RESEARCH, DESIGN AND APPLICATION OF HIGH PERFORMANCE EARTHQUAKE RESISTANT PRECAST STRUCTURE IN INDONESIA

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Abstract

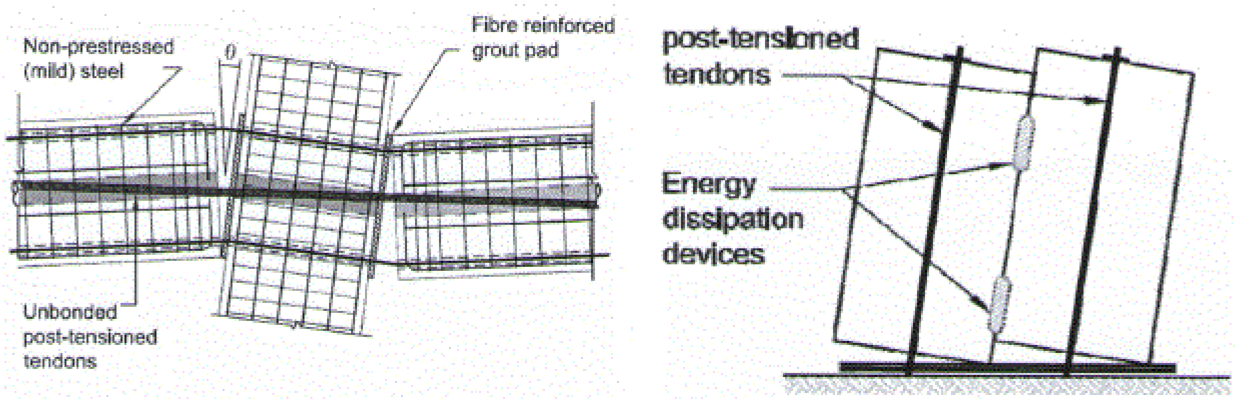
High performance earthquake resistant precast concrete structures are innovations among emerging technologies capable of achieving high performance structural systems at low cost. There are two main components included in this technology, i.e.,unbounded post tension tendon and mild reinforced concrete as energy dissipater. Unbonded post tension tendon may be provided at column-beam connection, and at connections of vertical components or connections of vertical and horizontal components. Unbonded post tension tendon is construed to provide re-centering effect so as to prevent residual deformations after earthquake event.Various technologies of this type have been developed and applied in California, Latin America, as well as in New Zealand. One structure using this kind of technology survived the 2010-2011 earthquake swarm in Christchurch, New Zealand. Since 2013, Indonesian precast and prestressed industry has been developing this kind of technology.This paper describes the significance of the research supporting the development of this emerging technology in Indonesia.The paper also describes some examples of application that have been achieved thus far.

Keywords: High performance earthquake resistant precast system,PRESSS, unbonded post tension, dissipater, re-centering;

1. Introduction

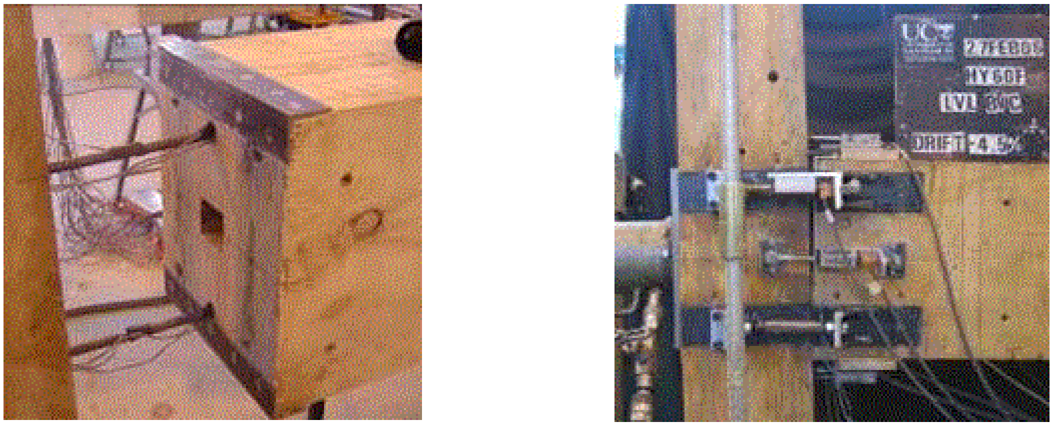
High performance earthquake resistant precast structure is a revolutionary alternative technological solution capable of achieving high-performance (low-damage) at low cost. This concept was developed in US-Japan joint research PRESSS Program (1994-2002)[12,13] and New Zealand in the late 1990s [16], as a response to public demands for the performance of classical ductile design concept that did not comply with their expectation in Loma Prieta (1989) and Northridge (1994) earthquakes.The well-known ductile design concept using collapse prevention performance criteria can indeed avoid casualties in a strong intensity earthquake, but the associated structural damage can result in significant business interruption. Furthermore, the post-earthquake repairs can be challenging and costly.

There are two main components involved within the system, i.e. : unbonded post-tensioning that provides re-centering effect, and mild reinforced concrete that provides energy dissipation(dissipater). Unbonded post-tensioning tendon may be applied in beam-column connections, and across vertical connection between precast wall, including walls and foundations [12]. Unbonded post-tensioning,while kept elastic, is engineered to prevent residual deformations. Dissipater [13], on the other hand, are used to provide hysteretic damping. Dissipaters can be designed as replaceable fuses in the structural system. The experience in Indonesia is that the use of these emerging technologies can be achieved without compromising the architecture of the building.



(a) (b)

Fig. 1 – Re-centering with post-tension unbonded connection, 1(a) Frame,1(b) Wall



(a) (b)

Fig. 2 – Dissipater, 1(a) Internal,1(b) External

Research results and recommendations included in ACI 318 since 2002 [10]. The concept then applied in California, Latin America, as well as in New Zealand. This concept was naturally tested directly in the 2010-2011 earthquake in Christchurch, New Zealand, and demonstrated the achievement of immediate occupancy performance [8].Development of re-centering systems began in Indonesia in 2012, when local industry was inspired by the developments summarized by Pampanin [13].This paper describes the research milestones reached so far in Indonesia, including testing of dissipaters, beam-column joint testing, and implementation in office buildings and low cost housing in Jakarta.

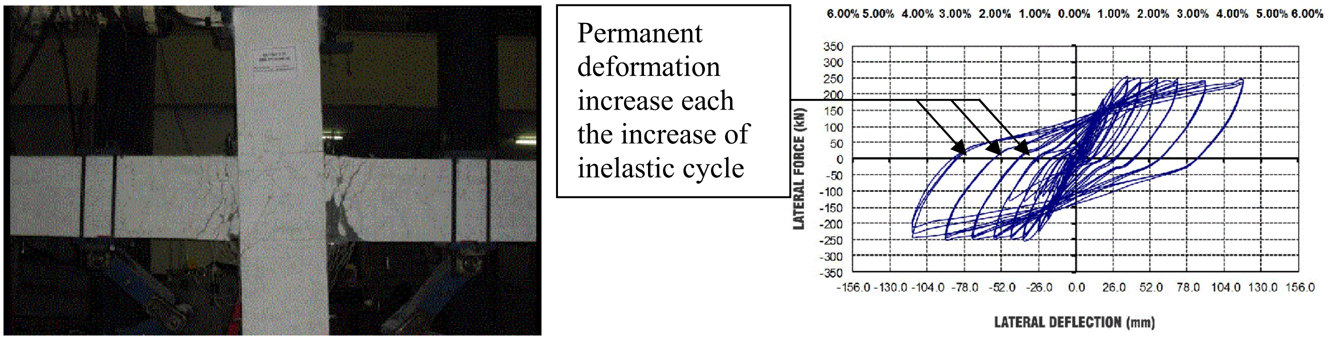
The behavior of high performance earthquake resistant structure is more clear if testing conducted by shaking table, such as done in University California at San Diego (2008) [17], as seen in Fig. 3. In the test scheme, build speciment of full scale 4 stories building which loaded by design earthquake record start from Knoxville (275 years), Seattle (500 years), Berkeley (500 years), and the strongest ever MCE_R Berkeley (2500 years). Amazingly post tension unbonded connection can prevent the building back to its position even has rocking in extreme condition.

(a) 275 years (b) 500 years (c) Berkeley 500 years (d) Berkeley MCE_R (2500 years)

Fig.3 – Testing of high performance earthquake resistant structure with shaking table equipment

2. High performance earthquake resistant precast concept

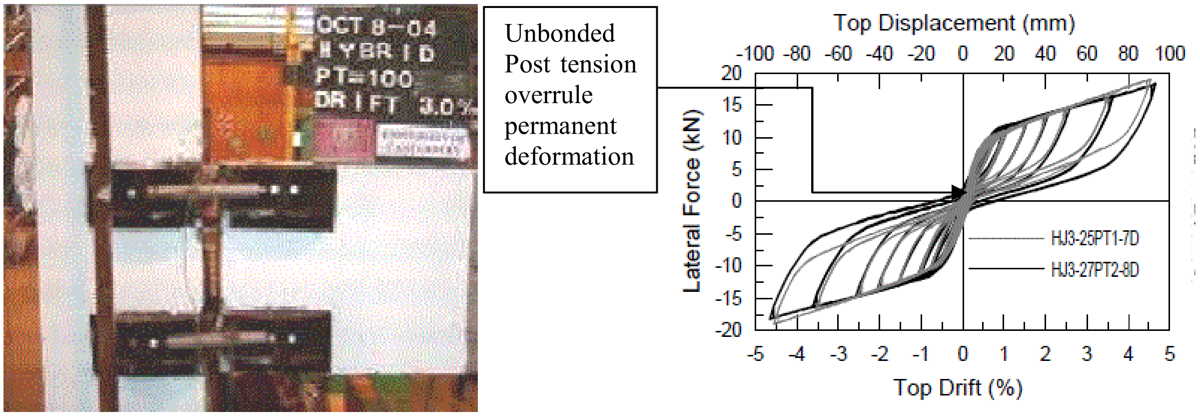
The difference in seismic response between high performance concept and the classical ductile design may be observed from the test results of beam-column joint. Fig. 4, shows the hysteresis loops and joint damage pattern of classical ductile design that meet the requirements of special moment resisting frame (SMRF) [19]. Hysteresis is described by reasonably "fat" loops that occur in all four quadrants. Inelastic response results from the development of plastic hinges, which exhibits structural damage and requires costly repairs. Moreover, such ductile system may experience residual deformations.


Permanent deformation increase each the increase of inelastic cycle

(a) (b)

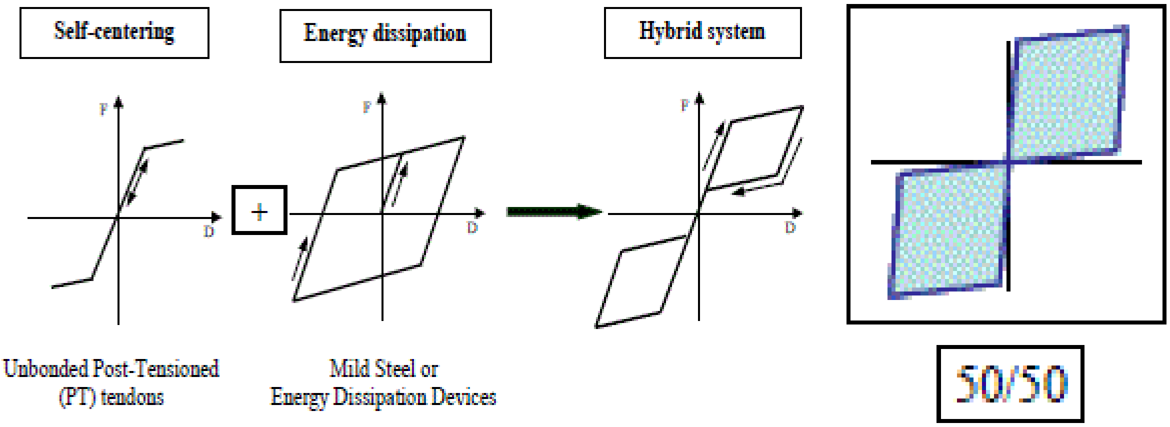
Fig. 4 – Classical ductile design behavior, 4(a) Speciment; 4(b) Hysteresis Loop

In a re-centering system, the hysteretic response is essentially described by loops that appear diagonally in two opposite quadrants, as depicted in Fig.5 [13].The beam-column joint in this figure exhibits re-centering effect due to the presence of an elastic unbonded post-tension tendon. This concept is also referred to as hybrid concept. The ratio of re-centering and ductile behavior will produce a spectrum hysteresis hybrid concept known as "flag shape" as seen in Fig. 6 [13]. ACI 550.3-13 [3] recommend prestressing force to be at least 50% of the load in order to conduct a re-centering remains effective.



(a) (b)

Fig. 5–High performance behaviour 5(a) speciment; 5(b) hysteresis loop



(a) (b) (c) (d)

Fig. 6– Hybrid behaviour ; 6(a) full post tension; 6(b) full ductile; 6(c) hybrid; 6(d) hybrid 50:50

3. Research, development and implementation in Indonesia

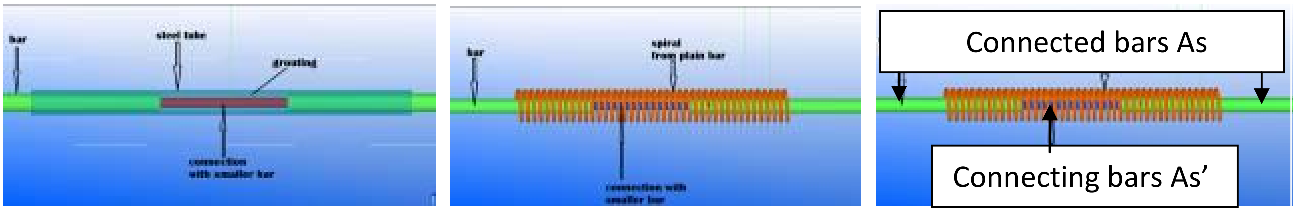
3.1 Local development in Indonesia

The development is based on technology and local materials that already exist. The concept of unbonded post tension is relatively well known, so that the material, equipment and construction methods is not difficult to be used as shown in Fig 7.

(a) (b) (c)

Fig. 7– Unbonded post tension, 6(a) strand; 6(b) stressing; 6(c) anchorage

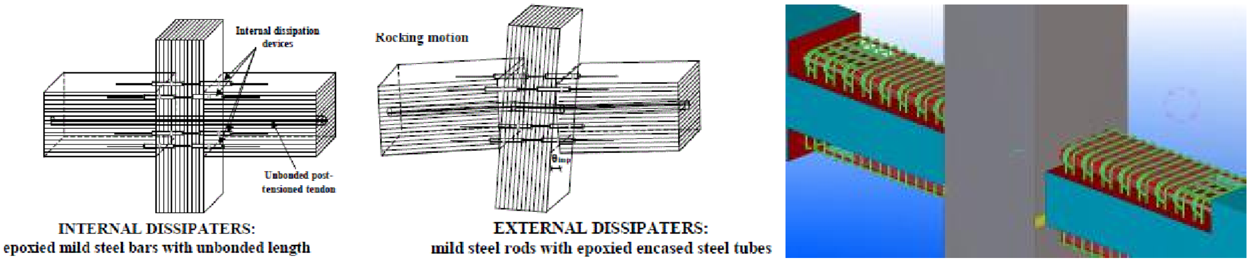
The common configuration of a dissipater device consists of the connection of a steel bar using a smaller bar confined within a metal tube sheet [13], as shown in Fig.8a. A local dissipater device was developed successfully in 2014, based on one of the Indonesian methods of connecting steel bars, with spiral reinforcements made from plain bars, as shown in Fig.8b. This spiral is equivalent to metal sheet tubes.



(a) (b) (c)

Fig. 8 –Dissipater configuration 8(a) common ;8(b) Indonesian;8 (c) Connection dan connected bars

Dissipater can be mounted externally or internally, as shown in Fig.9 [13]. The advantages of external dissipater is that it can be replaced if it was damaged, but consequently disturbing the outlook of the system. The development achieved in Indonesia is slipping this tool at the top and bottom of the beam, so it does not disturb the outlook, and still easily replaced if damaged.



(a) (b) (c)

Fig. 9–Dissipater location 9 (a) internal ; 9 (b) external; 9 (c) Indonesian development

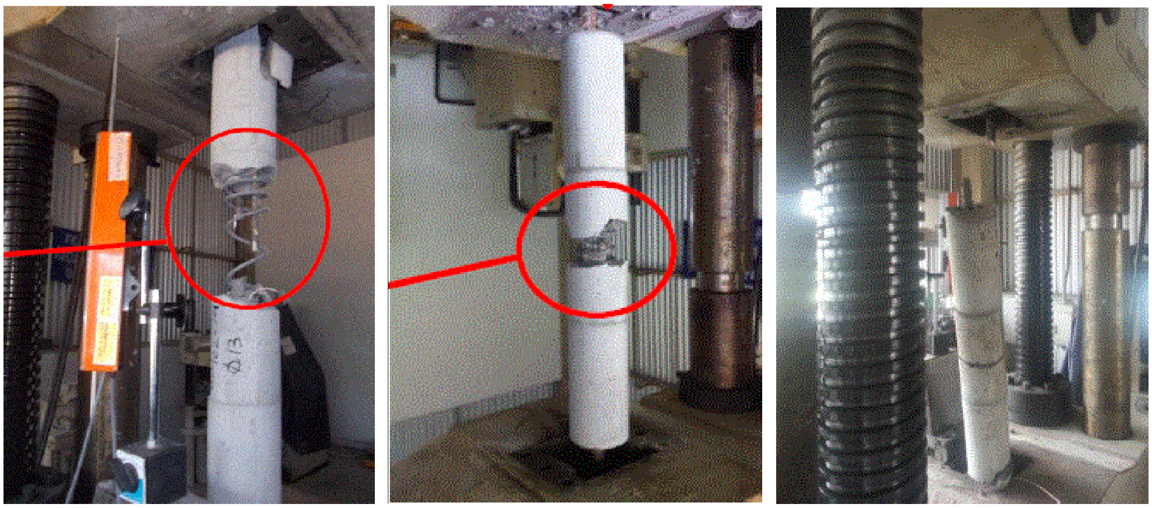
3.2 Dissipater test

Testing of dissipater development is carried out following ASTM E8 tensile testing procedures [6]. ACI 550.3-13 stated that the material must meet ASTM A706 Grade 60 [5]. The ratio of tensile strength to yield strength f_u/f_y is not less than 1.25, in accordance with Article 21.1.5.2 b ACI 318-08 [2]. It directs that the reinforcement ratio between connected bar to connection bar (As / As') must be between 1 - 1.25, so that yield occurs at connection bar, and the strain hardening phase will not overwhelm yield stress of connected bars. The testing performed in 3 ratios of As / As' as shown in Table 1.

Table 1 – Speciment data for dissipater test.

Type	Sample	Connected Bar As (mm2)	Connection Bar As' (mm2)
Dissipater (As/As' = 1.44)	1	380	264
Dissipater (As/As' = 1.14)	2	380	333
Strong Connection (As/As'=1.06)	3	380	402

The dissipater test results [14] physically can be seen in Fig.10, wherein the first 10 (a) and10 (b), yield occurs in connection bar. In Fig 10 (c), the yielding occurred at connected bars, because the third sample was designed as a strong connection.



(a) Dissipater As/As'=1.44 (b) Dissipater As/As'=1.14 (c) Strong connection As'/As = 1.06

Fig. 10– Dissipater test result

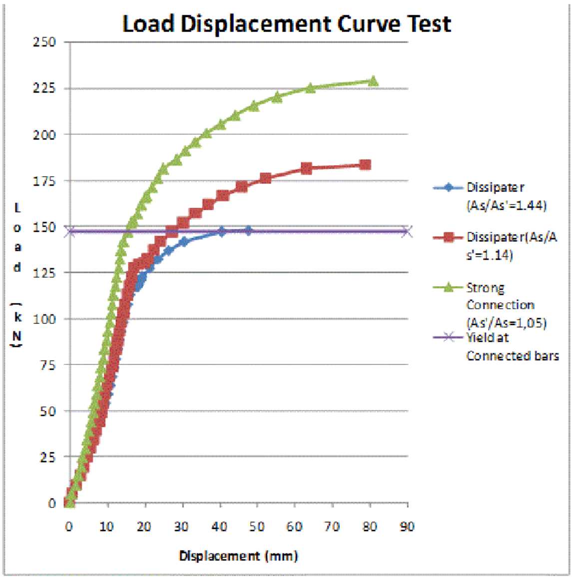


Fig. 11 – Dissipater test data

After knowing the behavior of dissipater in the tensile test, the bending test conducted on precast segmental hybrid beam connected by dissipater as shown in Fig.12. This test will confirm the ability of dissipater as damage locus in bending loads, both in the tensile and compression reinforcement. After tested, the dissipater is replaced, and then testing is carried again to see the performance of the structure after the repair. Testing was done by cyclic in one direction loading scheme, which was half the loading scheme stated in ACI 374-05 [1], up to a maximum drift ratio Δ = 3.5%. At first test, dissipater was mounted with the ratio of As/As '= 1.44, and then after repair, dissipater mounted with the ratio of As/ As' = 1.14

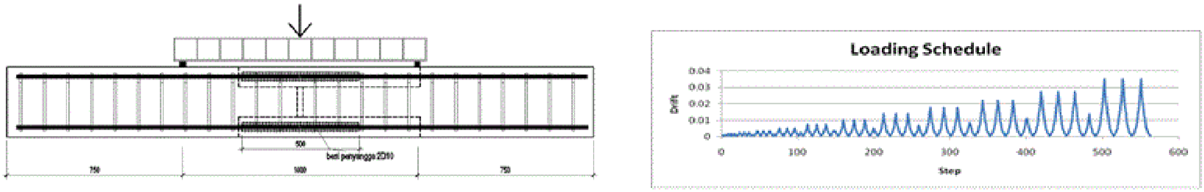


Fig. 12– Bending test of hybrid precast segmental beam dissipater connection

The results of first test (As / As' = 1.44) can be seen in Fig. 13. The first yield occurred in connection bar of dissipater, and then when entering strain hardening phase, the connected bar is still in elastic condition, so that the damage locus centralized in the connecting bar (not propagate into bending cracks elsewhere). The centralized physical damage then formed in a big gap, and flexural strength determined by the tensile strength of connector, and occured at Δ = 2.2%.

(a) (b) (c)

Fig. 13– Result of first test of precast segmental hybrid beam connected by dissipater (As/As'=1.44)

In addition to the damage in the gap position, there was no other damage to the sample, including in the compression area of dissipater. So repairs can be easily carried out in the connection area of dissipater, by replacing the first dissipater with a new one with the ratio of As/As' = 1.14 as shown in Fig.14.

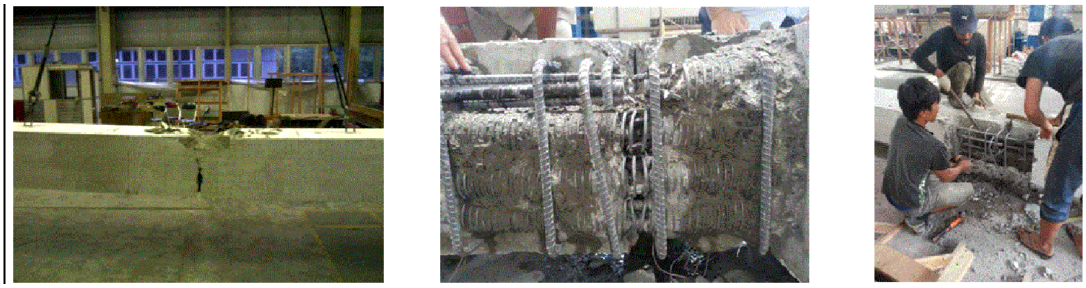


Fig. 14 – Repair of precast segmental hybrid beam and connected with new dissipater (As/As'=1.14)

The repaired precast segmental hybrid beam bending test results (As / As' = 1.14) can be seen in Fig. 15. The first yielding occurred in the connecting bar, which then form a large crack in that position. The next mechanism is different from the first test specimen, because the strain hardening of connecting bars lead the connected bar to enter strain hardening phase also. Additional flexural cracks began to form in different location from the location where first large crack formed. Collapse of the sample is characterized by the compression failure of the concrete on the ratio of drift over Δ = 3.5%

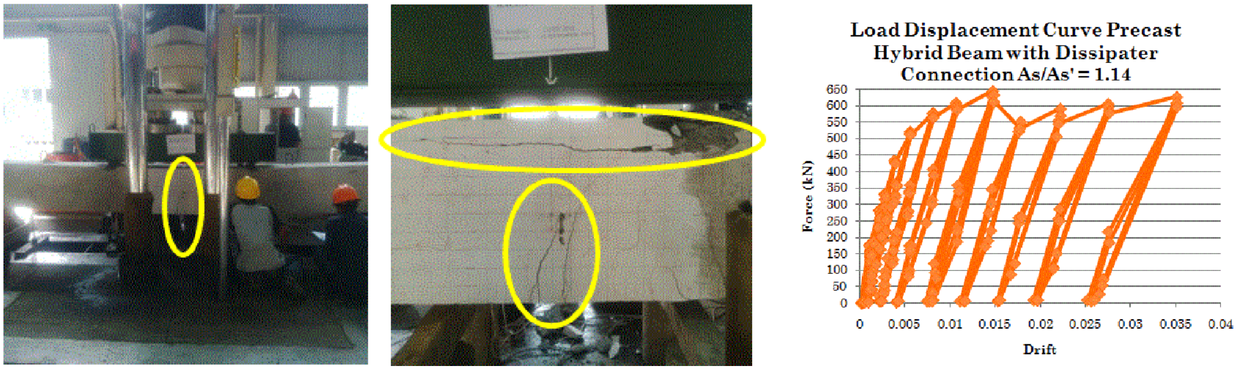
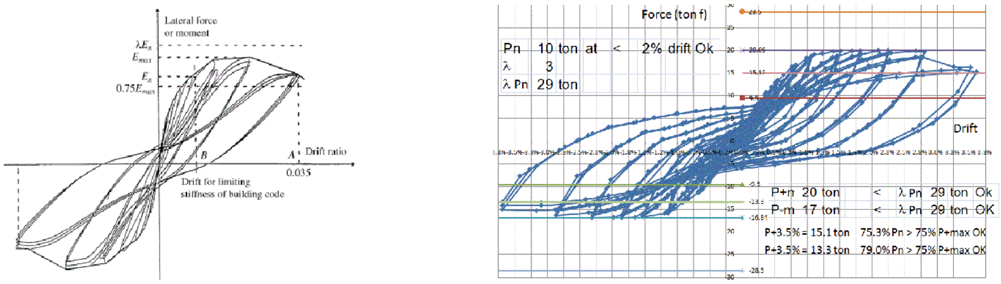


Fig. 15 – Testing result of repaired precast segmental hybrid beam and connected with new dissipater (As/As'=1.14)

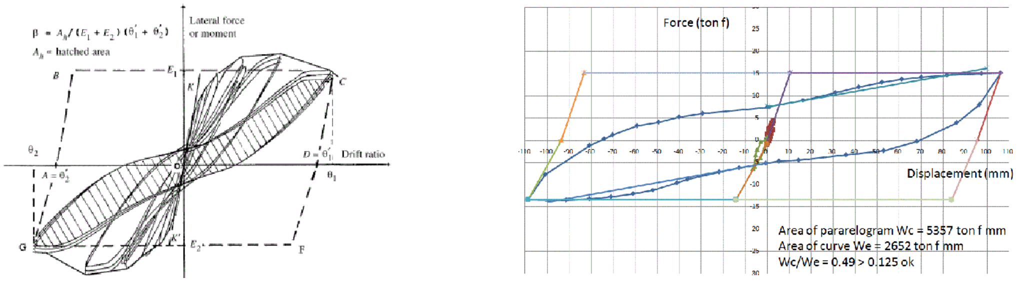
3.3 Beam Column Joint Testing

The beam-column joint testing was done after some preliminary testing phases. Reinforcement of hybrid beam made according to preliminary test sample with a moment capacity ratio of dissipater bar to the probable moment capacity (Ms / Mpr) approaching 0.5, in accordance with the recommendation of article 7.4.2 in ACI 550.3-13 [3]. Connected to connecting bar ratio was As / As' = 1.14. Joint and columns are designed in accordance with article 21.1.3, Article 21.6 and Article 21.7 of ACI 318-08 [2]. Loading scheme and acceptance test criteria are based on ACI 374-05 [1] as shown in Figure 15. In drift up to Δ = 3.5%, the specimen must meet three main criteria: strength, energy dissipation and rigidity in order to be categorized as Special Moment Resisting Frame (SMRF). Analysis of testing results [15] showed that the beam-column joint meets the criteria of ACI 374-05 [1] as shown in Fig. 17.

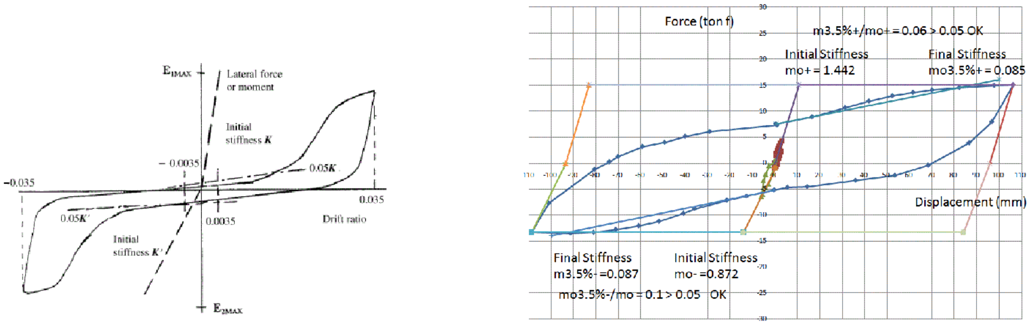
Fig. 16– Beam column join test



(a) Strength criteria



(b) Energy dissipation criteria

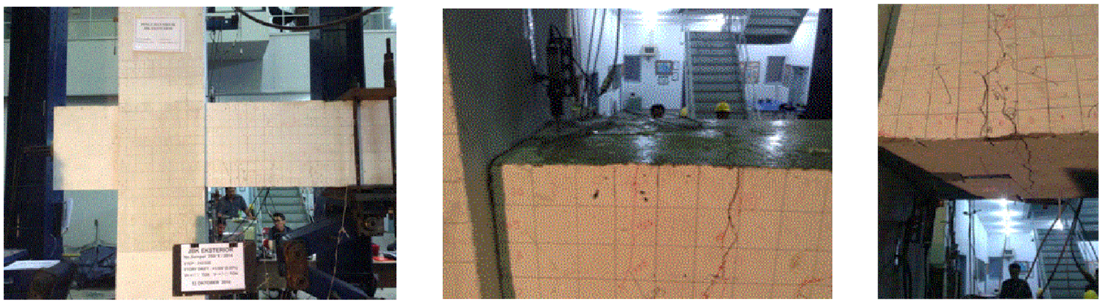


(c) Stiffness criteria

(d) Fig. 17– Beam column join test criteria check

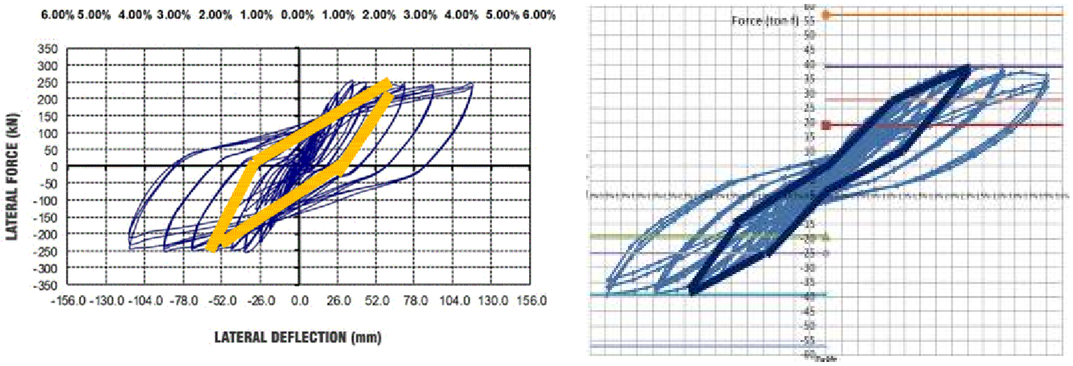
What is more interesting is the failure mechanisms of the test specimen and the performance level at each stage of the test, as shown in Fig. 18.

- On the serviceability limits, which refer to article 8.1.2 SNI 03-1726-2002 [7], where allowable floor drift (Δ) ranged of 0.03/ R, or about 0.35%, no damage in the speciment as shown in Fig. 18(a). This means that at the nominal base shear level (V), there will be no damage, even if the architecture component. The serviceability limit performance requirements are no longer in ASCE/SEI 7-10 [4].
- Yield on the connecting bar started at Δ = 1%, and began to cause a gap at Δ = 1.75%. This gap opens and closes during cyclic loading, which demonstrates the effectiveness of "re-centering" feature caused by unbonded post tensioned system, as shown in Fig. 18(b) and 18(c). The damage did not occur in other parts significantly until Δ = 2.2% , as shown in Fig. 18(d). Δ_a (allowable floor drift) on earthquake design (S_{DS}) as required in Table 12.2-1 ASCE/SEI 7-10 [4] is 2% for risk category I or II, So it demonstrates a proven high performance on the structural system's, which the building would return to the original position, with the damage was concentrated in the dissipater components. The retrofitting can be done by replacing dissipater components.
- On the next stage Δ = 2.2% ke 3.5%, strain hardening of connecting bar has already cause yield stage of connected bar. So the damage started to spread outside dissipater gap, and compression failure occured in concrete. Fig. 18(e) showed speciment condition at Δ = 3.5%, which the damage concentrated in the beam, and only hair crack occured in joint and column and did not propagate to compression diagonal failure. This demonstrated that the building was not collapse even in maximum consider earthquake (MCE_R), which is 2500 year earthquake.
- Testing continued until Δ = 5%, which indicated damage to remain centered on the beam as shown in Fig. 18(f), but the strength is already degraded and the condition of the buildings had been unable to return to its original position. Tests in very extreme conditions showed that this system can provide a guarantee that buildings still in near collapse performance.
- The comparison of hysteresis loop of hybrid system and ordinary reinforced concrete at ASCE/SEI 7-10 performance target (2.2%), can be seen in Fig. 18(g)
  - In reinforced concrete structure [19], one cycle starts in one direction accompanied by specific stiffness, loading to the peak load, and then unloading with unloading stiffness bigger than loading stiffness, causing permanent deformation. The hysteresis pattern is known as Takeda model
  - In hybrid structure, one cycle starts in one direction accompanied by specific stiffness loading. The stiffness is then degraded following the the yield on dissipater, and then reach the peak load. In unloading stage, the stiffness is relatively equal to degraded loading stiffness, causing smaller permanent deformation. The system recovers its initial position by post tension unbonded system. After permanent deformation diminishes, the loading is turned to opposite direction with loading stiffness rate equal to previous loading direction. This behavior close to flag shape pattern in proportion of 50 : 50.



(a) service limited Δ = 0,35%,equal V (b) gap in upper side Δ = 1.75% (c) gap in bottom side Δ = 1.75%

(d) Δ = 2.2% equal S_{DS} and Δ_a (e) Δ = 3.5% equal MCE_R (f) Δ = 5% equal near collapse



(g) (h)

Comparation of hysteresis pattern of RC joint (g) and hybrid joint at Δ = 2.2% (h)

Fig.18 –Failure mechanism and speciment performance at any stage

3.3 Application

The system was applied to a 12 – storey office building in Jakarta, as shown in Fig. 19, and to some multi story low cost housing in Jakarta, as shown in Fig. 20, High performance earthquake resistant precast system used in the columns, beams, and hollow core slab. The application proves resistant can reduce good quality construction with an easy, fast and economical.

Fig.19– Application in Twelves storey office building in Jakarta

Fig.20 – Application in multistory low cost housing in Jakarta

4. Conclusion

High performance earthquake resistant precast system is an alternative technology to follow the developments in the earthquake-resistant building design, that both seismic load and design philosophy have been changed as result of a series major earthquake in the last 20 years. The concept that underlying the current regulations for earthquake resistant buildings is known as the sustainability development concept. This technology is able to answer code requirement, as well as people demands: the structures are not significantly damaged even if exposed to a major earthquake, the initial investment cost are economical, easy to repair, an support equipment and material that can be produced locally.

Today the Indonesian precast and prestressed industry have completed the research, development tests, and implemented programs of high performance earthquake resistant precast systems for 3 years (2013-2015), so this technology may soon be used by all parties in supporting Indonesian development.

5. Acknowledgements

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6. Copyrights

7. References

[1] American Concrete Institute (2014), *ACI 374-05 Acceptance Criteria for Moment Frames Based on Structural Testing and Commentary*, Farmington Hills, USA, 8-9,

[2] American Concrete Institute (2008), *ACI 318-08 Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary*, Farmington Hills, US, 323-324,347-349,

[3] American Concrete Institute (2013), *ACI 550.3-13 Design Specification for Unbonded Post-Tensioned Precast Concrete Special Moment Frame Satisfying ACI 374.1 and Commentary*, Farmington Hills, USA, 11,19,20.

[4] American Society of Civil Engineers (2010), *ASCE/SEI 7-10 Minimum Design Loads for Buildings and Other Structures*, Virginia,USA,374,66,97

[5] American Standard of Testing Material (2014), *ASTM A706/A706M-14 Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement,* West Conshohocken,USA.

[6] American Standard of Testing Material (2009), *ASTM D : E8-09 Standard Test Methods for Tension Testing of Metallic Materials,* West Conshohocken,USA, 6-8,15-20.

[7] Badan Standard Nasional (BSN) Indonesia (2002), *SNI 03-1726-2002 Standar Perencanaan Ketahanan Gempa untuk Struktur Gedung,* Jakarta, Indonesia, 21,31

[8] Fleischman, R.B., Restrepo, J.I., Pampanin, S., Maffei, J.R., Seeber, K. and Zahn, F.A. (2014). Damage evaluations of precast concrete structures in the 2010-2011 Canterbury earthquake sequence. *Earthquake Spectra*, **30**(1),.277-306.

[9] Irsyam,M. ,I.W. Sengara (2010), Peta Zonasi Gempa*,Laporan,* Kementerian Pekerjaan Umum, 18,63,64.

[10] Nurjaman,H.N., L.Faisal, H.Sidjabat, B.Hariandja,Y.Put, R.Rivky (2014), Application of Precast System Buildings with using Connections of Unbonded Post-Tension and Local Dissipater Device*, Elsevier Procedia Engineering Journal*, **95**, 82-86.

[11] Nurjaman,H.N.,L.Faisal, H.R Sidjabat, B.Hariandja,R.Rivky, Y. Put (2014) , Research Development and Application of Precast Systems for Buildings, with Connections using Unbonded Post-Tension and Local Dissipater Device*, 6th International Conference of Asian Concrete Federation,* Seoul,Korea, 1045-1047.

[12] Pampanin,S.(2010), *PRESSS Design Handboook,* New Zealand Concrete Society,10-22,71-82.

[13] Pampanin,S (2012), Reality-check and Renewed challenges in Earthquake Engineering : Implementeing low-damaged structural System – from theory to practice*,15th World Conference of Earthquake Engineering,* Lisboa, Portugal,14-15, 24-27.

[14] Puslitbangkim (2014), Hasil Uji Benda Uji Dissipater Spircon*, Laporan,* Bandung, Indonesia.

[15] Puslitbangkim (2015), Uji Gempa Sistem Pracetak PRESSSINDO-WIKA BETON, *Laporan*, Bandung, Indonesia

[16] Rahman, A., and Restrepo, J. I. (2000). Earthquake resistant precast concrete buildings: Seismic performance of cantilever walls prestressed using unbonded tendons, *Research Rep. No. 2000*, University California at San Diego,USA

[17] Restrepo,J.I. (2014), PRESSS-Background, Research, and Development, Code and Application*, Prosiding Penyelenggaraan Sosialisasi dan Pameran Aplikasi SNI Pracetak dan Prategang pada Bangunan Gedung,* Puslitbangkim, Jakarta,Indonesia, 5,29-34.

[18] Schoettler, M.J., Belleri, A., Zhang, D., Restrepo, J.I. and Fleischman, R.B. (2009). Preliminary results of the shake-table testing for the development of a diaphragm seismic design methodology. *PCI Journal*, **54**(1),100.

[19] Yuwasdiki,S (2013), Prosedur Pendaftaran dan Penerimaan Sertifikasi Sistem Pracetak Beton di Puslitbang Permukiman Kementerian Pekerjaan Umum*, Prosiding Sosialisasi SNI Gempa dan Konstruksi Pracetak dan Prategang untuk Bangunan Gedung,* Puslitbangkim – IAPPI, Jakarta, Indonesia, 5-6.