A new approach to evaluate failure behavior of reinforced concrete beam-column connections under seismic loads

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SUMMARY
In the design of new buildings, modern seismic codes prevent failure in beam-column connections through the adoption of capacity design approaches. However, plasticity and damage is rarely limited to the beams of RC frames and joint failure or damage can potentially jeopardize the building safety or desired performance. Numerous models have been proposed in the past for representing the seismic behavior of beam-column connections, however there is no clear consensus on methods for identifying their modes of failure. In this paper a complete method for identifying connection failure mechanisms is presented, which employs a number of indices relating to the connection resistance mechanisms that are determined solely from the connection mechanical and geometrical properties, is presented. The method allows the identification of the mode of failure in a manner more detailed than currently available, but maintains simplicity of evaluation. The method is validated against results of 40 experimental tests carried out on beam-column connections sourced from the published literature. A good agreement between the results of the proposed method and experimental results is demonstrated.

Keywords: Beam-Column Joint, Reinforced Concrete Beam-to-Column Connection, Failure mode, Strut and Truss model.

1. INTRODUCTION

In the seismic design of new reinforced concrete (RC) frames, modern seismic codes adopt a capacity design approach to ensure that a hierarchy exists between the strength of columns, joints and beams. The assessment of the performance of RC frames should therefore consider potential failures in the beams, columns and the joints, i.e. in the beam-column connections. Despite the existence of numerous models in the literature for the representation of the cyclic behavior of beam-column connections (e.i. Kim and LaFave 2009, Lee et al. 2009), there is no clear consensus on methods for identifying their modes of failure. According to the most common models in the literature, this shear is transmitted from one side of the joint to another through a truss and strut mechanism. Some other models adopt a plane stress state inside the joint, but they are not well working when the joint becomes greatly cracked, because the stress state. In this paper a simple method is proposed for the evaluation of beam-column connection failure modes from their geometrical and mechanical properties. This proposed model has been validated against the results of 40 experimental tests on beam-column connections found in the literature. Only tests on one-way connections, identified as "seismically designed" (those provided with transversal reinforcement, strong-column-weak beam design and shear-resistant beams), have been used for the validation. Finally, the paper presents a suggested method for incorporating the failure mode identification method in the design verification of beam-column connections in RC frames at Damage Limitation and Ultimate Limit States.
Joint resistance has been defined according to the work of Russo and Somma, 2004 and 2001 relationship that is based on the Paulay and Priestley 1992 model that considers a strut and truss mechanism. The chosen relationship has been adopted because it has been statistically proved that it gives the most accurate and uniform shear connection strength prediction, when compared with

relationships given by ACI 318-99 and Eurocode 8-2005 and by Paulay &Priestley 1992 and Hwang&Lee 2000. In the proposed model four different resistant mechanisms have been identified: the truss, the strut, the confinement and the bond in longitudinal reinforcement. In this research all the four contributions have been evaluated together, in order to define a complete collapse case record and then it has been checked using the test data found in the literature.

2. BACKGROUND TO BEAM TO COLUMN CONNECTION FAILURE MODES

From a review of the literature on beam-column connection behavior in seismically designed RC frames subjected to earthquake excitations, four types of connection failure can be identified:
(1) Beam Failure, B, when the beam develops a plastic hinge;
(2) Joint Failure, J, when the joint fails in shear without the beam yielding;
(3) Beam-Joint Failure, BJ, when beam yielding precedes joint shear failure;
(4) Joint-Beam Failure, JB, when, in rare cases, the joint loses one of its resistant contributions and after that the beam.
Four types of reinforced concrete beam-column joint failure can occur: (1) failure of the concrete strut; (2) failure of the truss; (3) confining reinforcement failure; and (4) all of these depend on bond loss possibility. Strut failure may occur both when the concrete in the joint is in compression (pure strut failure) or in tension and when the joint stirrups reach their ultimate strain (loss of confinement). Loss of bond results in beam longitudinal bar slippage but does not cause the joint failure. The model suggested, in accordance with AIJ 1999 and with Fardis 1994, assumes that: (1) if the bond transfer, that can decrease after reinforcement yielding, is lost, then the shear is transmitted in the compressed area of the strut, limiting the truss contribution; (2) when the truss does not work because of the loss of bond, the entire shear is carried by the strut; (3) the strut resistance is dominated by the concrete resistance, while the transverse reinforcement provides confinement; and (4) stirrup yielding results in a rapid reduction in the concrete resistance.
The chosen model envisages two different mechanisms, the strut and the truss, that together provide in series the entire joint resistance, while confinement and bond in longitudinal reinforcement make the previous two resistant mechanisms work fully functional. Therefore the method takes into account few indexes that correlate the four previous described types of failure.

3. NEW APPROACH FOR THE ASSESSMENT OF BEAM TO COLUMN CONNECTION FAILURE MODES

The proposed model assumes that four mechanisms contribute to the resistance of the beam-column connection: the truss, the strut, confinement and bond of the beam longitudinal reinforcement. The assessment framework proposed in this paper suggests a number of indices to represent each of the four mechanisms and adopts evaluation criteria for failure based on all four indices in order to define a complete failure case record. The framework is summarized in Figure 2, and is based on an evaluation of the following indices for the beam-column joint being assessed:
-The Concrete strut resistance index, $C=V_{JhCR}/V_{ChYB}$, where V_{JhCR} is the concrete strut resistance and V_{ChYB} is the shear acting on the concrete strut at beam yielding;
-The Steel truss resistance index, $S=V_{JhSR}/V_{ShYB}$, where V_{JhSR} is the steel truss resistance and V_{ShYB} is the shear acting on the steel truss at beam yielding;
-The transversal reinforcement ratio index, $A=A_S/A_{Sh}$, where A_S is the Area of the stirrups in the spacing and A_{Sh} is the minimum area of stirrups in the spacing required by ACI 352 2002;
-The anchorage Length index, L=hc/20Ø, where hc is the joint depth, that is considered the anchorage length and 20Ø is the minimum anchorage length required by ACI 318 2011 in order to limit bar slippage;
-The secondary index of concrete strut resistance, $C_{tot}=V_{JhCR}/V_{JhYB}$, where V_{JhCR} is the concrete strut resistance and V_{JhYB} is the total shear acting in the joint at beam yielding;
-The ratio of the secondary concrete strut resistance index and the anchorage length index, $P=C_{tot}/L$.
Indices C and S are related to the joint resistance, while A and L are related to the geometrical

properties of the joint that are important to ensure its resistance. Indices C_{tot} and P are additional indices that are useful in the failure identification. Procedures for evaluating the individual components of the indices are also provided here.

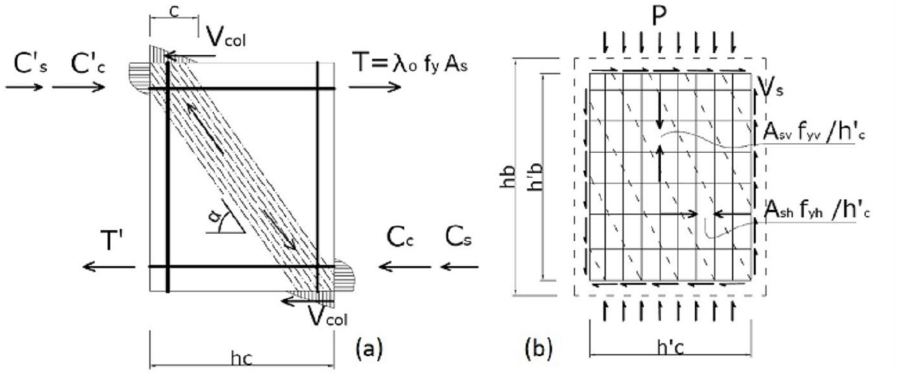


Figure 1. (a) Strut Mechanism; (b) Truss Mechanism; (according to the Model of Paulay and Priestley, 1992)

The concrete strut resistance, V_{jhCR}, (present in C and C_{tot}), can be calculated according to Russo and Somma, 2004, as:

$$V_{JhCR} = 0{,}68 f_{ctk} \sqrt{1 + \frac{\sigma + 1{,}05 \frac{A_C f_{ykC}}{A_J}}{f_{ctk}}}\, h_J b_J \quad (3.1)$$

Where: f_{ctk} is the characteristic concrete tensile strength; σ is the average axial stress in the column (so that both the cases with or without axial load can be considered); A_c is the area of the longitudinal reinforcement in the column; f_{ykc} is the yield stress of the column longitudinal reinforcement; Aj is the transverse joint area; hj and bj are respectively the joint width and depth.

The steel truss resistance, V_{jhSR}, (present in S), can be calculated, according to Russo and Somma, 2004 , as:

$$V_{JhSR} = 0{,}68 \left(5 \frac{f_{ykB} A_{sB,MIN}}{4 h_J b_J} + 4 \frac{f_{ykSt} A_{St\,TOT}}{5 h_J b_J} \right) h_J b_J \quad (3.2)$$

Where: f_{ykB} is the yield stress of the beam reinforcement; $A_{sB,min}$ is the area of the beam longitudinal reinforcement; f_{ykSt} is the yield stress of the joint stirrups; A_{StTOT} is the area of the joint transverse reinforcement; hj and bj are respectively the joint width and depth.

The entire joint resistance can be expressed as the sum of the previous two contributions: strut and truss shown in Figure 1. The shear acting on the two mechanisms can be determined according to Paulay and Priestley, 1992 , as further explained in the Appendix.

The shear acting on the strut ($V_{Ch,yb}$) and truss ($V_{Sh,yb}$) at beam yielding are given by:

$$V_{chyb} = \left(\beta - \frac{\gamma}{\lambda} + \frac{c}{h_c}\left(+ \frac{\gamma}{\lambda} \right) \right) T_{yb} - V_{col,yb} \quad (3.3)$$

$$V_{sh,yb} = \left(1 + \frac{\gamma}{\lambda} \right) \left(1 - \frac{c}{h_c} \right) T_{yb} \quad (3.4)$$

where T_{yb} is the force transmitted by the beam upper reinforcement at yielding, $V_{col,yb}$ is the shear in the column at beam yielding, and all other terms are as defined in the Appendix. Moreover in Paulay and Priestley, 1992, it is assumed that $V_{col,yb} \approx 0{,}15(1+\beta)T_{yb}$, hence:

$$V_{Jh,TOT} = 0{,}85(1 + \beta)T \quad (3.5)$$

Having defined a set of indices to represent the resistance mechanisms, in the following, a detailed failure mode case record is defined, considering each of the failure modes identified so far. The cases concerning JB failures will be omitted for simplicity and also because no JB failure has been found in the literature; for completeness of the indices arrangement, JB case will be however shown in Figure2.

3.1 CASE 1 - Resistant Joint, pure B Collapse

In this case the following combination of indices must be verified:

$$\begin{cases} C \geq 1 \\ S \geq 1 \\ A \geq 1 \\ L \geq 1 \end{cases} \tag{3.8}$$

Both concrete and struct mechanisms of resistance should not fail ($C \geq 1$; $S \geq 1$), confinement should be present ($A \geq 1$) and the bar anchorage should be sufficient ($L \geq 1$). Since the joint resistances are verified, the failure occurs as a plastic hinge in the beam and can be defined a pure B failure.

3.2 CASE 2 - Resistant Joint, Slippage of Beam Longitudinal Reinforcement

In this case the following combination of indices should be verified:

$$\begin{cases} C \geq 1 \\ S \geq 1 \\ A \geq 1 \\ L < 1 \end{cases} \tag{3.9}$$

The strut and truss resistances and reinforcement ratio are sufficient ($C \geq 1$; $S \geq 1$; $A \geq 1$), but the degree of anchorage is insufficient ($L<1$). Since the joint resistances are verified at beam yielding, B failure occurs first. However, as the longitudinal steel yields, the joint loses its bond within a few cycles. This results in the truss mechanism becoming ineffective since the shear cannot be transmitted by the bond to the concrete core. The stresses on the stirrups due to the truss mechanism are reduced and the transverse reinforcement acts only as confinement to the concrete core. The entire shear must be carried by the strut and the index C_{tot} can be used to identify two different failure cases:

-if $C_{tot} \geq 1$, BS failure occurs; which is a B failure characterized by longitudinal reinforcement yielding;

-if $C_{tot}<1$, BJC failure occurs; which is a BJ failure characterized by a concrete compression failure following the beam yielding and after the loss of bond in longitudinal bars.

3.3 CASE 3 - Insufficient Confinement

In this case the following combination of indices must be verified:

$$\begin{cases} C \geq 1 \\ S \geq 1 \\ A < 1 \\ L \lesseqgtr 1 \end{cases} \tag{3.10}$$

Here, the resistance of truss and strut are verified ($C \geq 1$; $S \geq 1$), but there is insufficient confinement ($A<1$). Hence the stirrups yield and the entire shear is carried by the strut. Moreover the concrete fails in tension because it is not confined. The presence of sufficient or not anchorage ($L>1$;$L<1$) is not relevant because the loss of bond happens in any case following the concrete dilatation. Due to stirrup yielding the truss cannot provide effective shear resistance so the index C_{tot} is used to evaluate the strut resistance. In order to determine the possible failure modes resulting from insufficient confinement, experimental results for beam-column connections observed to fail according to Case 3 were compiled from the literature and are presented in Table 1. The $P=C_{tot} / L$ index, that has a meaning only inside this Case, can be used. From observing Table 1 it can be seen that, while the main indices are not correlated with the failure, the indices P can determine the B or BJ failure. The values of P vary between 0,2 and 1,2 and, when $P>1$ only failures of type B occur, with BJ elsewhere. Based on this limited set of experimental observations, it can therefore be supposed that:

-If $P>1$, Bt failure occurs; this is a B failure characterized by the stirrups yielding; the ultimate

deformation should be greater than in Case 1 -B failures. The failure is of B type because the strut contribution and bond resistance are sufficient;
-If P<1, BJt failure occurs; this is of BJ-type with the final failure being characterized by the joint concrete failing in tension.

Table 1. Indices Evaluated for Connections Seen in Published Experimental Tests to Fail According to Case 3

Reference	Test	Test Collapse	C	S	A	L	C_{tot}	P
(Kamimura T, 2000)	Sp4	B	2,09	1,08	0,53	0,78	0,71	0,91
(Lee JY p. 2009)	B1	B	5,61	1,22	0,94	1,09	1,27	1,16
(Joh O, 2000)	PL16	B	2,31	1,14	0,54	0,94	0,79	0,84
(Noguchi H, 1992)	OKJ4	BJ	1,12	1,10	1,00	1,15	0,27	0,24
(Joh O, 2000)	PL10	BJ	2,19	1,11	0,52	1,50	0,75	0,50
(Lee JY p. 2009)	BJ2	BJ	3,37	1,01	0,94	1,09	0,76	0,70
(Lee JY p. 2009)	BJ3	BJ	4,21	1,09	0,94	1,09	0,95	0,87
(Joh O, 2000)	PL13	BJ	1,97	1,10	0,58	1,15	0,67	0,58
(Joh O, 2000)	PH16	BJ	1,72	1,15	0,85	0,94	0,59	0,63
(Kamimura T, 2000)	Sp2	BJ	1,39	1,00	0,53	0,78	0,47	0,61
(Kamimura T, 2000)	Sp3	BJ	1,39	1,10	0,86	0,78	0,47	0,61
(Joh O, 2000)	PH13	BJ	1,49	1,10	0,80	1,15	0,51	0,44
(Joh O, 2000)	PH10	BJ	1,70	1,13	0,84	1,50	0,58	0,39

3.4 CASE 4 - Insufficient Truss Resistance

In this case the following combination of indices must be verified:

$$\begin{cases} C \geq 1 \\ S < 1 \\ A \lesseqgtr 1 \\ L \lesseqgtr 1 \end{cases} \tag{3.11}$$

The truss mechanism fails (S<1), therefore the beam cannot reach its yield capacity. Once the stirrups yield, J-type failure occurs and the full shear is carried by the strut. A portion of the shear is however sustained by the longitudinal reinforcement, $V_{jhLR}=0,85A_{s,min}f_{ykB}$ / (bj hj), first addendum of Equation (3.2). If the bond is maintained, this implies that there is a reduction in the shear carried by the Strut. V^*_{jhLR} , can be estimated as:

$$V^*_{jhLR} = V_{jhLR}\,\zeta \tag{3.12}$$

where $\zeta=(\gamma+\lambda)/(\gamma_0+\lambda_0)$ is a the acting shear reduction factor. A dummy variable, the slip coefficient δ, can be introduced such that $\delta=0$ when bar slippage is likely and $\delta=1$ when the bond is ensured. For Case 4, since the beam does not yield, the C_{tot} index cannot be used, and a new index is introduced:

$$C^*_{tot} = \frac{V_{JhCR}}{V_{Jhb}-\delta\zeta V_{JhLR}} \tag{3.13}$$

A variation of the C^*_{tot} index, here called $C_{fin,tot}$, is obtained when the reinforcement bars have yielded, if the anchorage length is sufficient to ensure the bond demand, i.e. $\delta=1$ and $\zeta=1$ because the reinforcement bars reach their undimensional yield stresses λ_0 and γ_0. Finally, the following types of failure are identified for Case 4:
-J_{SC} failure: a J failure characterized by concrete shear crushing; this happens when one of the cases below (Jsc1, Jsc2 or Jsc3) is satisfied:

$$J_{SC1}\begin{cases} L \geq 1 \\ C^*_{tot} = \dfrac{V_{jhCR}}{V_{jhb} - \delta\zeta\, V_{jhLR}} \geq 1 \\ C^{fin}_{tot} = \dfrac{V_{jhCR}}{V_{jhyb} - V_{jhLR}} \geq 1 \end{cases} \quad J_{SC2}\begin{cases} 1 > L \geq \zeta \\ C^*_{tot} = \dfrac{V_{jhCR}}{V_{jhb} - \delta\zeta\, V_{jhLR}} \geq 1 \\ C^{fin}_{tot} = \dfrac{V_{jhCR}}{V_{jhyb}} < 1 \end{cases} \quad J_{SC3}\begin{cases} L \geq \zeta \\ C^*_{tot} = \dfrac{V_{jhCR}}{V_{jhb} - \delta\zeta\, V_{jhLR}} < 1 \end{cases}$$

-JB failure elsewhere: the first joint failure due to stirrups yielding is followed by beam failure. It must be highlighted that no examples of JB failure have been found in the literature.

3.5 CASE 5 - Insufficient Strut Resistance

In this case the following combination of indices must be verified:

$$\begin{cases} C < 1 \\ S \geq 1 \\ A \lesseqgtr 1 \\ L \lesseqgtr 1 \end{cases} \tag{3.14}$$

In this failure mode the strut collapse (C<1) causes failure of the joint in J mode. The presence or not of good bond is not important. The variations in the failure modes that can occur are as follows:
-if A≥1, J_C failure occurs. This is a J failure characterized by a well-confined joint, hence the concrete fails in compression with little deformation;
-if A<1, J_{CS} failure happens. This is a J collapse characterized by a poorly confined joint, where the stirrups yield and the concrete fails in tension.

3.6 CASE 6 Similar to Cases 4 and 6

In this case the following combination of indices must be checked:

$$\begin{cases} C < 1 \\ S < 1 \end{cases} \tag{3.15}$$

In this case no resistance is provided by the concrete strut and by the truss (C<1; S<1). The joint performance is determined by the weaker of the two mechanisms.
In Figure 2 all failure modes and indices that characterize them are summarized. The table can be read from left to right. The last two columns define the effective failure process and typical levels of deformation. For the latter, small joint ultimate distortions are regarded to be around 0,01rad, while large distortions are regarded to be in the range 0,03÷0.06rad.

4. VALIDATION OF PROPOSED METHOD WITH PUBLISHED EXPERIMENTS

The identified beam-column connection failure modes derive from theory and from observations made on a number of experiments carried out for the evaluation of connection shear strength in the literature (Kamimura et al. 2000, Goto and Joh 1996, Noguchi and Kurusu 1988, Blakeley et al. 1973, Lee et al. 2009, Joh and Goto 2000, Noguchi and Kashiwazaki 1992, Owada 2000, Kitayama et al. 1992, 1987, and 1991). The test data collected is insufficient for a statistical analysis to be carried out. However, the data is used here to check the validity of the proposed failure mode assessment method and indices used. The majority of the tests reported in the literature have been carried out on two-dimensional connections where beam ends are restrained from vertical displacements while the column is hinged at the bottom and subjected to the storey shear at the top. Cyclic load histories are typically applied, (adopting a displacement control), where the applied displacement is increased by 30% every three cycles. The tests used to verify the proposed failure mode assessment method are presented in Table 2, where their observed failure mode is compared to the one predicted by the proposed method. It can be seen that only 5 of the 39 connections report a predicted collapse different from the one observed in the tests. It is noted that the failure modes observed in the tests in Table 2 were not always explicitly stated by the authors or sufficient information provided for their detailed interpretation. However, the experimental detail was sufficient for these specimens to be assigned to the B, J, BJ and JB failure modes, and a "?" has been used in Table 2 to indicate these tests. In the following sections the four failure modes (B, J, BJ, JB) will be analyzed together with the six failure cases above (see sections 3.1 to 3.6) indicating those tests that confirmed the failure predictions.

4.1 B Failure

The B failure can be one of the following types: B (case1), Bs (case2) and Bt (case3).
In the B failure column of Table 2, the specimen Sp4 tested by Kamimura, 2000 is evaluated as a Bt failure with a tested ultimate joint distortion of about 0,0011rad, while the specimens N5 and N7 tested by Noguchi, 1988 are evaluated as a pure B failure and are characterized by deformations of about 0,0035Rad. As predicted (see Figure 2-deformations column) in the second tests smaller deformations are observed. The pure B collapse is the one that the designer must achieve to avoid a premature joint failure and to allow the beam to develop its plastic hinge. This important goal is not reached in the B_S of Case 2, where the beam bar slippage causes a tensile stress concentration at the beam-joint section; while in the B_t of Case 3 the stirrup yielding does not permit the truss mechanism activation because of the ineffectiveness of bond.

4.2 BJ Failure

BJ failure can be one of the following types: BJc (case2) and BJt (case3).
These two different failure modes involve different ultimate deformations. BJ_C collapse is characterized by the compressive failure of the concrete in the diagonal strut and this generates a reduced ultimate deformation (as testified for example by test Sp5 by Kamimura, 2000 with a distortion of 0,009rad). On the other hand BJ_t failure is characterized by a tensile concrete failure in the joint, with a greater deformation than the previous case (this is testified for example by the Sp3 test of Kamimura, 2000 with a distortion of 0,061rad and by the OKJ4 test of Noguchi, 1992 with 0,042rad). In any case it can be said that BJ failures present large distortions, with values around 0,04÷0,06rad.

4.4 J Failure

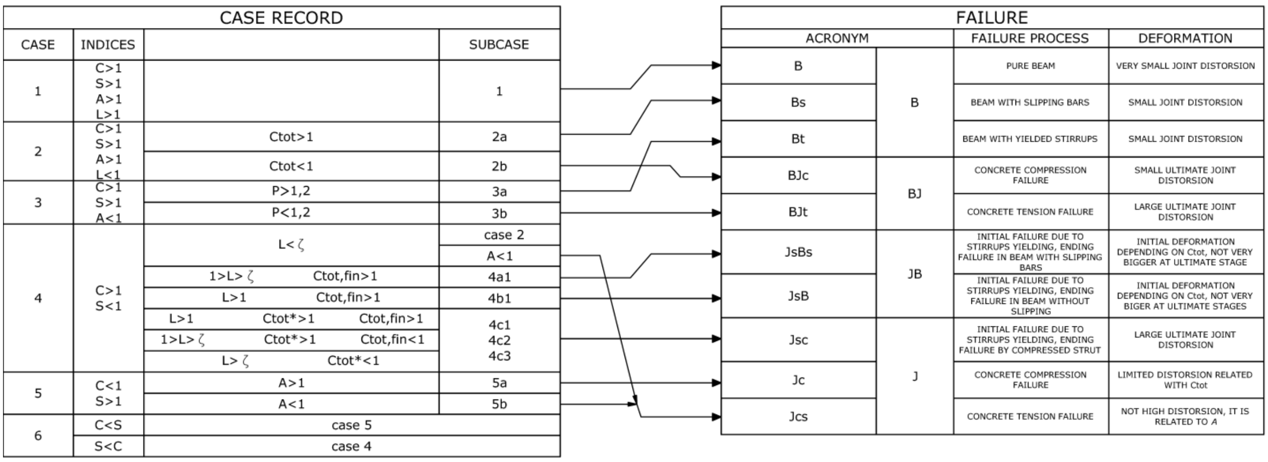
J failure can be one of the following types: Jsc (case4), Jc (case 5) and Jcs (case 5).
Regarding J_{SC} failures a logarithmic relationship between joint shear distortion and the C^*_{tot} index has been found and it seems reasonable to suppose that this relationship may be a fundamental one, as if the concrete strut is strong ($C^*_{tot}>1$), then less strain must develop, on the contrary, if the strut is weak ($C^*_{tot} <1$) then the diagonal compression strain increases and consequently so does the shear distortion. Regarding J_C and J_{CS} failures no clear conclusion can be made due to the small number of experiments found with these failure modes.

4.5 Discussion of the Reliability of the Proposed Method

From the comparison carried out between the test data and the theoretical failure modes the reliability of the developed method can be regarded as high. Only 5 of the 39 joints present a different type of collapse from that predicted by the method, and in two of these cases some of the determined indices are too close to 1 to reliably determine the real failure mode (for example Sp5 Kamimura 2000).
Three J failure evaluations (Jsc3 Collapses) do not agree with the authors indications (BJ failure). This is due to the fact that both BJ and J failures are characterized by a final concrete compression cracking in the joint (this is indicated by the “J”), while the first stage of the failure involves the yielding of the longitudinal reinforcement at the beam-joint interface section for BJ failures and yielding of the transverse reinforcement in the joint for J_{SC} failures. This difference can be easily misunderstood during test evaluation because of problems in positioning of the measurement apparatus.
Errors resulting from the failure mode evaluation method can be due to two other reasons. The first one is that the method is extremely sensitive to the data used in the index evaluation, as every denominator represents the forces acting that are calculated through the effective material resistances. A second source of error is to the uncertainty associated with the use of semi-empirical relationships (Equations (3.1) and (3.2)) in the resistance evaluations.

Table 2. Comparison of the Observed Failure Modes of Tests Found in the Literature and those Calculated

B Failure			BJ Failure			J Failure		
Reference	failure		Reference	failure		Reference test	failure	
	test	evaluated		test	evaluated		test	evaluated
(Blakeley RWG, 1973)			(Joh O, 2000)			(Goto Y, 1996)		
U1	?	B	PL10	B	BJt	JMO	J	Jc
U3	?	B	PL13	BJ	BJt	JLO	J	Jcs
(Joh O, 2000)			PH16	BJ	BJt	(Kamimura T, 2000)		
PL16	B	Bt	PH13	BJ	BJt	Sp1	BJ	Jsc3
(Kamimura T, 2000)			PH10	BJ	BJt	(Kitayama K p. 1987)		
Sp4	B	Bt	(Kamimura T, 2000)			C1	BJ	Jsc3
(Lee JY p. 2009)			Sp5	B	BJc	J1	J	Jsc3
B1	B	Bt	Sp2	BJ	BJt	(Kitayama K, 1991)		
(Noguchi H, 1988)			Sp3	BJ	BJ	B1	?	Jsc3
N°5	B	B	(Lee JY p. 2009)			B3	?	Jsc3
N°7	B	B	BJ1	BJ	BJc	(Kitayama K, 1992)		
			BJ2	BJ	BJt	I3	?	Jsc2
			BJ3	BJ	BJt	I1	?	Jsc3
			(Noguchi H, 1992)			I5	?	Jsc3
			OKJ4	BJ	BJt	I6	?	Jsc3
						(Lee JY p. 2009)		
						J1	J	Jsc3
						(Noguchi H, 1988)		
						No2	J	Jsc3
						No4	J	Jsc3
						(Noguchi H, 1992)		
						OKJ3	J	Jcs
						OKJ5	J	Jcs
						OKJ6	J	Jcs
						OKJ1	BJ	Jsc3
						OKJ2	J	Jsc3
						(Owada Y, 2000)		
						JO5	J	Jcs



* in the acronyms used for indicating the FAILURE modes, we'll use Capital letters to define the FAILURE way in Beam or Joint, while we'll use lower case letters to define the joint component that generate the FAILURE: "c" conpression of concrete, "t" tension of concrete, "s" yielding of stirrups (when postponed to J) or of longitudinal armours (when postponed to B). For example a "Jc" FAILURE indicate a J FAILURE with compression concrete failure.

Figure 2. The Proposed Framework for Determination of Beam-Column Connection Failure Mode

5. CONCLUSIONS

The failure behavior of beam-column connections cannot be evaluated considering only one parameter such as the shear stress level reached in the joint or the percentage of joint transverse reinforcement. In the determination of beam-column connection failure modes, mechanisms contributing to the joint resistance need to be considered. These are: the concrete strut; the truss generated by longitudinal and transversal armors and by the concrete core; the one due to the stirrups that contrasts the concrete expansion and finally the bond of the longitudinal reinforcement. This paper presents a behavioral model that analyzes the failure process and that defines four main failure modes (B, BJ, JB, J), each one characterized by a number of sub-cases. The suggested method adopts a number of defined indices to represent the resistance contributions of the mechanisms identified, that can be evaluated from knowledge of the geometric and mechanical properties of the beam-column connection. Each failure mode and sub-case can be identified by checks carried out on a combination of the indices, and is simple to carry out. The method is validated against the results of experiments on two-dimensional RC beam-column joints found in the literature, and is proven to be effective in predicting failure modes. The index evaluation and the method is seen to be sensitive to the accuracy of data regarding the geometric and mechanical properties of the connections and in particular to the as-built material resistances. Two important aspects of this method are firstly that it is based on knowledge of the geometrical and mechanical properties of the connection only and secondly that it works well for the prediction of B-type failures (and sub-classes). As B-failures are the desired type of failure in the seismic design of connections, the method and indices can be used as part of a design verification in order to identify desirable B-failure modes that do not result in non-repairable damage.

APPENDIX –DETERMINATION OF SHEAR ALIQUOTS ACTING ON STRUT AND TRUSS ACCORDING TO PAULAY AND PRIESTLEY

From Figure 1, by analyzing the strut, the following relationship can be reported:

$$V_{ch}=C'_c-V_{col}+\Delta T'_c \tag{A-1}$$

Where: C'_c is the beam concrete corner compression force; V_{col} is the column shear force; and $\Delta T'_C=C'_S+T_S$ depends on the bond. C'_S is the beam reinforcement compression force; T_S is the beam reinforcement tensile force. When the beam reaches its yielding the terms assume an additional subscript X_{yb}.
If A_S is the longitudinal reinforcement area and f_{yk} is its characteristic yielding strength, it can be also expressed that:

$$\begin{cases} T = f_{yk}A_s\lambda \quad \text{where } \lambda = \frac{f_s}{f_y} \quad \text{usually } \lambda_{max} = 1{,}25 \\ C'_s = f_{yk}A_s\gamma \quad \text{where } \gamma = \frac{f_s}{f_y} \quad \text{usually } \gamma_{min} = 0{,}8 \end{cases} \tag{A-2}$$

Let suppose that tangential tension brought by beam bars is constant and that acts along a length of $0{,}8c$ where c depends on the axial load. Hence $\Delta T'_C=(T+C'_S)\ c / h_c=(1+\gamma/\lambda)T\cdot c/h_C$. Now, since $T'=C'_S+C'_C$ because of the horizontal equilibrium of forces acting on a joint side, it can be obtained that $C'_C=(\lambda A'_S-\gamma A_S)f_y$. If $\beta=A_{Sinf} / A_{Ssup}$ it can be written that $C'_C=(\beta-\gamma/\lambda)A_{Sfy}$. Now, by using the Equation (A-1) and the relationships found above, the aliquot that acts on the Strut is:

$$V_{ch} = \left(\beta - \frac{\gamma}{\lambda} + \frac{c}{h_c}\left(+\frac{\gamma}{\lambda}\right)\right)T - V_{col} \tag{A-3}$$

Analyzing the Truss, the following Equation is found:

$$V_{sh} = \left(1 + \frac{\gamma}{\lambda}\right)\left(1 - \frac{c}{h_c}\right)T \tag{A-4}$$

Moreover in Pauly and Priestley, 1992, Authors assume that $V_{COL} \approx 0{,}15(1+\beta)T$, hence:

$$V_{jh}=0{,}85(1+\beta)T \tag{A-5}$$

Equations (A-3), (A-4) and (A-5) represent the two aliquots and the total shear acting on the joint.

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