International Journal of GEOMATE, June 2023, Vol. 24, Issue 106, pp.85-92
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.106.s8611
Geotechnique, Construction Materials and Environment

PUSHOVER ANALYSIS OF RC FRAMES WITH SUBSTANDARD BEAM-COLUMN JOINTS

*Zaidir[1] and Syafri Wardi[2]

[1]Faculty of Engineering, Andalas University, Indonesia; [2]Faculty of Engineering, Padang Institute of Technology, Indonesia

*Corresponding Author, Received: 07 May 2022, Revised: 05 Jan. 2023, Accepted: 19 March 2023

ABSTRACT: Recent earthquakes in developing countries showed that the failure of substandard beam-column joints often contributes to heavy damage or collapse of reinforced concrete (RC) buildings. Static nonlinear pushover analysis is one of the methods to evaluate the seismic capacity of RC frames/buildings. However, the pushover analysis commonly neglects the failure at beam-column joints because of the complex behavior. In this study, a nonlinear pushover analysis procedure considering the failure of exterior beam-column joints without shear reinforcement is presented. Specifically, the performance limit is assumed as a point at the failure of beam-column joints from the literature of experimental study and a simplified backbone of joint shear stress-strain response. The proposed analysis procedure was applied to one RC frame with substandard beam-column joints representing a collapsed building due to a recent earthquake in Indonesia. The proposed analysis procedure was applicable to estimate the seismic capacity of RC frames considering the failure of exterior beam-column joints.

Keywords: Beam-column joint failure, Plastic hinge, Reinforced concrete, Seismic capacity evaluation

1. INTRODUCTION

The beam-column joints that do not satisfy the requirements of the standard for seismic detailing often caused severe damage or collapse of RC buildings, as observed in recent earthquakes in developing countries [1]–[3]. Figure 1 shows a collapsed RC building with failure on the beam-column joint, in which the joint area had no shear reinforcement. The previous study by one of the authors [4], [5] also showed that beam-column joints without shear reinforcement still exist in newly built construction in an area that had experienced significant damage due to a past earthquake (Fig. 2). These indicated that many stocks of RC buildings with substandard beam-column joints exist in developing countries in earthquake-prone areas.

Fig.1 A collapsed building and its damaged exterior beam-column joint [1]

Fig.2 Substandard detail of exterior beam-column joint in construction [5]

The behavior and seismic capacity of existing buildings need to be evaluated using nonlinear analysis, i.e. static nonlinear pushover analysis (e.g. [6]–[8]). Pushover analysis of RC frames/buildings commonly considers the nonlinear behavior of beam and column members, assuming rigid beam-column joints [9]. However, this assumption may mislead the analysis results in the case of substandard beam-column joints, because the failure of the joint may occur as confirmed in the literature of experimental studies (e.g. [1], [2], [10]–[12]) and an experimental study by one of the authors [3].

Many literatures have developed detailed numerical models to analyze RC beam-column joints. Lowes et al. [13] proposed a four-node 12-degree-of-freedom element for modeling the hysteretic of beam-column joints. Shin et al. [14] proposed a modified compression field for approximating joint shear stress-strain response. Sung et al. [15] proposed a model with two diagonal cross struts. Ketiyot et al. [16] presented an application of the nonlinear strut-and-tie model. Khan et al. [17] proposed a zero-link element with a moment-rotation lumped plasticity hinge to model a beam-column joint. Yu et al. [18] proposed a model considering the inelastic rotation hinge mechanism and sliding hinge mechanism. Ahmad et al. [19] proposed an improved nonlinear model to simulate the behavior of beam-column joints considering fixed-end rotation. Demirtas et al. [20] presented a nonlinear lattice modeling approach to model substandard beam-column joints. Sabah et al. [21] and Khrisnan et at. [22] presented numerical models using finite element software with micro-modeling for analysis of beam-column joints. However, these models are not easy to be applied by a practical engineer because they require complex calculation and modeling techniques.

To overcome these problems, this study presents a simplified nonlinear pushover analysis procedure to evaluate the seismic capacity of RC frames with sub-standard beam-column joints. The analysis procedure assumes that the performance limit of the frame is at the failure of beam-column joints observed in previous experimental studies from the literature of experimental studies and a simplified backbone of joint shear stress-strain response. The presented analysis procedure utilized simple calculation and modeling techniques and was applied in a commercial software; thus, it has great potential to be used widely in practical applications.

2. RESEARCH SIGNIFICANCE

The pushover analysis of RC frame commonly doesn’t utilize the model of beam-column joint failure, and many existing models are not easy to be used in the analysis. This study presented a simplified pushover analysis procedure to evaluate the seismic capacity of RC frames with sub-standard beam-column joints. The presented analysis procedure effectively simulates the seismic behavior at a component level, i.e., a sub-assemblage exterior beam-column joint with substandard details. Then, the analysis procedure was applied at a structural level, i.e., a plane frame RC building with substandard beam-column joints. Through this study, academics and practitioners can better understand that the utililization of joint modelling is very important for seismic performance analysis of existing RC buildings with sub-standard beam-column joints.

3. REVIEW ON PERFORMANCE LIMIT OF SUB-ASSEMBLAGE BEAM-COLUMN JOINT WITH SUBSTANDARD DETAILS

Many experimental studies have been conducted on the seismic performance of substandard beam-column joints. This section focuses on the experimental studies of exterior beam-column, without shear reinforcement in which the joint shear failure occurred before yielding of adjacent beam [1], [10]–[12]. This kind of failure exhibited brittle failure, where the strength and the deformation capacity of the specimens significantly drop after the peak strength was observed. Therefore, in the current study, the drift ratio at the peak strength is assumed as the performance limit for the exterior beam-column joint without shear reinforcement.

Table 1 summarized the drift ratio at the peak strength of the sub-assemblage exterior beam-column joint specimens without shear reinforcement from the literature on experimental studies. The data used in table 1 was restricted only to the case of sub-assembled exterior beam-column joint specimens which were given static cyclic load at the beam end. The data was also restricted for the specimens with deformed bars with standard hooks; thus, anchorage failure of beam reinforcement in the joint did not occur.

The experimental results in table 1 showed that the conservative value of drift ratio at peak load of the specimens is 1,5%. This value is also confirmed as the median value of drift ratio at peak joint shear strength of unconfined exterior beam-column joint in the database used in a study by Hassan [23], in which most of the specimens with joint shear failure had a drift a peak strength around 1% - 2% as shown in Figure 3. In the figure, data for specimens with joint shear failure is indicated by a red open circle and a red solid circle.

In the next section, one sub-assemblage beam-column joint specimen representing an Indonesian building with the drift ratio at peak strength of 1,5% was used as the reference for verification of the numerical modeling.

Table 1 The drift ratio at peak strength of sub-assemblage exterior beam-column joints

Specimen ID	Drift ratio at peak strength	Case study
as-is joint [12]	2,0%	1960s building in the US.
C1 [10]	2,3%	Poorly - detailed joint.
C2 [10]	1,8%	
Test#1 [11]	1,5%	The 1960s-1990s building in Italy.
J2 [1]	1,5%	Indonesian building.

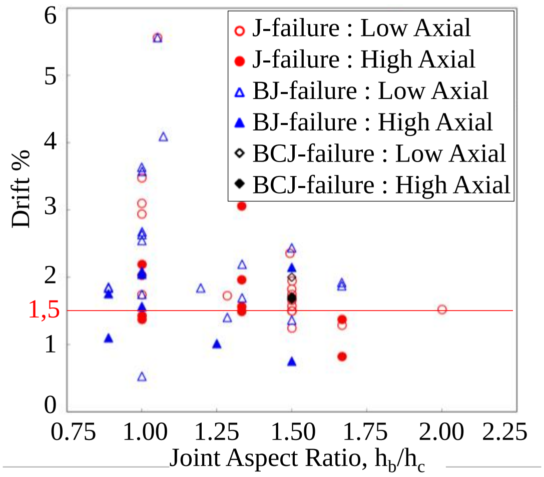


Fig.3 Drift ratio at the peak strength in the experimental database [23] (some notes in the figure were added by authors)

4. MODELLING OF SUB-ASSEMBLAGE BEAM-COLUMN JOINT WITH SUBSTANDARD DETAILS

A commercial finite element-based software Seismostruct was used for modeling the structure. The column and beam members were modeled using an inelastic force-based flexure type element (Fig. 4), that used the force-based finite element formulation [24], [25] in modeling geometric nonlinearity and material inelasticity of the member.

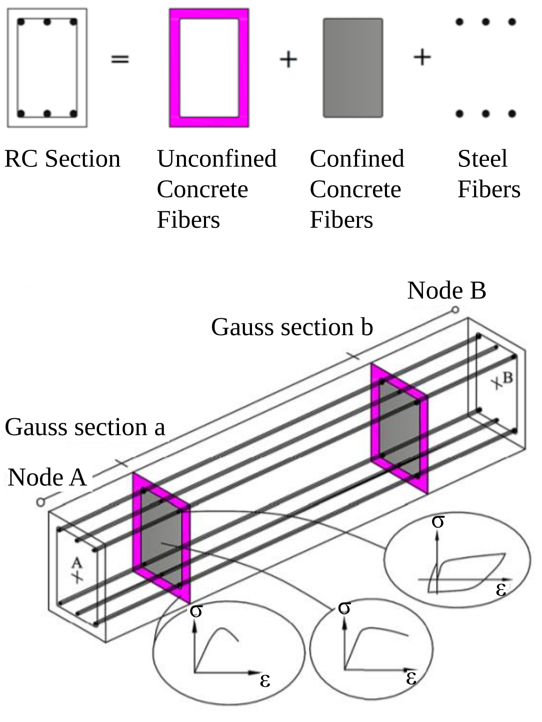


Fig.4 Modeling of columns and beams

This study used a simplified modeling technique to model the failure of the beam-column joint in one sub-assemblage beam-column joint specimen in the literature, specimen J2 [1]. The joint panel was idealized as rigid links with a rotational spring at the center of the joint, as shown in Fig. 5. This model was used widely in the literature (e.g. [26], [27]).

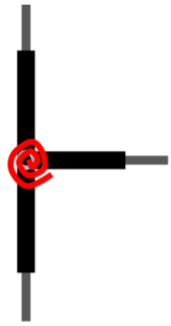


Fig.5 Beam-column joint modeling

The rotational spring at the center of the joint is defined by the backbone of joint shear stress – shear strain response. The backbone is generally controlled by four damage states: cracking of concrete, pre-peak (yield) strength, peak strength, and residual strength, as shown in Figure 6. These damage states were adopted in many constitutive models in the literature (e.g. [28]–[30]).

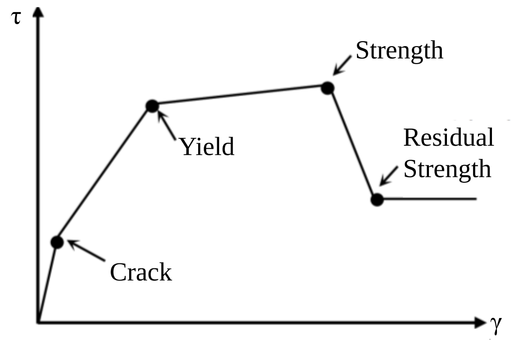


Fig.6 Backbone of the joint shear stress-strain

This study considered a backbone of the joint shear stress-strain developed by DeRisi [28]. The model was developed for unreinforced exterior beam-column and verified with the experimental database. The summary of the key parameters defining the shear stress (τ_j) of the backbone curve for the exterior beam-column with joint shear failure before yielding of the beam is shown in Table 2. However, in this study, the backbone curve is simplified as follows:

1. $\tau_{j,max}$ is determined as a conservative value of $0{,}42\sqrt{f_c'}$. This value is used widely in the literature (e.g.[31]–[33]) as a conservative value of shear stress of unreinforced exterior beam-

column joint with beam rebars bent into joint.

2. The performance limit of the joint is assumed as the first point when the maximum shear stress is achieved because the literature of the experimental studies (e.g. [1], [10]–[12]) showed that the unreinforced exterior beam-column specimens exhibit a brittle failure after this point. Therefore, the backbone curve for the post-peak behavior is not considered.

The simplified backbone curve used in this study is shown in Figure 7. The backbone of the stress–shear response was converted into a moment-rotation response by applying the equations by Celik and Ellingwood [26].

Table 2 Summary of the key parameters defining the shear stress (τ_j) of the backbone curve for the exterior beam-column [28]

Backbone point	τ_j
Cracking ($\tau_{j,cr}$) [34]	$\tau_{j,cr} = 0{,}29\sqrt{fc}\sqrt{1 + 0{,}29\frac{P}{A_j}}$
Pre-peak ($\tau_{j,p-p}$)	$\tau_{j,p-p} = 0{,}85\ \tau_{j,max}$ if J-failure
Peak ($\tau_{j,max}$) [35]	$\ln(\tau_{j,max}) = -0{,}81 + 0{,}46\ln(fc) + 0{,}50\ln(\tau_d) + 0{,}68\ln(JP) + 0{,}62\ln(TB) - 0{,}25\ln(h_b/h_c) + 0{,}08\ln(M_R) + 0{,}14\ln(\theta)$
Residual	$0{,}43\ \tau_{j,max}$

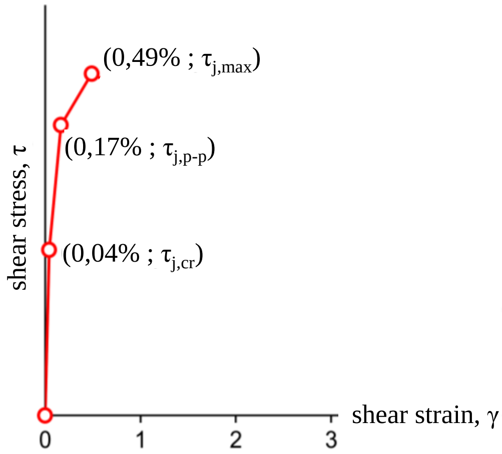
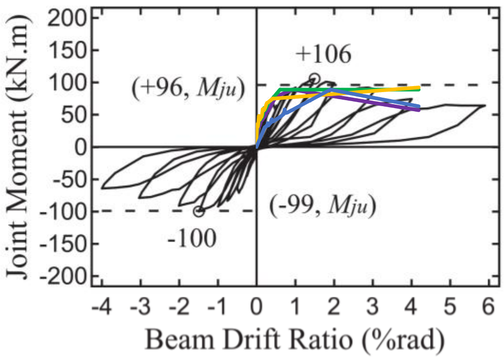


Fig.7 Simplified principal tensile stress–shear deformation (adapted form [28], modified by authors)

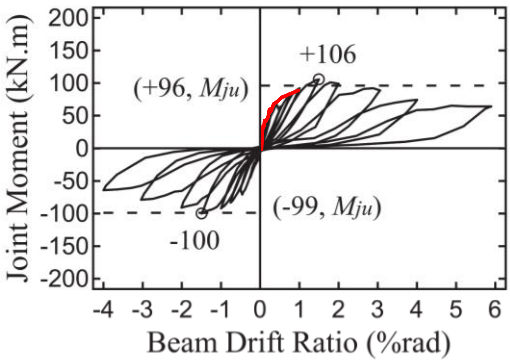
The modeling technique explained above was applied to a sub-assemblage beam-column joint specimen from the literature [1] using static pushover analysis.

Figure 8(a) shows the numerical results using several existing models for the backbone curve of stress-strain response of the joint [28], [33], [36], [37], and experimental results from the literature. The figure shows that the existing models cannot give a good estimation for the stiffness up to the peak strength or the residual stiffness after the peak strength, and there are no explicit criteria for the performance limit of the joint.

Figure 8(b) shows the comparison between the numerical modeling with pushover analysis using simplified model (red line) and the experimental hysteretic curve from the literature (black line). The numerical pushover curve was close to the experimental results, especially in estimating the stiffness. The numerical pushover curve also conservatively estimates the peak strength and the drift at the peak strength, which are assumed as the performance limit at the joint failure in this study. These results show the soundness of the proposed modeling procedure in simulating the behavior of the sub-assemblage exterior beam-column joints without shear reinforcement in the joint; thus, it can be applied for pushover analysis of RC frames/RC buildings with such kind of details in the joints.



(a) Existing models



(b) Simplified model (this study)

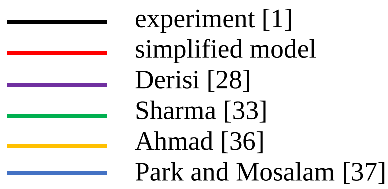


Fig.8 Experimental hysteretic curve for specimen J2 [1] and numerical pushover results

5. PUSHOVER ANALYSIS OF A RC FRAME WITH SUBSTANDARD BEAM-COLUMN JOINTS

5.1 Case Study

A plane frame of a three-stories office building in Indonesia is examined in this study. The building collapsed due to the 2018 Earthquake in Palu [38]. The photos from the field investigation in Figure 9 show that no shear reinforcement was installed in the exterior joint and buckling of column longitudinal reinforcement was observed in the joint. These indicated that the collapse of the building might occur because of the failure of the joint.

The details of the structural member and the plane frame of the building are shown in Figure 10 and Figure 11, respectively. In this study, the analysis is conducted only for one plane frame of the focused building, because the building has a similar plane frame in both directions of the building. The design strength of concrete used in the building is 22.8 MPa for concrete. The specified yield strength of reinforcement is 390 MPa and 240 MPa for longitudinal and transverse reinforcement, respectively.

5.2 Analytical Assumptions

Seismostruct 2022 academic license was used for modeling the frame. The assumptions for modeling were similar to those in the modeling of sub-assemblage beam-column joint specimens in the previous section of this article. Two models were analyzed in this study. The first model is the frame without nonlinear modeling of the beam-column joint, in which the beam-column joints were assumed as a rigid zone. The second model is the frame with non-linear modeling of the exterior beam-column joints with the same assumption as those in the analysis of the sub-assemblage beam-column joint in the previous section. For the second model, interior joints were also idealized as rigid links with a rotational spring, but the rotational spring was assumed as linear elastic.

The gravity load of the building was calculated based on the Indonesian code [39]. The distribution of lateral load for pushover analysis was assumed as an inverted triangular distribution and the analysis was performed using a displacement control approach.

The performance limit of the frame was set to the point at the failure of the exterior beam-column joints. The failure of exterior beam-column joints is more critical than interior beam-column joints, as confirmed in a literature by Priestley [31].

Fig.9 A collapsed building due to the 2018 Palu Earthquake and damage to the exterior beam-column joints. (Photo courtesy of Syafri Wardi)

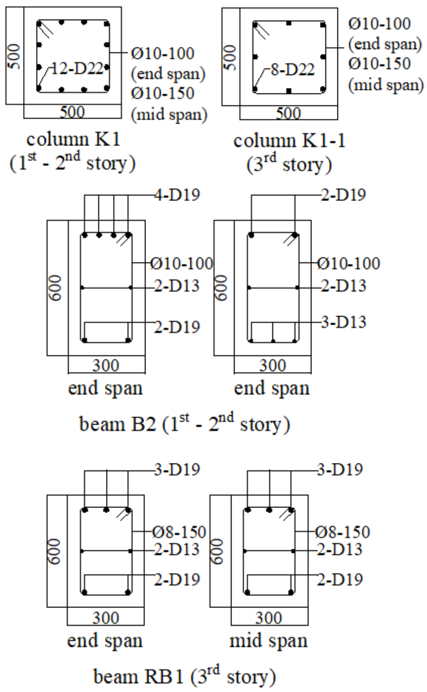


Fig.10 The details of the structural member

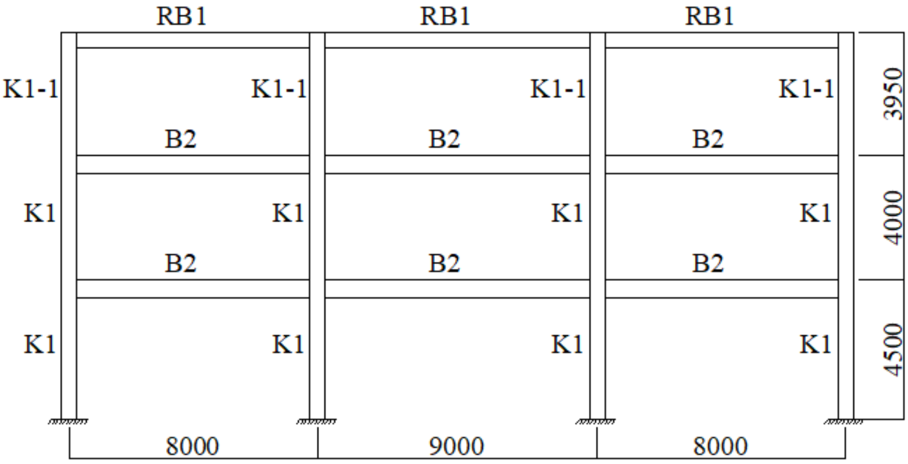


Fig.11 Plane frame of the building

5.3 Analytical Results

The capacity curve (base shear vs roof displacement) relationship of the first model without modeling the beam-column joints is shown in Figure 12. The figure also includes the target displacements at the performance level of life safety (LS) and Collapse Prevention (CP) under the earthquake hazard level of BSE-1E and BSE-2E, according to ASCE 41-17 [40]. The capacity curve shows that the frame maintained its strength and ductility exceeding the target displacement. This result misleads the behavior and seismic performance of the building.

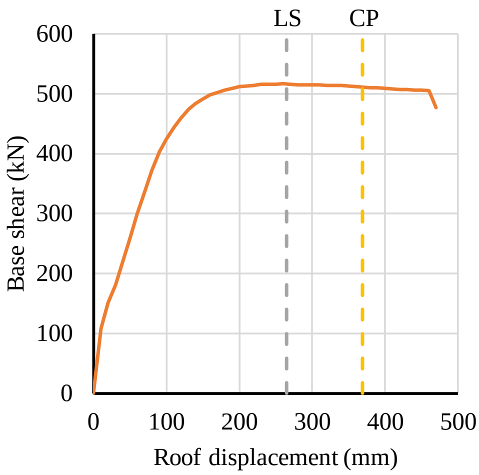


Fig.12 Base shear vs. roof displacement for the frame without joint modeling

The capacity curve of the second model with the modeling the beam-column joints as presented in study is shown in Figure 13. The capacity curve shows that the performance limit of the frame was occured at a point before the target displacements. This represent the collapsed of the building under the earthquake.

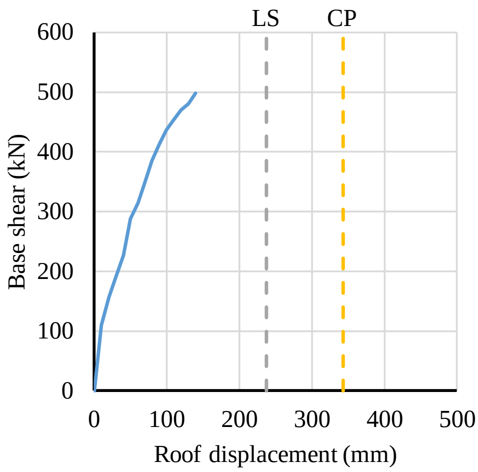


Fig.13 Base shear vs. roof displacement for the frame with joint modeling

6. CONCLUSIONS

This study presented a nonlinear pushover analysis procedure considering the failure of exterior beam-column joints without shear reinforcement, in which the performance limit of the frames is assumed as a point at the peak strength of the joints. A simplified numerical modeling assumption for the joints was presented and verified to a sub-assemblage exterior beam-column joint.

The pushover analysis procedure was applied to one RC frame with substandard beam-column joints representing collapsed buildings due to the 2018 Earthquake in Palu, Indonesia. Application of the analysis procedure was applicable to estimate the seismic capacity of RC frames/buildings considering the failure of beam-column joints, especially in the case of the unreinforced beam-column joints using deformed bars and beam rebars bent into joints with sufficient anchorage length.

7. REFERENCES

[1] Li, Y. and Y. Sanada, Seismic strengthening of existing RC beam-column joints by wing walls, Earthq. Eng. Struct. Dyn., vol. 46, no. 12, 2017, pp. 1987–2008, doi: 10.1002/eqe.2890.

[2] Li, Y., Y. Sanada, S. Takahashi, K. Maekawa, H. Choi, and K. Matsukawa, Seismic Performance Evaluation and Strengthening of RC Frames with Substandard Beam-Column Joint: Lessons Learned from the 2013 Bohol Earthquake, J. Earthq. Tsunami, vol. 10, no. 03, Sep. 2016, pp. 1640007, doi: 10.1142/S1793431116400078.

[3] Wardi, S., Y. Sanada, N. Saha, and S. Takahashi, Improving integrity of RC beam-column joints with deficient beam rebar anchorage, Earthq. Eng. Struct. Dyn., vol. 49, no. 3, Mar. 2020, pp. 234–260, doi: 10.1002/eqe.3229.

[4] Wardi, S., Y. Sanada, M. Kita, J. Tanjung, and Maidiawati, Investigation on implementation of seismic detailing of reinforced concrete buildings in West Sumatra Indonesia, in Proceedings of the 7th Asia Conference on Earthquake Engineering (7ACEE), 2018, p. ACEE0069.

[5] Wardi, S., Y. Sanada, M. Kita, J. Tanjung, and M. Maidiawati, Common Structural Details and Deficiencies in Indonesian RC Buildings: Preliminary Report on Field Investigation in Padang City, West Sumatra, Int. J. Adv. Sci. Eng. Inf. Technol., vol. 8, no. 2, Mar. 2018, pp. 418, doi: 10.18517/ijaseit.8.2.4207.

[6] Natepra, P., Seismic Response of Deteriorated Residential RC Buildings in The Northeastern Region of Thailand, Int. J. GEOMATE, vol. 19, no. 75, Nov. 2020, pp. 160–167, doi: 10.21660/2020.75.99782.

[7] Tanjung, J., Effect of Brick Masonry Infills to Seismic Capacity of Indonesia Multi-Story RC Building, Int. J. GEOMATE, vol. 16, no. 57, May 2019, pp. 42–48, doi: 10.21660/2019.57.4617.

[8] Mouloud, M., Seismic Behaviour of Reinforced Concrete Frame Buildings with Masonry Infill, Int. J. GEOMATE, vol. 17, no. 63, Nov. 2019, pp. 203–209, doi: 10.21660/2019.63.72884.

[9] Kang, J.-D., T. Nagae, S.-H. Jeong, and K. Kajiwara, Accuracy of Seismic Response Evaluation of Two-Dimensional Analysis Model with Rigid Joints for RC Frame Buildings, Materials (Basel)., vol. 15, no. 22, Nov. 2022, p. 8027, doi: 10.3390/ma15228027.

[10] Antonopoulos, C. P. and T. C. Triantafillou, Experimental Investigation of FRP-Strengthened RC Beam-Column Joints, J. Compos. Constr., vol. 7, no. 1, Feb. 2003, pp. 39–49, doi: 10.1061/(ASCE)1090-0268(2003)7:1(39).

[11] De Risi, M. T., P. Ricci, G. M. Verderame, and G. Manfredi, Experimental assessment of unreinforced exterior beam–column joints with deformed bars, Eng. Struct., vol. 112, Apr. 2016, pp. 215–232, doi: 10.1016/j.engstruct.2016.01.016.

[12] Pantelides, C., C. Clyde, and L. Reaveley, Rehabilitation of R/C Building Joints With FRP Composites, in 12th World Conference on Earthquake Engineering, 2000, p. 2306.

[13] Lowes, L. N. and A. Altoontash, Modeling Reinforced-Concrete Beam-Column Joints Subjected to Cyclic Loading, J. Struct. Eng., vol. 129, no. 12, Dec. 2003, pp. 1686–1697, doi: 10.1061/(ASCE)0733-9445(2003)129:12(1686).

[14] Shin, M. and J. M. LaFave, Testing and modelling for cyclic joint shear deformations in RC beam-column connections, in Proceedings of the Thirteenth World Conference on Earthquake Engineering, 2004, p. s0301.

[15] Sung, Y. C., T. K. Lin, C. C. Hsiao, and M. C. Lai, Pushover analysis of reinforced concrete frames considering shear failure at beam-column joints, Earthq. Eng. Eng. Vib., vol. 12, no. 3, Sep. 2013, pp. 373–383, doi: 10.1007/s11803-013-0179-8.

[16] Ketiyot, R., Nonlinear Strut–and–Tie Model with Bond–Slip Effect for Analysis of RC Beam–Column Joints Under Lateral Loading, Int. J. GEOMATE, vol. 15, no. 47, Jul. 2018, pp. 81–88, doi: 10.21660/2018.47.STR120.

[17] Khan, M. S., A. Basit, and N. Ahmad, A simplified model for inelastic seismic analysis of RC frame have shear hinge in beam-column joints, Structures, vol. 29, Feb. 2021, pp. 771–784, doi: 10.1016/j.istruc.2020.11.072.

[18] Yu, D.-H., G. Li, Z.-Q. Dong, and H.-N. Li, A fast and accurate method for the seismic response analysis of reinforced concrete frame structures considering Beam-Column joint deformation, Eng. Struct., vol. 251, Jan. 2022, p. 113401, doi: 10.1016/j.engstruct.2021.113401.

[19] Ahmad, N. et al., Nonlinear Modeling of RC Substandard Beam–Column Joints for Building Response Analysis in Support of Seismic Risk Assessment and Loss Estimation, Buildings, vol. 12, no. 10, Oct. 2022, p. 1758, doi: 10.3390/buildings12101758.

[20] Demirtaş, Y., Ö. Yurdakul, and Ö. Avşar, Lattice modelling of substandard RC beam-column joints considering localization issues, Structures, vol. 47, Jan. 2023, pp. 2515–2530, doi: 10.1016/j.istruc.2022.12.062.

[21] Sabah, H. A. H. and I. S. I. Harba, Numerical Analysis of Reinforced Concrete Exterior Beam-Column Joints Under Limited Cycles of Repeated Loading, Diyala J. Eng. Sci., vol. 15,

no. 4, Dec. 2022, pp. 108–129, doi: 10.24237/djes.2022.15410.
[22]Krishnan, A. and G. D. Ramtekkar, Numerical Study On Response Of Exterior Beam-Column Joint Under Cyclic Loading, ASPS Conf. Proc., vol. 1, no. 1, Dec. 2022, pp. 387–394, doi: 10.38208/acp.v1.526.
[23]Hassan, W. M., Analytical and Experimental Assessment of Seismic Vulnerability of Beam-Column Joints without Transverse Reinforcement in Concrete Buildings, University of California, Berkeley, 2011, pp. 1-471.
[24]Neuenhofer, A. and F. C. Filippou, Evaluation of Nonlinear Frame Finite-Element Models, J. Struct. Eng., vol. 123, no. 7, Jul. 1997, pp. 958–966, doi: 10.1061/(ASCE)0733-9445(1997)123:7(958).
[25]Spacone, E., V. Ciampi, and F. C. Filippou, Mixed formulation of nonlinear beam finite element, Comput. Struct., vol. 58, no. 1, Jan. 1996, pp. 71–83, doi: 10.1016/0045-7949(95)00103-N.
[26]Celik, O. C. and B. R. Ellingwood, Modeling Beam-Column Joints in Fragility Assessment of Gravity Load Designed Reinforced Concrete Frames, J. Earthq. Eng., vol. 12, no. 3, Mar. 2008, pp. 357–381, doi: 10.1080/13632460701457215.
[27]Jeon, J.-S., A. Shafieezadeh, and R. DesRoches, Statistical models for shear strength of RC beam-column joints using machine-learning techniques, Earthq. Eng. Struct. Dyn., vol. 43, no. 14, Nov. 2014, pp. 2075–2095, doi: 10.1002/eqe.2437.
[28]De Risi, M. T., P. Ricci, and G. M. Verderame, Modelling exterior unreinforced beam-column joints in seismic analysis of non-ductile RC frames, Earthq. Eng. Struct. Dyn., vol. 46, no. 6, May 2017, pp. 899–923, doi: 10.1002/eqe.2835.
[29]Anderson, M., D. Lehman, and J. Stanton, A cyclic shear stress–strain model for joints without transverse reinforcement, Eng. Struct., vol. 30, no. 4, Apr. 2008, pp. 941–954, doi: 10.1016/j.engstruct.2007.02.005.
[30]Birely, A. C., L. N. Lowes, and D. E. Lehman, A model for the practical nonlinear analysis of reinforced-concrete frames including joint flexibility, Eng. Struct., vol. 34, Jan. 2012, pp. 455–465, doi: 10.1016/j.engstruct.2011.09.003.
[31]Priestly, M. J. N., Displacement-Based Seismic Assesment of Reinfirced Concrete Buildings, J. Earthq. Eng., vol. 1, no. 1, 1997, pp. 157–192.
[32]Pampanin, S., G. M. Calvi, and M. Moratti, Seismic behavior of R.C. beam-column joints designed for gravity only, in Proceedings of the 12th European conference on earthquake engineering, 2002, p. 726.
[33]Sharma, A., R. Eligehausen, and G. R. Reddy, A new model to simulate joint shear behavior of poorly detailed beam–column connections in RC structures under seismic loads, Part I: Exterior joints, Eng. Struct., vol. 33, no. 3, Mar. 2011, pp. 1034–1051, doi: 10.1016/j.engstruct.2010.12.026.
[34]Uzumeri, S. M., Strength and Ductility of Cast-In-Place Beam-Column Joints, Symp. Pap., vol. 53, 1977, pp. 293–350.
[35]Jeon, J. S., L. N. Lowes, and R. DesRoches, Numerical models for beam-column joints in reinforced concrete building frames, ACI Spec. Publ., vol. 297, 2014, pp. 1–26, [Online]. Available: https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/51686900
[36]Ahmad, N., A. Shahzad, Q. Ali, M. Rizwan, and A. N. Khan, Seismic fragility functions for code compliant and non-compliant RC SMRF structures in Pakistan, Bull. Earthq. Eng., vol. 16, no. 10, Oct. 2018, pp. 4675–4703, doi: 10.1007/s10518-018-0377-x.
[37]Park, S. and K. M. Mosalam, Simulation of Reinforced Concrete Frames with Nonductile Beam-Column Joints, Earthq. Spectra, vol. 29, no. 1, Feb. 2013, pp. 233–257, doi: 10.1193/1.4000100.
[38]USGS, M 7.5 - 72 km N of Palu, Indonesia, 2018. https://earthquake.usgs.gov/earthquakes/eventpage/us1000h3p4/executive (accessed Jun. 01, 2022).
[39]National Standardization Agency of Indonesia (BSN), Design Load Procedure for Homes and Buildings, Jakarta, 1989, pp. 1-17.
[40]ASCE, Seismic Evaluation and Retrofit of Existing Buildings. Reston, VA: American Society of Civil Engineers, 2017, pp. 1-26. doi: 10.1061/9780784414859