Development of Numerical Model of a High Performance Precast Concrete System Equipped with Base Isolation

Nurjaman, Hari
Faculty of Civil Engineering Department, Universitas Persada Indonesia

Suwito, Suwito
Faculty of Construction Engineering and Management Department, Universitas Agung Podomoro

Dinariana, Dwi
Faculty of Civil Engineering Department, Universitas Persada Indonesia

Suprapto, Gambiro
Senior Research Engineer, PT Wijaya Karya Beton

他

https://doi.org/10.5109/4794186

出版情報：Evergreen. 9 (2), pp.547-555, 2022-06. 九州大学グリーンテクノロジー研究教育センター
バージョン：

Development of Numerical Model of a High Performance Precast Concrete System Equipped with Base Isolation

Hari Nurjaman[1], Suwito Suwito[2,*], Dwi Dinariana[1], Gambiro Suprapto[3], Bambang Budiono[4], Martinus Fau[5]

[1]Faculty of Civil Engineering Department, Universitas Persada Indonesia, Indonesia
[2]Faculty of Construction Engineering and Management Department, Universitas Agung Podomoro, Indonesia
[3]Senior Research Engineer, PT Wijaya Karya Beton, Tbk., Indonesia
[4]Faculty of Civil Engineering Department, Institut Teknologi Bandung, Indonesia
[5]Graduate School of Civil Engineering Department, Institut Teknologi Bandung, Indonesia

*Author to whom correspondence should be addressed:
E-mail: suwito@podomorouniversity.ac.id

(Received February 11, 2022; Revised June 20, 2022; accepted June 20, 2022).

Abstract: This study focuses on combining precast concrete system and base isolation technique that could lead to a high-performance seismic resistance structural system. Some previous experimental results on precast concrete modules are presented and discussed. Principles and numerical implementation of base isolation technique are described and presented in details. Analysis of life cycle cost that compares the conventional system and a system that combines precast concrete system and base isolation technique shows promising results. The result from this study is a structural system that has high seismic performance and cost efficiency for certain class of structures and site conditions.

Keywords: structural system; precast concrete; base isolation; seismic design; earthquake; LCC analysis

1. Introduction

Indonesia is located in a pacific ring of fire that has generated a lot of earthquake occurrences. Generally, these earthquakes damaged infrastructures and buildings, and thus caused loss of lives and disrupted the business activities. To restore normal activities after an earthquake, damaged infrastructures and buildings need to be repaired or rebuilt. Most of the time, the earthquake induced damages on buildings and other infrastructures are severe so that they are deemed too expensive to be repaired and thus must be demolished and rebuilt. This condition demands a new structural system that may lead to controlled structural damage when design-level earthquake occurred. In this study, a structural system that combines the use of precast concrete system and base isolation is proposed. This is inline with worldwide movement on sustainable development in various sectors, including in services sector[1)].

Concrete is a major construction material normally used in Indonesia because all of its components are available in Indonesia. Unfortunately, concrete also has been known to be one of major contributors to the carbon dioxide being emitted into the atmosphere[2)]. As such, there is a need to develop construction technology that produces less carbon dioxide[3)]. In general, there are two types of concrete technologies that can be used to construct frame structures these days, i.e., conventional and precast concrete. Up to now, conventional concrete technology is still the one that is mainly used in the construction industry in Indonesia even though it is an older technology that is considered less efficient and difficult to achieve a standard quality. On the other hand, a precast concrete technology offers construction industry with a better construction technology in terms of efficiency, durability and quality[4)]. In addition, the precast structural system has been used successfully to in resisting earthquake load[5)]. Another study on performance of precast concrete floor systems during earthquake showed an overall good performance[6)]. Also studies on precast concrete structures during October 2011 Van earthquake, Turkey[7)] and the L'Aquila earthquake[8)] had shown good structural performance. The precast concrete technology has also been implemented in the construction of buildings in Indonesia.

During several occurrences of design-level earthquakes or higher such as Palu earthquake that took place in 2018 and Mamuju earthquake in 2021 (Fig. 1) the impacted buildings constructed using precast concrete technology satisfy performance level requirement of collapse prevention (buildings suffered heavy damage but not collapse). The traditional seismic design philosophy (capacity design concept) allowing those damages to take place in certain locations in building structures needs to be improved to minimize the disruption of building use.

The urgency of this research is the need to develop high seismic performance structural system to anticipate accelerated infrastructure development through direct investment initiated by government. This massive direct investment is needed to stimulate Indonesia's economic growth. Direct investment requires supports in the form of buildings and infrastructures such as elevated road. These facilities should have capability to achieve high seismic performance level so that they can still function when the design-level earthquake takes place and thus no disruption to business activities. Figures 2 and 3 show some example precast concrete buildings designed to obtain structures with high seismic performance.

(a)

(b)

Fig. 1: Building affected by the Mamuju earthquake: (a) PUPR Office of Mamuju; (b) Korem housing flat.

Even though a precast concrete system offers a lot of advantages in terms, it still poses difficulty in the connection detail both in design and installation. Thus, in this study, the proposed technology is in the form of precast and prestressed concrete that is combined with base isolation. Precast concrete element can be produced with faster rate, better quality control, more efficient, more economic, larger quantity and is considered as green construction. Prestressed technology is a construction technology that can be used to connect precast concrete elements so that they have seismic performance level higher than those connected using other technologies. At high-rise building, the prestressed connection can be used to connect beam to column and between vertical walls. And finally, the base isolation technology can be used to reduced seismic load received by building structures so that the detail connection between precast concrete elements can be made simpler.

Finished building

Construction phase of building

Fig. 2: The Hive office in Jakarta, Indonesia: an example of high seismic performance building made of precast concrete structural system.

Numerical technique is a computation tool that can be employed in science and engineering to obtain better performance of materials and structures[9]. Studies in the precast concrete system, in addition to using experimental work, also use numerical methods. Experimental and numerical investigations of beam-column connections were conducted by Yekrangnia et al.[10], Cai et al.[11] and Korkmaz and Tankut[12] to obtain innovative connection systems that will perform well during earthquake. Meanwhile, Nguyen and Hong[13] conducted a numerical study on column precast connection systems using mechanical connections and Lu et al.[14] developed innovative joint to connect beam to shear wall. In addition to the studies conducted on the element level, Celik and Gülkan[15] carried out the numerical study on dynamic behavior of precast concrete system on structural frame level. Along this line, the focus of study is to utilize the numerical method to analyze and design the precast concrete system equipped with base isolation, from element level to structural frame level.

2. Experimental work on precast concrete system

Experimental work on precast concrete system has been actively conducted worldwide. For example, Xue at al.[16] conducted experimental work on seismic behavior of precast concrete beam-column connections. Meanwhile, Lu and Wu[17] studied on seismic performance of prestressed precast concrete walls through cyclic lateral loading test.

In Indonesia, there have been many research, developments and implementations of high-performance precast concrete and precast prestressed concrete systems using prescriptive design concept. All of those components used in precast concrete and precast prestressed concrete systems have been able to be produced locally in Indonesia.

Design codes suitable for precast prestressed concrete system subjected to earthquake load are SNI 1726:2019[18] or ASCE/SEI 7-16[19] and SNI 2847:2019[20] or ACI 318-14[21]. These codes give room for a progressive innovative design especially for precast prestressed system that is combined with base isolation to produce a structural system that has an excellent seismic performance and is economically efficient. The use of a combination of base isolation and precast prestressed system in a high seismic zone is expected to result in less detailing requirement at connection and thus reduces the complexity and also cost.

Finished building

Construction phase of building

Fig. 3: The Presidential Security Force Housing Flat in Jakarta, Indonesia: an example of high seismic performance building made of precast concrete structural system.

Before being implemented, a proposed structural precast frame system must be validated by means of testing conducted according to SNI 7834:2012[22] which mostly adopted provisions from ACI 374.1-05[23]. The test modules must be prepared to represent each characteristic configuration of intersecting beams and columns in the moment frame. Both interior and exterior joints of the proposed precast frame system must satisfy the acceptance criteria stated in SNI 7834:2012[22] so that the frame can be classified as special moment frame system. The test is carried out using displacement control in terms of sequence of drift ratios. For a certain drift ratio, three full cycles of drift ratio must be conducted. For a special moment frame, the test must be continued until minimum drift ratio of 0.035 is achieved. Figure 4 shows the configuration and details of precast test module of a special moment frame and Fig. 5 its hysteresis results.

Other precast test modules that have been tested are the use of unbounded post-tensioned tendons to connect precast beam-column elements. The test modules were prepared according to ACI 550.3-13[24]. This connection system has the recentering capability. Figure 6 (a) and (b) show test results for beam-column joint test module using 50% and 75% post-tensioned tendons, respectively.

Hysteresis loop flag shape in test results describe recentering high performance precast system. The test results also show that the higher amount of post-tensioned tendon, the higher recentering capability. With 50% of post-tensioned tendon, the recentering effect is still effective up to Design Basis Earthquake (DBE) level or drift of 2.2%. Meanwhile with 75% of post-tensioned tendon, the recentering is still effective up to Maximum Considered Earthquake (MCE) level or drift of 3.5%.

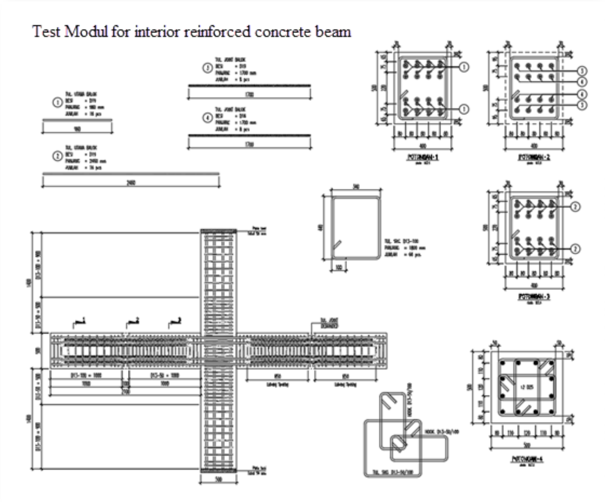


Fig. 4: Precast beam-column joint test module of special moment frame (Drift > 3.5%).

3. Numerical analysis on testing module

In this study, numerical analysis of testing module was also carried out to verify the testing results. First, moment-curvature relationship of cross-section of a testing model was developed. The moment-curvature was then used in the nonlinear structural analysis of the testing model. An example of numerical analysis of a testing module is discussed in this section. Figure 7 show the flowchart for conducting this study.

Figure 8(a) shows the setup configuration of a testing module of four-point flexural test and Fig 8(b) shows the picture taken during the test. The test result of load-deflection curve of the beam module is shown in Fig. 9. The numerical analysis is to be used to develop material and structural model that can simulate the test module in terms of load-deflection curve. Once the numerical analysis can produce the load-deflection curve similar to that of test module, the developed material dan structural model can then be used to analyze frame structures.

The numerical analysis results of beam model in the forms of stress contour and load-deflection curve are shown in Fig. 10 and Fig. 11, respectively. Comparing load-deflection curves from test result and numerical analysis result in Fig. 11, one can say that they are close. Therefore, the numerical analysis strategy developed in study can be used for evaluating frame structure.

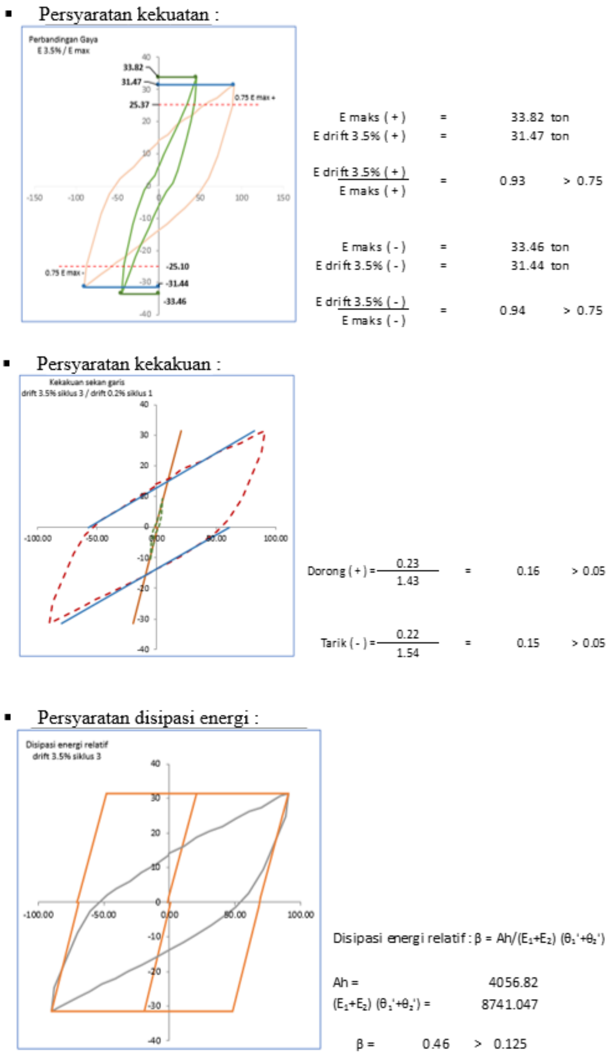
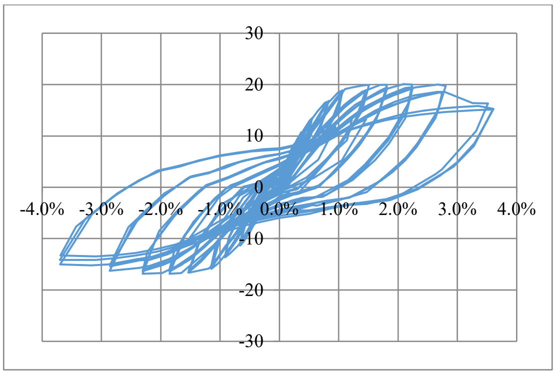


Fig. 5: Hysteresis results of beam-column joint test module of special moment frame.

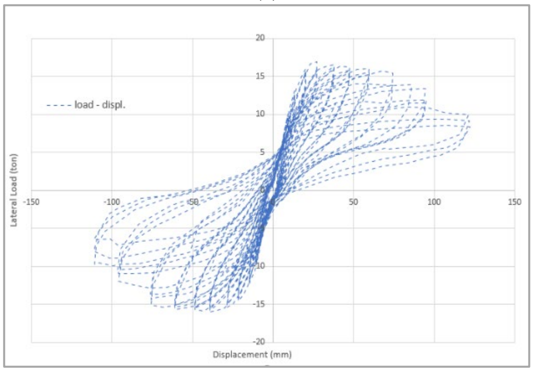
4. Base isolation

In general, seismic energy dissipation technologies can be categorized into three types, namely active control, semi-active control and passive control methods. Base isolation is a technique that can be used to reduce earthquake load received by structures and is classified as passive control methods. By installing seismic devices (isolators) on structures, one can increase the period and damping of building structures, and thus reduces the earthquake demand on structures. As illustrated in Fig. 12, the use of base isolation technology on a structure that has relatively short period (T_{fixed}) results in reduced design base shear due to the increase of structure's period ($T_{isolated} = 3\times T_{fixed}$) and damping (βiso > 5%, normally use damping ratio in fixed base system). conducting this study.

It should be noted though that the above perspective only valid for a site with the response spectrum pattern as shown in Fig. 8 in which it rapidly reaches a peak seismic acceleration and then gradually drops to low seismic acceleration. For a site with response spectrum pattern where the seismic acceleration increases gradually until it reaches the peak value as illustrated by Fig. 13 (an example of response spectrum for Mexico City located on a thick layer of clay sedimentation, the use of base isolation technique will not be effective and in this case increase the design base shear.



(a)



(b)

Fig. 6: Hysteresis result beam-column joint testing with: (a) 50% post-tensioned tendon and (b) 75% post-tensioned tendon.

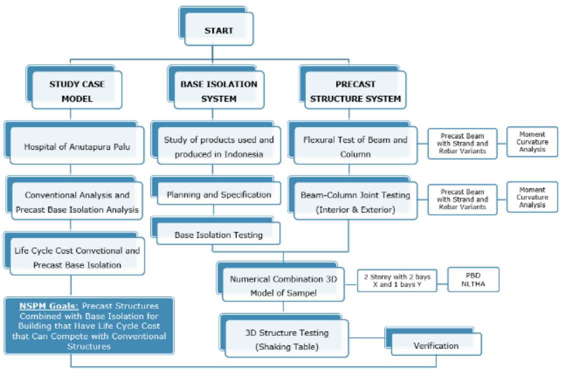
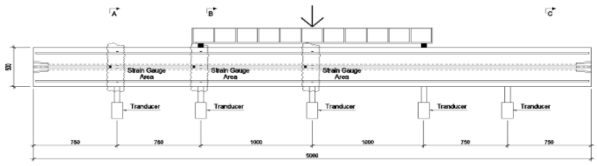


Fig. 7: Flow chart of research of precast system combined with base isolation.



(a)

(b)

Fig. 8: (a) Setup configuration for a four-point flexural beam test module and (b) Picture of the module during the test.

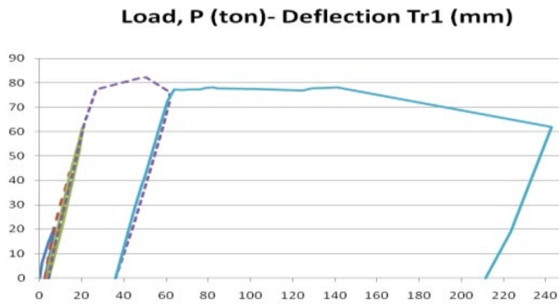


Fig. 9: Load-deflection curve of beam test module.

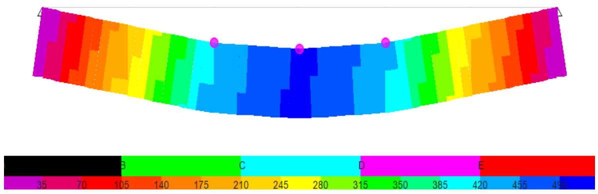


Fig. 10: Stress contour from numerical analysis.

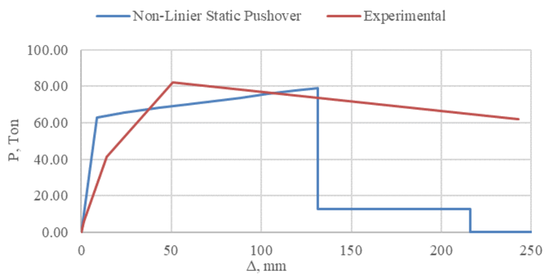


Fig. 11: Comparison between load-deflection curve from numerical analysis and result test.

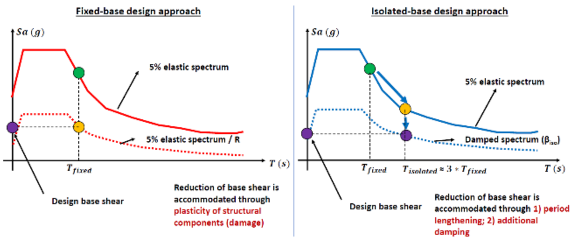


Fig. 12: Comparison of fixed-base and isolated-base design from spectrum perspective.

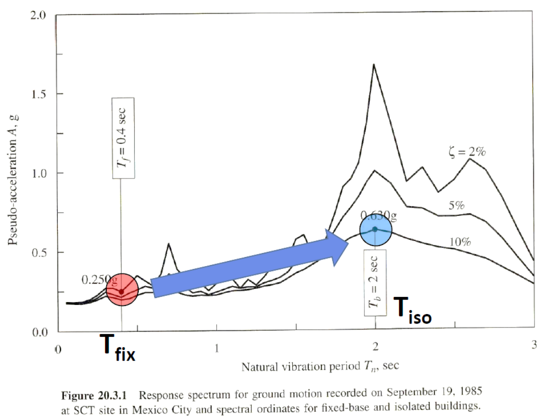


Fig. 13: Comparison of fixed-base and isolated-base design from spectrum perspective.

Based on the above discussion, it is clear that base isolation technique can only be effective on certain types of buildings and site conditions. In addition, the implementation of base isolation technique on structures that have relatively long periods will not be effective as increasing the period of the structure will result in only small decrease in seismic demand. Moreover, to achieve a long period of structure, one needs to use large size of base isolators, which is impractical. An effective range of periods in base isolation technique can be effective is shown in Fig. 14.

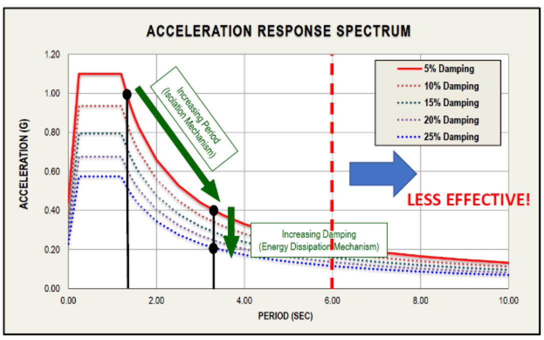


Fig. 14: Comparison of fixed-base and isolated-base design from spectrum perspective.

In general, there are three types of base isolators that are normally used to improve seismic performance of structures, namely High Damping Rubber Bearing (HDRB), Lead Rubber Bearing (LRB) and Friction Pendulum System (FPS) with each characteristic of them shown in Fig. 15. In HDRB uses high damping rubber and thus requires no separate damper. In addition, HDRB has smooth hysteresis curves which means that the response on the seismic isolated building will be smooth and therefore good for buildings containing precision equipment. Meanwhile, LRB is formed by embedding a lead plug in the middle of rubber bearing. The main function of lead plug is to provide damping capability. LRB can also be used without the need of separate damper. The last one, Pendulum system isolator is based on the application of a special sliding material, which has controlled friction. The damping capability of pendulum system is provided by the friction coefficient of the sliding surface.

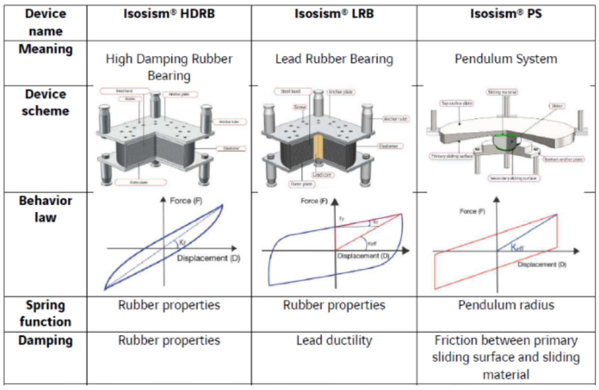


Fig. 15: Comparison of three base isolators (Source: Freyssinet's Product Brochure).

Even though there are many potential advantages offered by base isolation technique, this technology is still not widely used in Indonesia. One of the reasons is that any building owners still consider this technology is expensive.

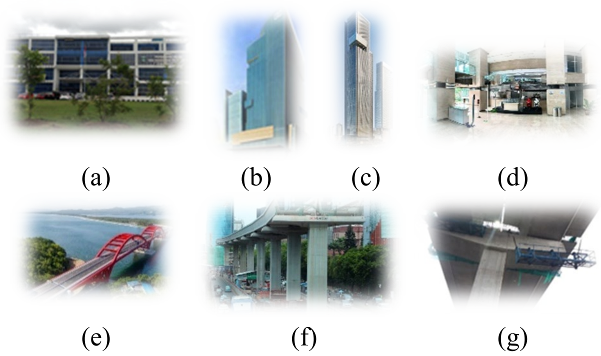


Fig. 16: Implementation examples of base isolation in Indonesia: (a) Office of PUPR Padang (2010); (b) Gudang Garam Office (2013); (c) Thamrin Nine (2020); (d) Office of Wijaya Karya (2018); (e) Holtekamp Bridge (2020); (f) LRT Jabodetabek (2019); (g) Pettarani toll road (2021).

Another issue is the lack of real performance examples of base isolated buildings and bridges experiencing large earthquakes. Nevertheless, at present, base isolation technology has been implemented on several projects in Indonesia, both in building and bridges, as shown in Fig. 16.

A study conducted by Budiono and Setiawan[25)] shows that isolated structures have "elastic" performance level under DBE and "immediate occupancy" level under MCE as shown in Fig. 17. Structures using base isolation technique have higher level of seismic performance compared to those of conventional structures. This shows the potential advantage of implementing base isolation technique in high seismic zone areas.

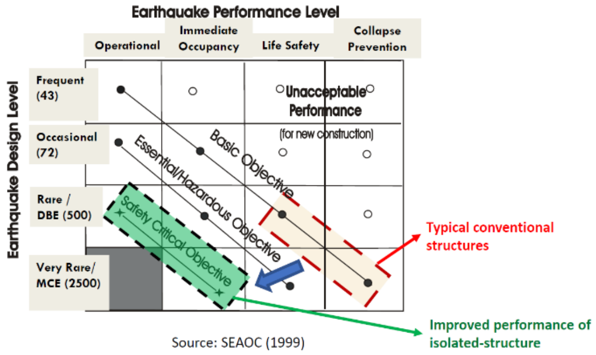


Fig. 17: Seismic performance objective with base isolation system.

Figure 18 shows the 25-story building model located on site with SDC D that will be used as an example of base isolation implementation. When the building model supported by fixed base is analyzed, the resulting fundamental period is of 2.8 second. On the other hand, when the building model decoupled from fixed base support by inserting base isolators (as shown in Fig. 19) is analyzed, the fundamental period of the building is of 4.52 second. The result shows the effectiveness of base isolation in lengthening the period of the building under consideration. The shift in the period of building leads to significantly reduced base shear and drift of the structure as shown in Fig. 20. Finally, the performance of base isolation technique on the example building is indicated by significant improvement on target performance in terms of roof absolute acceleration and comfort level at MCE as depicted by Fig. 21.

Precast concrete system offers excellent field performance but oftentimes needs complex connection systems, while base isolation technique offers reduction of seismic demand. Thus, combining them and using seismic performance-based design result in precast structures that are less demanding on their connections, and thus can be constructed simpler. The steps shown in the flowchart in Fig. 7 require test verification both at the material and structural level of precast system combined with base isolation.

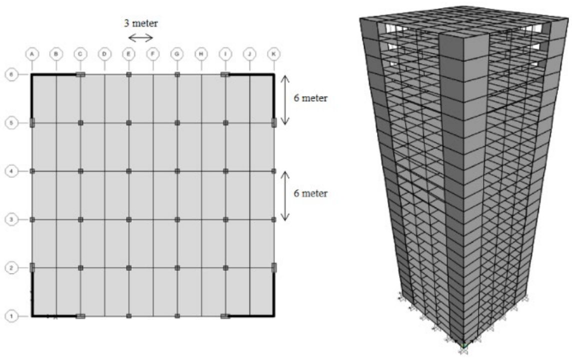


Fig. 18: Example building for study base isolation.

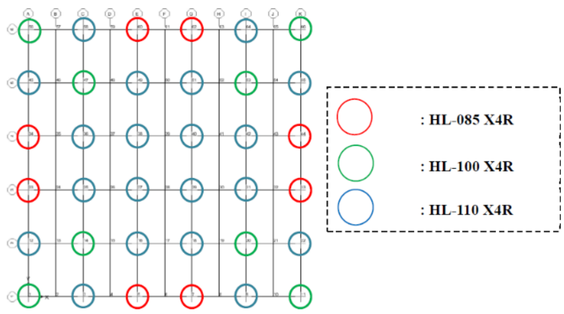


Fig. 19: Layout of HDRB for example building.

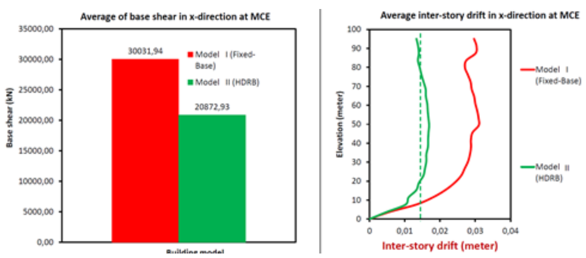
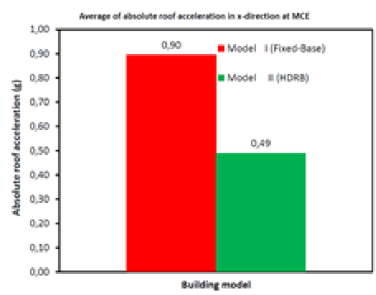


Fig. 20: Base shear and inter-story drift at MCE.



	ACCEPTANCE CRITERIA			
	Physiological vibration effects	*Frequency dependence of the human perception of vibration accelerations*	*KB Intensity Variable from DIN 4150, Part 2 (1975)*	*SUMMARY*
Model I	*UNPLEASANT*	*ABOVE UNPLEASANT THRESHOLD*	*NOT ACCEPTABLE*	Rank 3 (LESS COMFORT)
Model II (HDRB)	*ANNOYING*	*BELOW UNPLEASANT THRESHOLD*	*ACCEPTABLE*	Rank 1 (MORE COMFORT)

Fig. 21: Roof Absolute Acceleration & Comfort Level at MCE.

5. Life cycle cost analysis

In The Life Cycle Cost (LCC) analysis, cost comparison is made between the conventional system and the combination of precast with base isolation system based on building service life plan of 50 years. The earthquake occurrence once during the life of the building (50 years) with a simulation if the earthquake events taken place in the 5th, 10th, 15th, 20th, 25th, 30th, 35th, 40th or 45th year. The investment cost for a precast system with base isolation is 103% of the investment cost for a conventional system. The cost of repairing damage in the event of an earthquake for a conventional system is 35% of the investment cost, while the cost of repairing for a combination of precast system with base isolation is only the cost for replacing the base isolators for each earthquake event, which is about 5% of the investment cost. For operational and maintenance costs in concrete buildings is 0% and the amount of interest, i = 8%.

The comparison of LCC value between the conventional system and the combination of the precast with base isolation system is shown in Fig. 22. From the comparison, it can be seen that when the occurrence of earthquake event affects the deviation of LCC values between the two systems. The earlier the earthquake event takes place, the greater the LCC deviation/efficiency value in the two systems. This means that the use of a combination of precast with base isolation will be very profitable or efficient if an earthquake event occurs at the beginning of the life cycle. The LCC deviation value will approach 0 (zero) if the earthquake occurs at about 30th year. Moreover, if the earthquake occurs after 30th year toward the end life of the building (50 years), the deviation value or efficiency was negative, which means that the LCC value for combination of precast with base isolation system is greater than that of the conventional system as shown in Figs. 22 and 23.

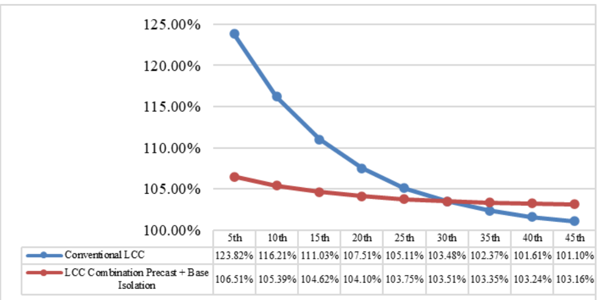


Fig. 22: Conventional LCC and combination of precast and base isolation LCC based on occurrence of earthquake event.

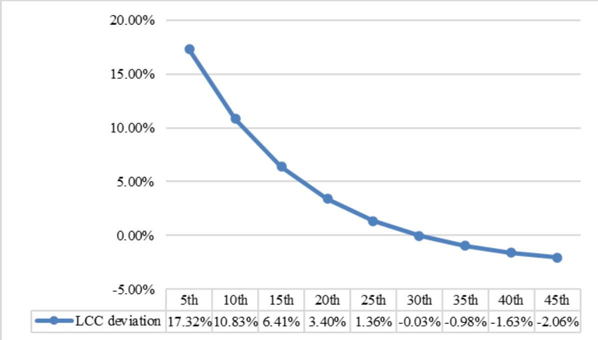


Fig. 23: The difference between conventional and combination of precast with base isolation LCC based on occurrence of earthquake events.

6. Conclusion

The new Indonesian design codes of SNI 1726:2019 and SNI 2847:2019 related to seismic and concrete design, respectively, allow the use of innovative design in addition to the traditional prescriptive design. To take advantage of the alternative way of designing building structures, "link and match" among stakeholders need to be established so that the public will have an alternative design and construction technology that is suitable for geologic condition of Indonesia where most of its regions located on high seismic zone. The technology should have high seismic performance, competitive cost from life cycle cost perspective and be able to be produced locally in the country.

The proposed technology uses a combination of precast concrete system and base isolation technique to produce high performance seismic resisting system that is economically efficient. Precast concrete system offers excellent field performance but oftentimes needs complex connection systems, while base isolation technique offers reduction of seismic demand. Thus, combining them and using seismic performance-based design result in precast concrete structural system that are less demanding on their connections, and thus can be constructed simpler.

The proposed structural system shows promising results from standpoint of structural response and LCC analysis. From design perspective, the seismic load demand becomes significantly lower. Meanwhile, from LCC analysis, the system shows economically competitive as an earthquake taken place before 30 years of building age. Obviously, the system needs to be studied and developed further so that it can be implemented safely in real design and construction.

Acknowledgements

Financial support from Ministry of Research, Technology and Higher Education of the Republic of Indonesia is highly appreciated.

References

1) S.R. Hamid, C.B. Cheong, A. Shamsuddin, N.R. Masrom and N.A. Mazlan, "Sustainable development practices in Services Sector: A case of the Palace Hotel from Malaysia," *Evergreen* **8**(4) 693-705 (2021). https://doi.org/10.5109/4742113
2) M.I. Sabtu, H. Hishamuddin, S. Nizaroyani, and M.N.A. Rahman, "A review of environmental assessment and carbon management for integrated supply chain models," *Evergreen* **8**(3) 628-641 (2021). https://doi.org/10.5109/4491655
3) K.T. Zingreu, X. Yang, and M.P. Wan, "Performance analysis of cool roof, green roof and thermal insulation on a concrete flat roof in tropical climate," *Evergreen* **2**(2) 34-43 (2015). https://doi.org/10.5109/1544078
4) Y.C. Kurama, S. Sritharan, R.B. Fleischman, J.I. Restrepo, R.S. Henry, N.M. Cleland, S.K. Ghosh and P. Bonelli, "Seismic-resistant precast concrete structures: state of the art," *J. Struct. Eng.* **144**(4) 1-18 (2018). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001972
5) S. Pampanin, W.Y. Kam, G. Haverland and S. Gardiner, "Expectation meets reality: Seismic performance of a post-tensioned precast concrete building (PRESSS technology) during the 22nd Feb 2011 Christchurch Earthquake," in *New Zealand Concrete Industry Conf.*, New Zealand Concrete Society, Auckland, New Zealand (2011).
6) S.B. Corney, R.S. Henry and J.M. Ingham, "Performance of precast concrete floor systems during the 2010/2011 Canterbury earthquake series," *Mag. Concr. Res.*, **66**(11) 563-575 (2014). http://dx.doi.org/10.1680/macr.13.00106
7) S. Ozden, E. akpinar, H. Erdogan and H.M. Atalay, "Performance of precast concrete structures in October 2011 Van earthquake, Turkey," *Mag. Concr. Res.*, **66**(11) 543-552 (2014). http://dx.doi.org/10.1680/macr.13.00097
8) G. Toniolo and A. Colombo, "Precast concrete structures: the lessons learned from the L'Aquila earthquake," *Struct. Concr.*, **13**(2) 73-83 (2012).
9) A. Kumar, A.K. Chanda and S. Angra, "Numerical modelling of a composite sandwich structure having non metallic honeycomb core," *Evergreen* **8**(4) 759-767 (2021). https://doi.org/10.5109/4742119
10) M. Yekrangnia, A. Taheri and A. S.M. Zahrai, "Experimental and numerical evaluation of proposed precast concrete connections," *Struct. Concr.*, **17**(6) 959-971 (2016).
11) X. Cai, Z. Pan, Y. Zhu, N. Gong and Y. Wang, "Experimental and numerical investigations of self-centering post-tensioned precast beam-to-column connections with steel top and seat angles," *Eng. Struct.*, **226** 111397 (2021). https://doi.org/10.1016/j.engstruct.2020.111397
12) H.H. Korkmaz and T. Tankut, "Performance of a precast concrete beam-to-beam connection subject to reversed cyclic loading," *Eng. Struct.*, **27** 1392-1407 (2005).
13) D.H. Nguyen and W.K. Hong, "Nonlinear finite element analysis of mechanical connections splicing precast columns with stiffened laminated metal plates," *J. Asian Archit. Build. Eng.*, **9**(6) 670-699 (2020).
14) X. Lu, L. Wang, D. Wang and H. Jiang, "An innovative joint connecting beam for precast concrete shear wall structures," *Struct. Concr.*, **17**(6) 972-986 (2016).
15) O.C. Celik and H.P. Gülkan, "System identification for a six-storey precast concrete frame building," *Mag. Concr. Res.*, **73**(10) 527-539 (2021).
16) W. Xue, H. Bai, L. Dai, X. Hu and M. Dubec, "Seismic behavior of precast concrete beam-column connections with bolt connectors in columns," *Struct. Concr.* , **22**(3) 1297-1314 (2021).
17) X. Lu and H. Wu, "Study on seismic performance of prestressed precast concrete walls through cyclic lateral loading test," *Mag. Concr. Res.*, **69**(17) 878-891 (2017).
18) SNI (Standar Nasional Indonesia), SNI 1726:2019, "Tata cara perencanaan ketahanan gempa untuk struktur bangunan gedung dan non gedung," BSN, Jakarta, Indonesia, 2019.
19) ASCE (American Society of Civil Engineers) ASCE/SEI 7-16, "Minimum Design Loads for Buildings and Other Structures," Virginia, USA, 2010.
20) SNI (Standar Nasional Indonesia), SNI 2847:2019, "Persyaratan Beton Struktural Untuk Bangunan Gedung," BSN, Jakarta, Indonesia, 2019.
21) ACI (American Concrete Institute), ACI 318-14, "Building Code Requirements for Structural Concrete and Commentary (Farmington Hills, MI, 2008), pp 323-324,347-349.
22) SNI (Standar Nasional Indonesia), SNI 7834:2012, "Metode Uji dan Kriteria Penerimaan Sistem Struktur Rangka Pemikul Momen Beton Bertulang Pracetak untuk Bangunan Gedung, " BSN, Jakarta, Indonesia, 2012.
23) ACI (American Concrete Institute), ACI 374.1-05, "Acceptance criteria for moment frames based on structural testing and commentary," Farmington Hills, MI, 2005, reapproved 2014.
24) ACI (American Concrete Institute), ACI 550.3-13, "Design Specification for Unbonded Post- Tensioned Precast Concrete Special Moment Frame Satisfying ACI 374.1 and Commentary," Farmington Hills, MI, USA, 2013.
25) B. Budiono and A. Setiawan, "Studi komparasi sistem isolasi dasar High-Damping Rubber Bearing dan friction pendulum system pada bangunan beton bertulang," *J. Teknik Sipil*, **21**(3) 179-195 (2014).