force is supplied by the steel corbel, it is not strictly necessary to design the Brooklyn system according to an IP approach and a Partial Prestressing (PP) design approach can be adopted. In the latter approach, the onset of cracking is allowed at service stage at both the critical sections: mid-span of the beam (maximum positive moment) and beam-column interface (maximum negative moment) where the joint gap opening occurs. An additional design parameter, given by the ratio between prestressing and ordinary steel reinforcement in the beam, can thus be introduced. The most appropriate "balanced" condition has to be defined on the basis of an accurate evaluation of the opening of the joint (crack width, equivalent rotation and level of restraint) and of the corresponding redistribution of bending moments. Adequate non linear analysis should thus be performed. Alternatively, simple and reliable analytical procedure to define the full moment-rotation at the critical section of a jointed or hybrid precast connection or system (when strain incompatibility issues arise due to the presence of unbonded tendons) can be adopted, as proposed in [13,14].

At the present time, also due limitations imposed by the Italian design code provisions for prestressed concrete structures, the first applications of the system were designed according to the IP approach, leaving as future developments a comprehensive analytical investigation which can lead to the reliable control and extensive use of the PP approach.

EXPERIMENTAL INVESTIGATIONS

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 design and analysis purposes. The efficiency and structural performance of the proposed solutions were experimentally validated through monotonic cyclic tests under simulated gravity loads corresponding to increased limit states.

At a local level, independent shear tests on the steel corbel-to-column system were carried out at preliminary stages. At a global level, six tests on one storey one-bay full-scale frame systems were performed at the Department of Structural Mechanics of the University of Pavia with the following alternative solutions:

1) Simply supported scheme representing traditional precast solution (one specimen, bay length 6.5 m)
2) Brooklyn Cable-stayed solution with inclined bars, with or without initial pre-tensioning (four specimens, bay length 6.5 m)
3) Brooklyn Suspended solution with unbonded post-tensioned tendons (one specimen, bay length 9 m)

Extremely satisfactory performance were observed for both the proposed Brooklyn

[1] Senior Lecturer, University of Canterbury, Christchurch, New Zealand
[2] Chief Engineer, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy
[3] Architect and Principal, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy

solutions, either relying on inclined bars or continuous tendons, which can thus represent viable structural systems to be alternatively adopted in practical applications, depending on a case-by-case basis (i.e. geometrical dimensions and expected loads). The number of specimens allowed for significant improvement and refinement of the system constructability along with its structural efficiency.

Due to limited space, main focus in this contribution will be given to the observed performance of the suspended solution (post-tensioned tendons), which can be adopted for frame systems with medium-high bay length and design loads. More detailed information on the experimental program and results will be presented in further publications under preparation.

Test set-up and loading regime

The test set-up of the cable stayed and suspended solutions were quite similar in concept, while differing in beam bay length and gemetric and mechanical properties of the members.

In the Brooklyn suspended solution, a full scale one-storey one-bay frame, with interstorey height of 3.6 m and bay length of 9 m (from centre to centre of column) was tested under monotonic cyclic loading up to failure (Fig. 6). The prototype structure consisted on a four storey office building, which represented, as described in the following sections, the first on site application of the suspended solution.

The test set-up is shown in Fig. 5: assuming a point of contraflexure at mid-height of the columns, steel hinge connections were used at the base as well as at the top of the columns (with a steel truss to provide restrain to lateral deflection). The beam was supported on two steel-corbels inserted in the external columns. Unbonded post-tensioned tendons with an appropriately designed longitudinal shape were located in existing ducts and anchored at both ends of the exterior columns. Vertical post-tensioned bars were used to apply a constant axial load in the columns of 200 kN corresponding to the 70% of the permanent gravity load acting on the top storey of the prototype. The simulated gravity load was imposed to the beam through an hydraulic jack with two symmetric points of applications in order to have a reasonably wide area of constant moment and pure flexural behaviour.

The loading regime as well as the application of initial post-tensioning in the tendons was accurately defined to represent the actual sequence of loading during the different construction phases as follows:

1) beam self-weight;
2) initial post-tensioning of tendons (50% of target level);
3) application of slab load through actuator;
4) full post-tensioning of tendons (100% target level) while maintaining constant the vertical load;
5) increasing (monotonic) load with unloading and reloading (cycles) at critical stages corresponding to accepted limit states (i.e. cracking or service loads, whichever occurred first, equivalent yielding point and ultimate conditions).

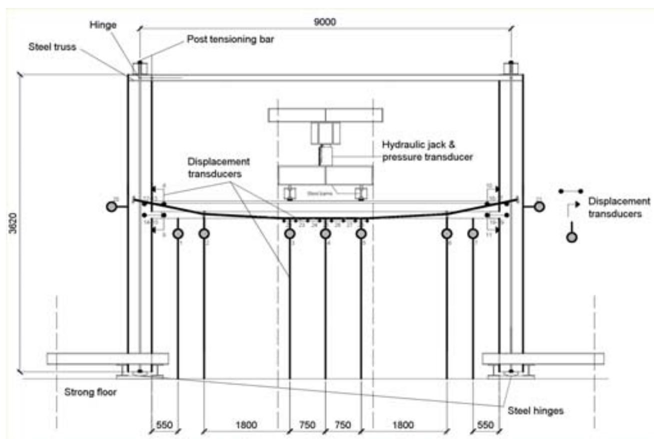

Fig. 6 – Test set-up for the Brooklyn suspended solution (units in mm)

Experimental results

The experimental results showed a very satisfactory performance of both the proposed solutions for the Brooklyn system (cable-stayed and suspended).

The overall force-displacement behaviour curves (applied actuator force vs. vertical deflection at mid-span of the beam), reported in Fig. 7, confirm the efficiency of the "cable-stayed" solution with a significant increase of the overall strength and stiffness of the system when compared to a traditional simply supported solution (with same geometry and longitudinal beam reinforcement). Furthermore, as expected, for a given increase in overall flexural strength due to the change of the static scheme (four supports instead of two [5]), significantly higher stiffness

[1] *Senior Lecturer, University of Canterbury, Christchurch, New Zealand*
[2] *Chief Engineer, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*
[3]*Architect and Principal, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*

(thus lower deflection under service load) can be obtained by prestressing the inclined bars.

Similar considerations on the increase in stiffness and strength of the overall system can be derived for the suspended solution, based on continuous unbonded post-tensioned tendons. The initial post-tensioning level governed the decompression limit state, postponing, when comparing to an equivalent simply supported solution, the opening of flexural cracks. At service load (actuator force F=530kN) no flexural cracks were observed. A generally limited crack width and beam deflection was reported up to first yielding of the bottom longitudinal bars.

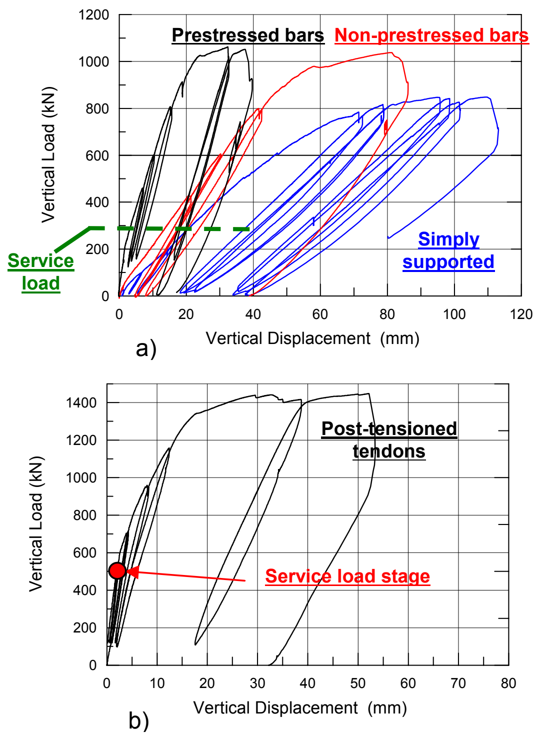

Fig. 7 – Experimental global force-displacement behaviour of Brooklyn systems: a) cable-stayed solution (L= 6.5m); b) suspended solution (L=9 m)

As expected, the combined effect of prestress state within the member (i.e. uncracked section stiffness) and of the rigid joint condition (boundary condition for the beam similar to a fixed-end situation) resulted to significant reduction of vertical deformation/deflection under service load . At increasing level of vertical load, well beyond the service level, minor (limited width) flexural cracking in the beam as well as partial opening of the gap (decompression) at the beam-to-column interface occurred (Fig.8), leading to a reduction of the global stiffness, as evident in the global force-displacement behaviour shown in Fig.7.

It is however important to underline that, as proper of a jointed ductile connection, the opening of the gap at the beam-column interface does not correspond to damage in the structural beam as it would occur in a traditional cast-in-place (monolithic) solution, where the rotation demand at the end of the member would lead to the development of flexural cracks within a plastic hinge region.

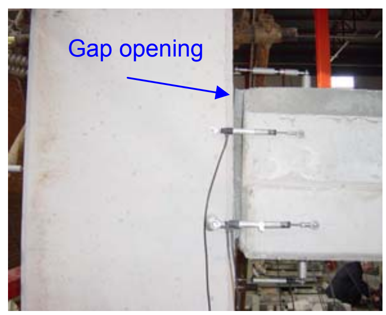

Fig. 8 – Brooklyn suspended solution: gap opening at beam-column interface well-beyond service load level (right)

The frame system based on the Brooklyn suspended solution showed a significant displacement ductility capacity up to the ultimate limit state: yielding of the mild steel bars occurred, while the increase in strain in the tendons was limited (averaged along the unbonded length). The test was interrupted for safety reasons at a beam mid-span deflection of more than 130 mm, without any structural failure. Figure 9 shows a snap-shot of the global deflection of the suspended system during the experimental test (well before ultimate conditions).

[1] *Senior Lecturer, University of Canterbury, Christchurch, New Zealand*
[2] *Chief Engineer, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*
[3] *Architect and Principal, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*

Fig. 9 – Global deflection of the Brooklyn suspended system

Furthermore, as shown in the experimental curve of Figure 7, an adequate design of the tendons can provide self-centring properties to the overall system, when unloading from the service (dead + live) load level to the condition of permanent load (i.e. slab-load), by closing the aforementioned gap at the column interface as well as the existing flexural cracks in the beam mid-span section. After yielding of the longitudinal mild steel bars occurs, appropriate ratio of the post-tensioned steel and ordinary steel is required in order to guarantee full self-centring capacity (as in the case of the PRESSS hybrid system shown Fig. 4)

Practical applications on site

Given the evident structural efficiency and cost-effectiveness of the system (e.g. high speed of erection) as well as flexibility in the architectural features (typical of precast concrete), there are already several applications of the Brooklyn System in Italy, based on either the cable stayed or suspended solutions. Ten buildings, with different use (commercial, offices, exposition, industrial, hospital), plan configurations, beam bay 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).

Great flexibility in the structural configuration was achieved, allowing to meet complex and articulated architectural requirements. 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.

Cable stayed solution

The first application of the "cable stayed version" (figures 4a and 4b) dates back to approximately 5 years ago and is given by the offices of B.S. Italia. It consists of a three-storey office block (11 meter high) with a particularly irregular plan and 1400 m^2.

The irregular architecture of the building required the use of highly varied structural solution, consisting of floors with extremely variable spans and geometries, inverted T beams and L beams with medium-small span length. Thanks to the contribution of the inclined bars, reduced-depth (flat) structural beam with same depth of the floor system were used.

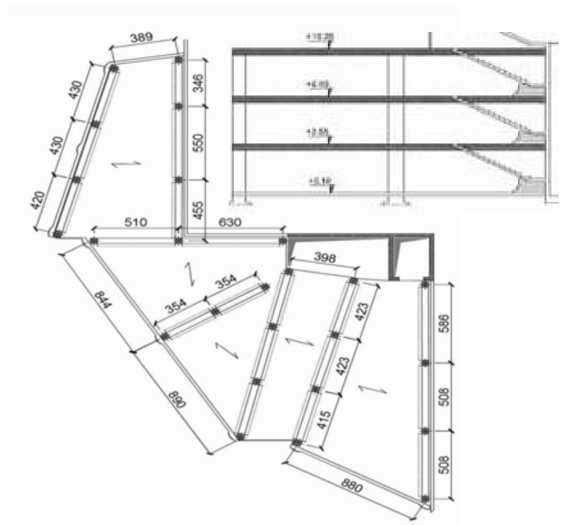

Fig. 10 – Plan view and elevation of the first application of the cable-stayed solution

Fig. 11 – Prestressing the inclined bars

Suspended solution

[1] *Senior Lecturer, University of Canterbury, Christchurch, New Zealand*
[2] *Chief Engineer, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*
[3] *Architect and Principal, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*

The first practical application on site of the Brooklyn suspended solution (continuous unbonded post-tensioned tendons) is given by a four storey (12.7 m high) commercial building, located in Varese (Italy). A plan view at different storey levels and an elevation view of the building are shown in Figure 12. A rectangular plan of 25.3 m x 26 m is used at the different levels, resulting in a total effective area of 2,630 m^2.

The asymmetric building structure consists of three precast frame systems in the longitudinal direction, with precast concrete floor slab (units of 2.50 m width and 0.45 m depth) spanning in the transverse direction. Two large openings span for the entire transverse length of the building at the first and second floor. The external wall consists of vertical precast panels supported on foundations and anchored to the precast floor slabs. Pile foundations were adopted.

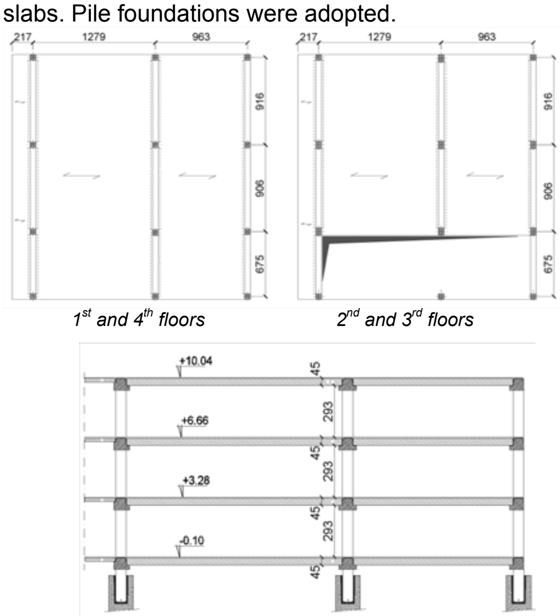

Fig. 12 – Plan and elevation view of an office building with Brooklyn suspended solution

A moment resisting frame solution was achieved in both directions. In the longitudinal one, the suspended Brooklyn solution was adopted, with unbonded post-tensioned tendons located in two sets of metallic ducts, running for the entire length with appropriate longitudinal profile (Figs. 13).

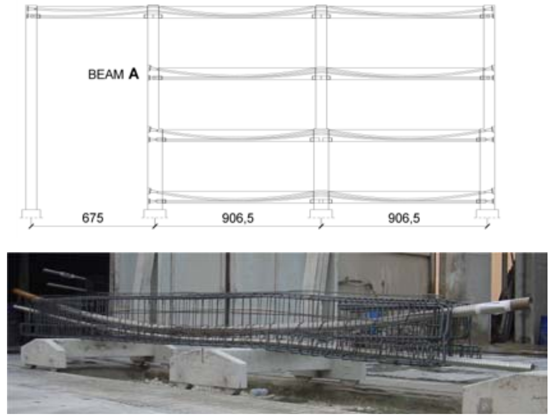

Fig. 13 –Tendons profile in the longitudinal building direction and beam elements

As fundamental part of the Brooklyn system, special steel corbels were used to absorb the design shear at the beam-to-column connection. Appropriate seats were embedded in the columns before casting and the corbels were subsequently inserted in situ, thus resulting to particularly simple, smooth and regular formworks for the square or rectangular column elements. Inverted T- or L-shaped beams of lightly reinforced concrete were adopted.

Fig. 14 –Inverted T-beam for a post-tensioned frame (suspended solution)

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.

[1] *Senior Lecturer, University of Canterbury, Christchurch, New Zealand*
[2] *Chief Engineer, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*
[3] *Architect and Principal, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*

Fig. 14 –Structural skeleton of a building adopting the Brooklyn suspended solution

Design approach and criteria

As already mentioned, the opening of the existing gap at the beam-column interface, as in a jointed ductile connection, does not imply any structural damage but only a reduction of the global system stiffness with increased deformability and vertical beam deflection under service loads, when compared to an ideal rigid joint (monolithic) solution.

However, in order to achieve a fully prestressed system according to the Integral Prestress (IP) design approach (adopted in the first application of the suspended solution), the governing criterion was to avoid any cracking in the structural elements at service loads as well as the opening of the gap at the beam-column interface (decompression). As a result, a very limited deformability typical of a fully restrained beam-to-column connection (rigid joint or equivalent monolithic solution) was obtained.

It is worth mentioning that the adoption of such a requirement was also partly dictated by the Italian code provisions for prestressed concrete structures, which, for the time being, does not provide special recommendations for special post-tensioned frame system similar to the one proposed. When neglecting the non-linear behaviour due to the opening of the gap, simplified elastic analyses can be carried out and a reliable control of the overall response achieved. On the other hand, an excessively conservative design would result, particularly when dealing with moderate lateral loads which naturally will require the opening of the gap.

It can be generally suggested that the level of restraint at the beam-column connection (moment resistance when compared with a monolithic solution) is chosen as a design parameter, thus leading to a more "flexible" design approach, where simply supported or fully moment resisting frame represent lower and upper bound structural schemes.

Consistently with the adopted design approach and due to the structural irregularity (different bay lengths and presence of openings) in the first application, optimum solution has been adopted in the dimensioning of the post-tensioning reinforcement for each beam-column connection and each beam element, by varying the number as well as the longitudinal profile of the tendons. As a result of this exercise, forty-five different beam-column joints were designed, under the clear intent to exploit, in this practical application, the potentiality of the proposed structural system, following a an academic solution more than a more economically convenient standard production approach.

The design internal forces were calculated as a result of ten load combinations including prestress force, gravity loads and low-to-moderate lateral loads corresponding to wind effects and to overall lateral stability verification (the latter being conventionally equal to 2% of the floor total gravity loads).

CONCLUSIONS

An overview of the main peculiarities of an innovative structural solution and construction system, named "Brooklyn", for beam-column connections in precast concrete frame, based on post-tensioning techniques (either inclined bars or unbonded continuous tendons) and with the intent to incorporate the efficiency of cable-stayed or suspended bridge structural scheme within a multi-storey building system, has been herein given.

The structural concept and behavior as well as the efficiency of the system (in both the solutions with inclined bars or unbonded post-tensioned tendons) have been validated through extensive experimental tests on full scale one-storey one bay-frame system. In conclusion, a brief overview of few practical applications on site (either based on a cable/stayed or suspended solution) primarily designed for gravity, wind loads and low seismic loads, has been given.

[1] *Senior Lecturer, University of Canterbury, Christchurch, New Zealand*
[2] *Chief Engineer, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*
[3]*Architect and Principal, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*

The development and natural extension of the proposed solution to sustain significantly higher lateral loads (i.e. seismic resisting system, provided adequate sources of energy dissipation) is currently under investigation.

References

[1] Watanabe F., 2000 *Seismic Design for Prefabricated and Prestressed Concrete Moment Resisting Frames* Proceedings of the 46th PCI Annual Convention, Orlando, Florida

[2] Park, 2002 *Seismic Design and Construction of Precast Concrete Buildings in New Zealand* PCI Journal, Vol. 47, No. 5, pp. 60-75

[3] Sanpaolesi, L., 1995 *Sperimentazione su Prototipi di Strutture Prefabbricate per Edilizia Civile in Zona Sismica*, C.N.R. Progetto finalizzato Edilizia

[4] Priestley, M.J.N. 1991. *Overview of the PRESSS Research Programme* PCI Journal, Vol.36, No.4, pp.50-57.

[5] 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, Vol. 44, No.6, pp. 42-67

[6] Christopoulos, C. 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) Vol. 41, No.1, paper 440

[7] Stanton, J.F., Stone, W.C., and Cheok, G.S., 1997. *A hybrid reinforced precast frame for seismic regions*, PCI Journal, Vol. 42, No.2, pp.20-32.

[8] Pagani, C., 2001 *Four is better than two – The principle of cable-stayed bridges applied to building beams*, Elite Journal, Vol.4, pp. 50-69, Vol.5, pp 42-57

[9] ACI Comiitee 318 *Building Code Requirement for Structural Concrete (ACI 318-99 mad 318-02) and commentary*, American Concrete Institute, Farmington Hills, Mich, 1999 (2002)

[10] ACI T1.2-03 ACI Innovation Task group 1 and collaborators, 2003 *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

[11] Pampanin, S., Priestley, M.J.N, Sritharan, S., 2001. *Analytical modelling of the seismic behaviour of precast concrete frames designed with ductile connections*, Journal of Earthquake Engineering, Vol.5, No.3, pp.329-367.

[12] International Federation for Structural Concrete, 2003, *Seismic design of precast concrete building structures*, Bulletin 27, Lausanne, 254 pp.

Formatted: Font: Not Italic

Formatted: Font: (Default) Arial, Not Italic

Formatted: Font: Not Italic

[1] *Senior Lecturer, University of Canterbury, Christchurch, New Zealand*
[2] *Chief Engineer, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*
[3] *Architect and Principal, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*

[1] *Senior Lecturer, University of Canterbury, Christchurch, New Zealand*
[2] *Chief Engineer, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*
[3]*Architect and Principal, B.S. Italia s.r.l., Styl-Comp Group, Zanica, Bergamo, Italy*