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REVIEW ARTICLE

State-of-art summary of the strength hierarchy assessment and its applications

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Abstract

Strength hierarchy assessment is a method developed to be able to identify the governing failure mechanisms at reinforced concrete (RC) beam-column joints. The main failures that can be identified in this method are: i) beam plastic hinge; ii) column plastic hinge/shear failure; iii) beam-column joint shear failure. Through the identification of the governing failure mode in a joint, the validity of the capacity design principles can be checked for the considered RC beam-column joint. The obtained observations can then be used in finding the most optimal repair/strengthening application. This method has been going through updates and developments in the last decade and new applications have emerged. In this article, a state-of-the-art summary of the procedure is reported with its most recent updates as well as its practical engineering applications.

1. Introduction

Capacity design is the backbone of the modern seismic design of reinforced concrete (RC) structures. According to this design philosophy, the columns and beam-column joints must be stronger than the connected beams to facilitate the formation of the beam-sway mechanism. This is the main mechanism through which the earthquake energy is dissipated at the beam ends through the formation of the beam plastic hinges. This design concept was conceptualized by various researchers in the 1960s [1] and it has been included in the seismic design codes since the 1970s.

On the other hand, strength hierarchy assessment is the analysis procedure of an existing RC beam-column joint to identify the weakest element connected to the joint: i) RC beam; ii) RC column; iii) RC beam-column joint panel zone. As a result of this assessment method, the weakest member can be identified and either the capacity design gets confirmed or the required repair/strengthening approach can be decided. The earlier versions of this method were used in various research carried out over the last 20 years [2-6]. These earlier versions of the strength hierarchy assessment methods were only able to roughly identify the sequence of the failures in unreinforced RC beam-column joint sub-assemblies (test specimens) and they were unable to relate these failures to the global base shear demands imposed on the structures. This prevented their practical application in real engineering problems in frame structures. In the last 10 years, further developments have been made and a more accurate description of the sequence of failures is obtained

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with improved capacity/demand representation equations as well as their accurate relation to the global base shear demand [7]. These improvements facilitated more practical usage of this assessment method by practicing engineers and it has been incorporated into the structural assessment guidelines in New Zealand [8]. A typical strength hierarchy assessment can be summarized as a graphical demand capacity comparison as shown in Fig. 1. As can be observed in this figure, the capacities of the beam and the beam-column joint are represented in the N-M interaction diagram of the connected column. This forms the capacity domain required in the assessment. The parametric earthquake demand is evaluated as per the portal frame method of analysis and plotted on the same N-M interaction diagram. Details about this assessment method can be found in the related publication [7]. It should be noted that in a structure, many beam-column joints are connected. Therefore, after the weakest element takes damage, the remaining damage types identified in the strength hierarchy might occur under increasing seismic forces.

2. Overview of strength hierarchy assessment

Strength hierarchy assessment is mainly a graphical demand and capacity comparison procedure that accurately checks the capacity design principles at an RC beam-column joint. The demand is simply estimated using the portal frame method [9] and the resulting N, M values at each joint are plotted on the considered column's N-M interaction diagram. A resulting generic joint demand variation is shown in Fig. 2.

The main capacity domain on which this comparison is to be made is the column's N-M interaction diagram. To carry out this assessment, the capacities of three key structural elements connected at the joint must be considered: i) RC column; ii) RC beam; iii) RC beam-column joint. The column capacity is represented as its N-M interaction diagram whilst the ultimate bending moment capacity of the connected beams is represented on the column's N-M diagram based on equilibrium considerations at the joint. On the other hand, the representation of the joint shear capacity on the column's N-M diagram is an aspect that has undergone improvements/updates over the years. The details regarding the capacity representation of RC beam-column joints' shear strength are mentioned separately in the next section. A general summary of the method is shown as a flow chart in Fig. 2. However, for more in-depth details, the reader is referred to the related publication made for the application of this method elsewhere [7,10].

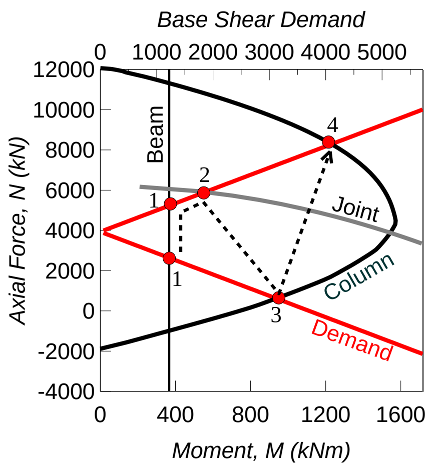
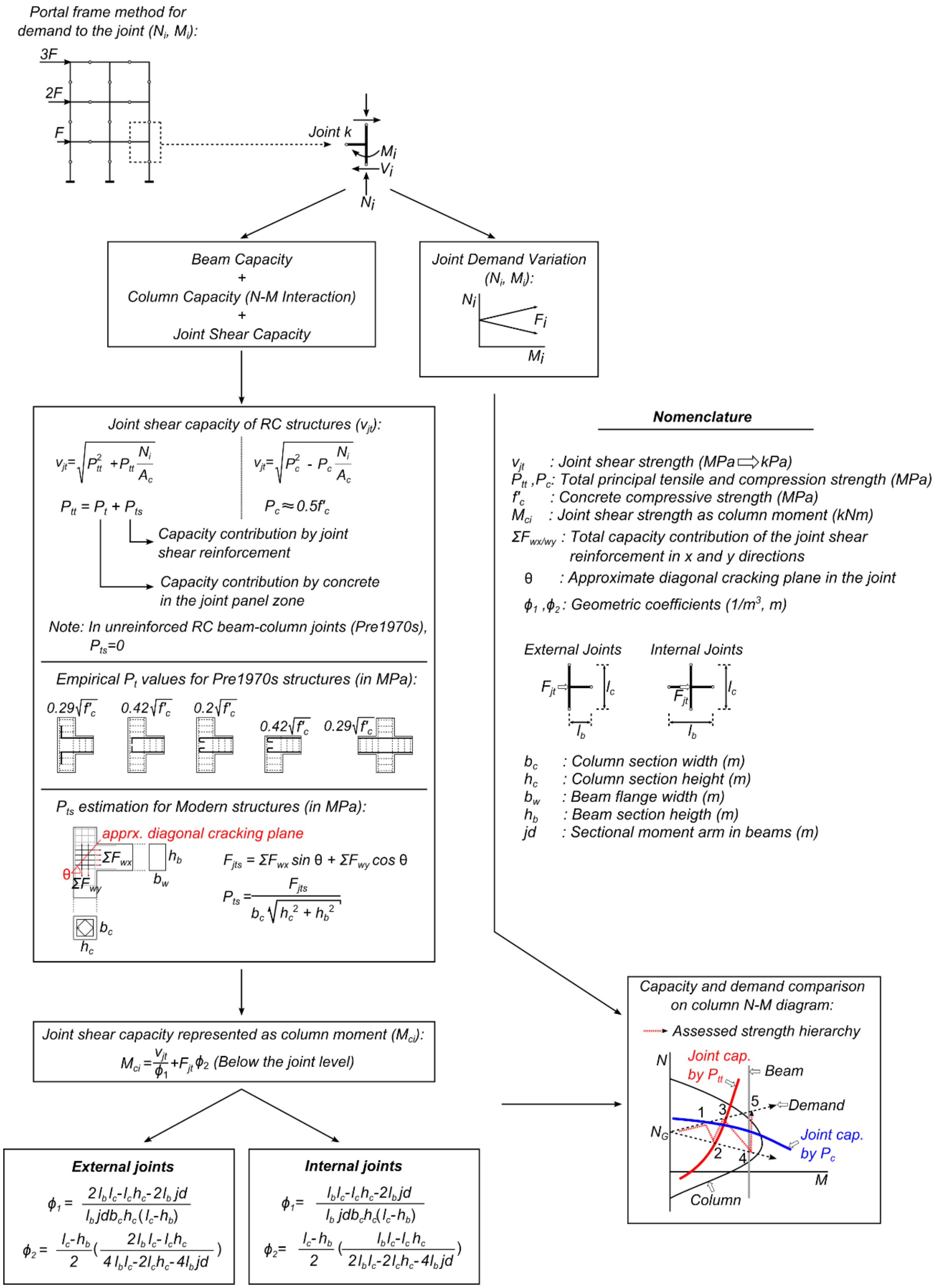


Fig. 1. A generic strength hierarchy assessment carried out for an RC beam-column joint (Identified strength hierarchy is the dashed line numbered 1, 2 to 4)



$$v_{jt}=\sqrt{P_{tt}^2+P_{tt}\frac{N_i}{A_c}} \qquad v_{jt}=\sqrt{P_c^2-P_c\frac{N_i}{A_c}}$$

$$0.29\sqrt{f'_c} \quad 0.42\sqrt{f'_c} \quad 0.2\sqrt{f'_c} \quad 0.42\sqrt{f'_c} \quad 0.29\sqrt{f'_c}$$

$$P_{ts}=\frac{F_{jts}}{b_c\sqrt{h_c^2+h_b^2}}$$

$$M_{ci}=\frac{v_{jt}}{\phi_1}+F_{jt}\phi_2$$

External joints:

$$\phi_1=\frac{2l_bl_c-l_ch_c-2l_bjd}{l_bjdb_ch_c(l_c-h_b)} \qquad \phi_2=\frac{l_c-h_b}{2}\left(\frac{2l_bl_c-l_ch_c}{4l_bl_c-2l_ch_c-4l_bjd}\right)$$

Internal joints:

$$\phi_1=\frac{l_bl_c-l_ch_c-2l_bjd}{l_bjdb_ch_c(l_c-h_b)} \qquad \phi_2=\frac{l_c-h_b}{2}\left(\frac{l_bl_c-l_ch_c}{2l_bl_c-2l_ch_c-4l_bjd}\right)$$

Fig. 2. Summary of strength hierarchy assessment

3. RC beam-column joint shear strength representation on column N-M diagram

As summarized in Fig. 2, the total principal tensile capacity in an RC beam-column joint can typically be described as

$$P_{tt} = P_t + P_{ts} \tag{1}$$

where P_t represents the principal tensile capacity of the concrete itself in the joint and P_{ts} represents the principal tensile capacity provided by the joint shear reinforcements. The total principal tensile capacity P_{tt} is then expressed as the summation of both [10]. It should be noted that in vulnerable RC beam-column joints without any joint shear reinforcement, P_{ts} is zero. Therefore, for such older joints, principal tensile capacity is only calculated using the P_t value.

3.1. RC beam-column joints without joint shear reinforcement: P_t representation (Pre 1970s' vulnerable joints)

Several empirical values from the literature for P_t are shown in Fig. 3. Fig. 3a, b, d, and e are obtained from Prof. Nigel Priestley's research [11] whilst Fig. 3c is obtained from Prof. Stefano Pampanin's related research [12]. These values are used depending on the detailing observed in old structures. On the other hand, in modern structures, such details (Fig. 3a-d) are not utilized. In these cases, $0.29\sqrt{f_c'}$ can be used as an approximate value for external and internal RC beam-column joints as shown in Fig. 3e. It should be noted that the principal tensile capacity for concrete is never an exact value and it can range among various values. As can be seen in Fig. 3, P_t ranges from $0.2\sqrt{f_c'}$ to $0.42\sqrt{f_c'}$. The design codes across the world report a typical P_t value for concrete of approximately $0.35\sqrt{f_c'}$ [13] or $0.36\sqrt{f_c'}$ [14]. Therefore, in modern structures the practicing engineer can take an average value ranging from $0.29\sqrt{f_c'}$ to $0.35\sqrt{f_c'}$.

3.2. RC beam-column joints with joint shear reinforcement: P_{ts} representation (Post-1970s Joints designed as per capacity design principles)

In the modern seismic design of structures, the RC beam-column joints must be well reinforced for shear [14, 15]. This is typically achieved by reinforcing the beam-column joints with a number of sets of transverse steel provided within the joint panel zone. This is illustrated with n sets of transverse steel arrangement in Fig. 4. Combined with this, the m number of intermediate steel provided within the column (as shown in Fig. 4) forms a mesh at the considered RC beam-column joint panel zone. This combined mesh resists the principal tensile forces developing in the joint panel zone after the formation of the joint shear cracks. As a result, the capacity contribution solely provided by the joint shear reinforcement, P_{ts}, can be evaluated as summarized in Fig. 4. For more details regarding the development and validation of this approach, the reader is recommended to refer to the detailed publication on this subject [10].

3.3. RC beam-column joints' shear capacity under extreme axial compression: P_c representation

Modern capacity design principles require RC beam-column joints to be well-reinforced using sets of transverse steel reinforcements provided in the joint panel zone. It is commonly stated that the provided joint shear reinforcements would prevent/limit the joint shear damage/failure expected at RC beam-column joints. However, in literature such well-reinforced RC beam-column joints were observed to fail in shear: such failures might occur especially under extreme principal compression levels [16, 17]. Therefore, joint shear failure possibility in modern RC beam-column joints designed as per capacity design principles cannot be ruled out. For such joints, an approximate principal compression level of $P_c = 0.5f_c'$ is reported in the literature [11]. Similar to P_{tt}, P_c is used for the construction of the N-M capacity envelope for the considered RC beam-column joint.

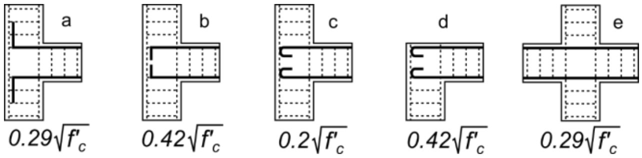


Fig. 3. Empirical P_t values from the literature for Pre 1970s RC structures, i.e. no joint shear reinforcement [7, 11, 12]

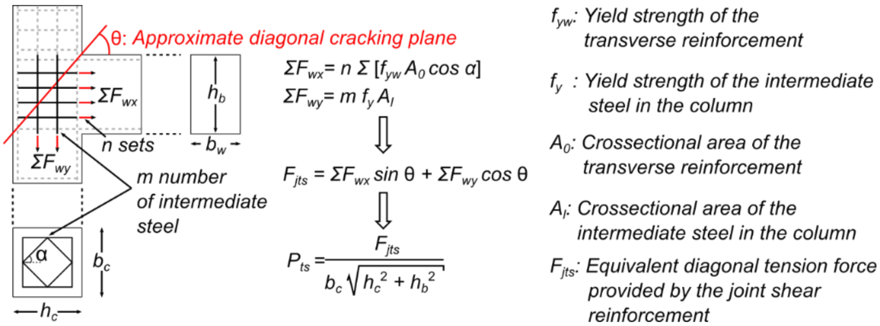


Fig. 4. Summary of the P_{ts} representation in RC structures with joint shear reinforcement [10]

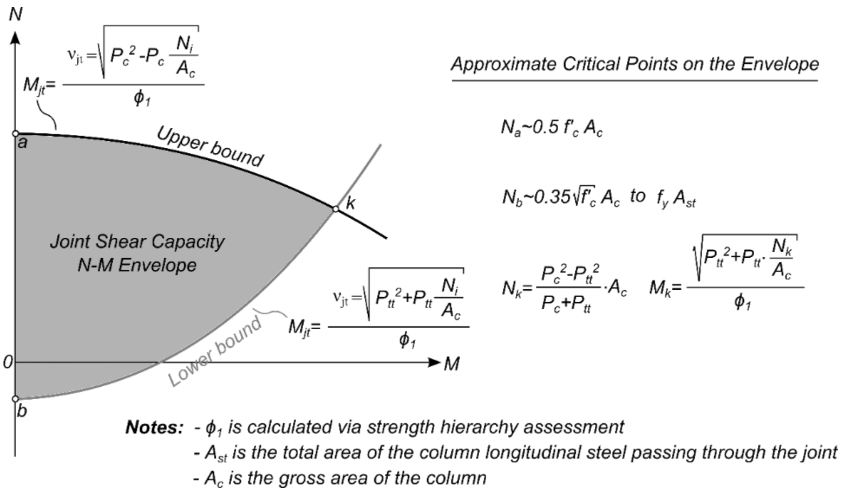


Fig. 5. RC beam-column joint's shear strength representation in the N-M domain

3.4. RC beam-column joint shear capacity N-M representation

Using the information summarized in sections 3.1, 3.2, and 3.3, the RC beam-column joint shear capacity N-M envelope can be established as shown in Fig. 5. It should be noted that the P_{tt} expression defines the lower bound whilst P_c expression defines the upper bound of this envelope. As can be observed in this representation, the increasing levels of column axial forces are expected to increase the joint shear strength. However, after a certain level of axial load (as defined by point k), further increases in column axial forces are expected to cause a reduction in joint shear strength. It should be emphasized that this theoretical response is in line with some of the observations made in the literature [18-22]. More details regarding the development and validation of this approach can be found in the related publication [10].

4. Applications of strength hierarchy assessment

Through the strength hierarchy assessment, the weakest element in any RC beam-column joint(s) can easily be identified. As a result of this outcome, a proper repair/strengthening technique can be utilized in the structure. RC column and RC beam strengthening methods are well established in the existing literature. Therefore, the focus will be given to the application of this method in RC beam-column joint strengthening methods. Moreover, the recent developments made with the N-M interaction envelope concept for the RC beam-column joint shear strength make it a potential modeling tool for the beam-column joints.

4.1. RC beam-column joint strengthening applications

In the strengthening of RC beam-column joints, the main purpose is to protect the column, and the beam-column joints and shift any potential damage mechanism into the beams (i.e. weak beam-strong column or beam sway mechanism). In such applications, strength hierarchy assessment is first utilized to identify the probable failure mode (e.g. shear failure at a joint, plastic hinge at a column, or a beam). After this assessment, depending on the results, the appropriate strengthening method is decided: a) if the columns are found to fail, either column jacketing or any other column strengthening application can be carried out; b) if the beam-column joints are found to fail, one of the available joint strengthening approaches can be utilized; c) if the beam is found to fail first, it is a confirmation of the weak beam-strong column concept (as long as the vertical load carrying capability of the beams are sufficient). Following this assessment step, the next stage is the strength hierarchy assessment of the strengthened beam-column joint, which is carried out to confirm the provided capacity by the strengthening.

In the literature, there are various strengthening approaches for vulnerable RC beam-column joints. Some approaches utilize Fiber Reinforced Polymers (FRPs) adhered to the side surfaces of RC beam-column joints forming an orthogonal mesh at the joints [3], shown in Fig. 6a. Other approaches may utilize FRPs to be adhered diagonally at the joints [23], shown in Fig. 6b. In addition to FRPs, steel rebars may be used for the strengthening of the RC beam-column joints [24], shown in Fig. 6c.

Among the mentioned RC beam-column joint strengthening approaches in Fig. 6, development and validation studies have been carried out considering the approach shown in Fig. 6a. This approach requires the calculation of the de-bonding forces that can be carried by the FRP sheets adhered to the beam ($F_{b,f}$) and the column ($F_{c,f}$), which cross each other orthogonally at the joint panel zone. These values are then combined to calculate $F_{jt,f}$ using an approximate diagonal cracking plane extending between the corners of the joint. For the other alternative strengthening applications, $F_{jt,f}$ can be used as shown in Fig. 6b-c. $F_{jt,f}$ is then utilized in strength hierarchy assessment as summarized in Fig. 7. More information on the development and the validation of this approach can be found in the related publication [25].

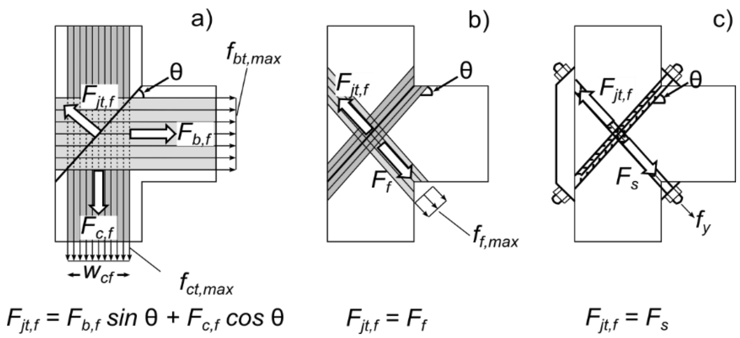


Fig. 6. Various RC beam-column joint strengthening approaches: a) FRPs adhered to side surfaces of the joints [3]; b) FRPs adhered diagonally to the side surfaces of the joints [23]; c) Steel rebars diagonally anchored within the joints [24]

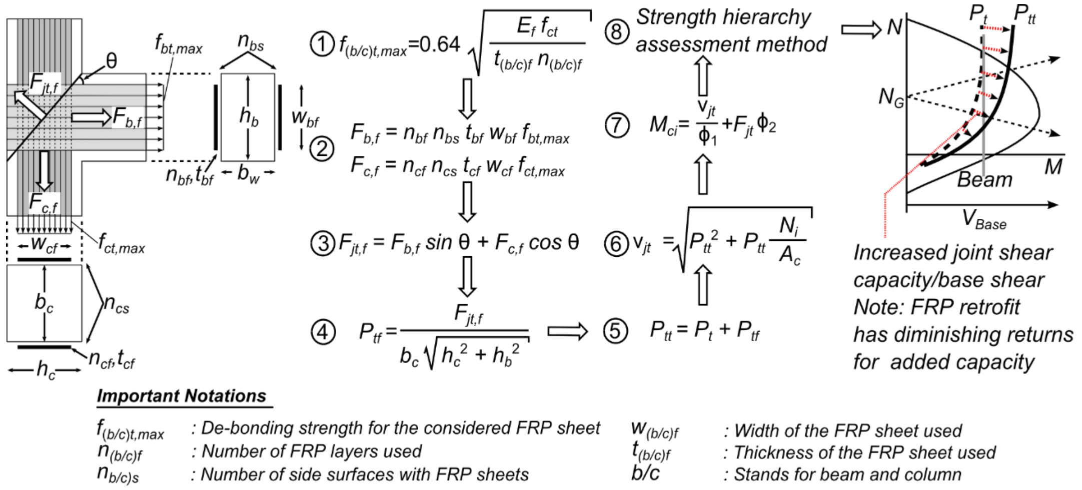


Fig. 7. Assessment of the strengthened capacity of the RC beam-column joints as per strength hierarchy assessment principles [25]

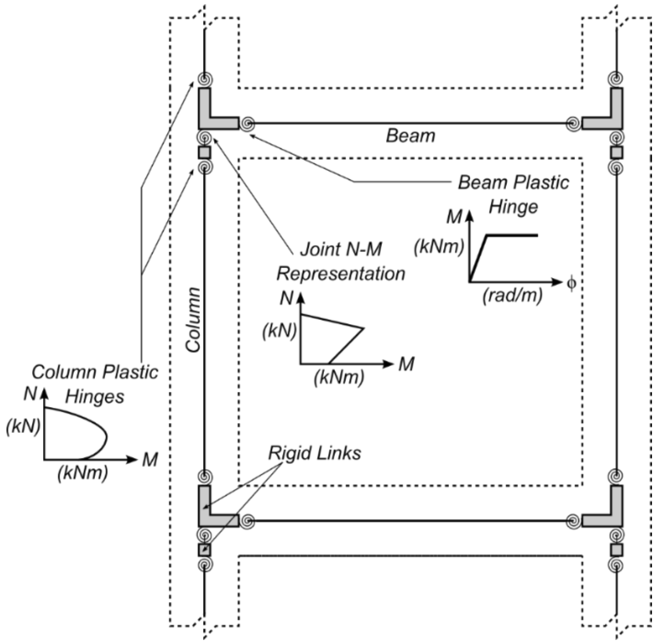


Fig. 8. Structural modeling approach incorporating the joint capacity N-M envelope concept

4.2. Applications in structural modeling of RC beam-column joints

In practice, the typical structural finite element modeling approach is carried out through elastic members with concentrated plasticity at their ends. In most applications, the practicing engineer can easily build a non-linear structural model by defining plastic hinges at the ends of the beams and the columns. On the other hand, the modeling of the RC beam-column joint is a neglected part of the structural model. The reason for this neglect can be attributed to the RC beam-column joints' being neither beams nor columns. As a result, their capacity and response cannot be easily quantified by the engineer. Most of the models developed and used in this regard are mostly utilized in academic research works with no widespread adoption by practicing engineers [26-30]. On the other hand, using the strength hierarchy assessment, the joint shear capacity is represented in the N-M domain, analogous to the column N-M diagram. This facilitates their ease of use in structural models. A generic representation of a structural model formed is shown in Fig. 8. This approach has recently been studied in a post-graduate study [31, 32].

5. Conclusions

Strength hierarchy assessment is the analysis tool used to identify the governing failure mechanism at an RC beam-column joint. The method can be typically used in assessment and strengthening applications as well as potential modeling uses. In this article, a state-of-the-art summary of the method and its applications is reported. For detailed information, the reader is strongly recommended to refer to the related publications.

Conflict of interests

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Data availability statement

No new data were created or analyzed in this study.

References

[1] Fardis MN (2018) Capacity design: early history. Earthquake Engineering and Structural Dynamics 47:2887-2896.
[2] Chen TH (2006) Retrofit strategy of non-seismically designed frame systems based on a metallic haunch system. MSc Dissertation, University of Canterbury.
[3] Akguzel U (2011) Seismic performance of FRP retrofitted exterior RC beam-column joints under varying axial load and bidirectional loading. Ph.D. Dissertation, University of Canterbury: Christchurch.
[4] Kam WY (2010) Selective Weakening and Post-Tensioning for the Seismic Retrofit of Non-Ductile RC Frames. Ph.D. Dissertation, University of Canterbury: Christchurch.
[5] Hertanto E (2005) Seismic assessment of pre-1970s reinforced concrete Structure. MSc Dissertation, University of Canterbury: Christchurch.
[6] Pampanin S, Bolognini D, Pavese A (2007) Performance-based seismic retrofit strategy for existing reinforced concrete frame systems using fiber-reinforced polymer composites. Journal of Composites for Construction 11(2):211-226.
[7] Tasligedik AS, Akguzel U, Kam WY, Pampanin S (2018) Strength hierarchy at reinforced concrete beam-column joints and global capacity. Journal of Earthquake Engineering 22(3):454-487.
[8] NZSEE (2006) Assessment and improvement of the structural performance of buildings in earthquakes. New Zealand Society for Earthquake Engineering.
[9] Smith A, Wilson WM (1915) Wind stresses in frames of office buildings. Journal of Western Society of Engineers XX(4):341-365.
[10] Tasligedik AS (2022) Shear capacity n-m ınteraction envelope for RC beam-column joints with transverse reinforcement: a concept derived from strength hierarchy. Journal of Earthquake Engineering 26(5):2194-2224.
[11] Priestley MJN (1997) Displacement-based seismic assessment of reinforced concrete buildings. Journal of Earthquake Engineering 1(1):157-192.
[12] Pampanin S, Magenes G, Carr AJ (2003) Modeling of shear hinge mechanism in poorly detailed RC beam-column joints. In: Proceedings of FIB 2003: Concrete Structures in Seismic Regions Symposium. Athens, Greece.
[13] TS500-2003 Requirements for Design and Construction of Reinforced Concrete Structures.
[14] NZS 3101.1&2:2006 (Inc A1, A2 A3) Concrete Structures Standard, Standards New Zealand.

[15] Tukey Building Earthquake Code (2018) Disaster and Emergency Management Presidency, Ankara, Turkey.
[16] Beckingsale CW (1980) Post elastic behaviour of reinforced concrete beam-column joints. Ph.D. Dissertation, University of Canterbury: Christchurch.
[17] Pessiki SP, Conley CH, Gergely P, White RN (1990) Seismic behavior of lightly reinforced concrete column and beam-column joint details. NCEER Technical Report No. 90-0014, State University of New York at Buffalo.
[18] Beres A, White RN, Gergely P (1992) Seismic performance of interior and exterior beam-to-column joints related to lightly RC frame buildings: Detailed experimental results. Structural Engineering Report No: 92-7, School of Civil and Environmental Engineering, Cornell University.
[19] Clyde C, Pantelides CP, Reaveley LD (2000) Performance-based evaluation of exterior RC building joints for seismic excitation. PEER Report No: 2000/05, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley.
[20] Pantelides CP, Hansen J, Nadauld J, Reaveley LD (2002) Assessment of RC building exterior joints with substandard details. PEER Report No: 2002/18, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley.
[21] Park S, Mosalam KM (2009) Shear strength models of exterior beam-column joints without transverse reinforcement. PEER Report No: 2009/106, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley.
[22] Vecchio FJ, Collins MP (1986) The modified compression-field theory of reinforced concrete elements subjected to shear. ACI Structural Journal 83(2):219-231.
[23] Cosgun C, Comert M, Demir C, Ilki A (2019) Seismic retrofit of joints of a full-scale 3d reinforced concrete frame with FRP composites. ASCE Journal of Composites for Construction 23(2).
[24] Gokdemir H, Tankut AT (2017) Kiris-kolon birlesim bölgesinin depreme karşı çelik donatılarla güçlendirilmesi. İMO Teknik Dergi 28(3):7977-7992 (in Turkish).
[25] Tasligedik AS (2018) Capacity estimation of FRP strengthened RC beam-column joints using hierarchy of strength assessment. Bulletin of Earthquake Engineering 16(3):1323-1340.
[26] Birely AC, Lowes LN, Lehman DE (2012) A model for the practical nonlinear analysis of reinforced-concrete frames including joint flexibility. Engineering Structures. 34:455-465.
[27] Borghini A, Gusella F, Vignoli A (2016) Seismic vulnerability of existing r.c. Buildings: a simplified numerical model to analyse the influence of the beam-column joints collapse. Engineering Structures. 121:19-29.
[28] Elmorsi M, Kianoush MR, Tso WK (2000) Modeling bond-slip deformations in reinforced concrete beam-column joints. Canadian Journal of Civil Engineering 27:490-505.
[29] Favvata MJ, Izzuddin BA, Karayannis CG (2008) Modelling exterior beam-column joints for seismic analysis of RC frame structures. Earthquake Engıneerıng and Structural Dynamics 37(13):1527-1548.
[30] Youssef M, Ghobarah A (2008) Modelling of RC beam-column joints and structural walls. Journal of Earthquake Engineering 5(1):93-111.
[31] Sahutoglu O (2022) Understanding the Behavior of Modern Reinforced Concrete Beam-Column Joints Towards the Development of a Simplified Structural Model. Middle East Technical University.
[32] Sahutoglu O, Tasligedik AS (2021) Numerical Case Studies Towards the Validation of an RC Beam-Column Joint N-M Interaction Model. In: Proceedings of 6ICEES: 6th International Conference on Earthquake Engineering and Seismology. Kocaeli, Turkey.