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Assessment of RC exterior beam-column Joints based on artificial neural networks and other methods

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ABSTRACT

A database on the behaviour of reinforced concrete external beam-column joint sub-assemblages established from the results of over 150 tests is developed and used for the development, training and validation of an artificial neural network (ANN) based model. The ANN model predictions on the mode of failure and load-carrying capacity of the joints, together with the predictions of widely used code methods and those of a recently proposed method, which does not require calibration through the use of test data, are compared with their counterparts stored in the database developed herein. The comparison confirms the already reported shortcomings of current code methods and demonstrates that both ANN model and the recently proposed method can provide reliable alternatives to the code methods.

1. Introduction

The structural assessment of reinforced concrete (RC) beam-column joints is normally based on the design methods incorporated in current codes of practice such as, for example, ACI 318 [1] and EC2 [2]-EC8 [3]. However, in spite of the considerable research carried out to date on the subject, the code specified amount of stirrup reinforcement exhibits significant discrepancies. An example of such discrepancies has been reported in Ref. [4] where it was shown that the amount of stirrup reinforcement specified by EC2 and EC8 can be more than four times the amount specified by ACI 318. And yet, even for such a case, designing a beam-column joint in accordance with the EC2 and EC8 provisions for the design of earthquake-resistant structures cannot safeguard structural performance which satisfies the code requirements; in fact, not only does the joint suffer considerable cracking before the formation of a plastic hinge in the adjacent beam, but also such cracking occurs at early load stages, and thus violates the assumption of 'rigid joint' which underlies the methods adopted in practice for structural analysis [5]. Similar results have been obtained from a number of investigations [6–9]. It appears from the above, therefore, that the need for a reliable structural assessment method is as urgent as ever.

To this end, the present work has been aimed at developing a procedure suitable for the structural assessment of RC external beam-column joints in the form of an analytical algorithm derived through the use of artificial neural networks (ANNs). In fact, the use of ANNs has already led to the development of analytical algorithms found to produce very accurate predictions of the behaviour of simply-supported RC beams [10]. In contrast with most methods proposed to date, those incorporated in current code methods included, the development of an ANNs-based procedure does not rely on preconceived theories describing the mechanism of load transfer within a structural element or structure which are subsequently calibrated through the use of experimental data, but on the ability of the ANNs to produce the closest possible fit to such data.

In what follows, the description of the development of the proposed procedure is preceded by the presentation of the database used in the subsequent stages of the work and followed by a discussion of the results obtained from the application of the proposed procedure for predicting the mode of failure and load-carrying capacity of the external RC beam-column joints comprising the database. Finally, the proposed procedure's predictions are compared with their ACI 318 and EC2-EC8 counterparts in an attempt to obtain an indication of the effectiveness of the current code methods. The procedure's predictions are also used to establish the effectiveness of one of the methods proposed as an alternative to those adopted by current codes, this method being selected not only because it has been claimed to be effective (on the basis of a comparative study of its predictions with experimental

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information, not however as extensive as that included in the database developed in the present work) [5], but also, unlike any other method proposed to date, has been derived without the need of calibration with data obtained from tests on RC beam-column joints [10].

2. Experimental database

The database developed for the needs of the present work comprises experimental information on 153 exterior reinforced concrete beam-column joint sub-assemblages, such as those schematically shown in Fig. 1, obtained from the literature. This experimental information includes design details, material properties and structural response to the imposed loading history such as load-deflection curves, failure mode and load-carrying capacity. The linear elements (beam and columns) of these sub-assemblages are considered to represent the portions of frame-type structures extending between the joint-element interface and the nearest point of contra-flexure (point of zero bending moment). In most cases, the beam-column sub-assemblages were subjected to transverse loading (cyclic or monotonic) usually applied near the beam end, and only in a small number of cases near the end of the upper column. In most of the sub-assemblages the transverse load was combined with a constant axial compressive force exerted concentrically at the end of the upper column.

The parameters widely considered to affect the behaviour of the joints are: the dimensions of the beam/column elements and the joint; the compressive strength of concrete; the amount, arrangement and yield stress of the longitudinal (tensile and compressive) reinforcement of beams and columns; the amount, arrangement and yield stress of the transverse and diagonal reinforcement of the joints; the amount of the imposed axial load on the upper column element; the height of the column; and the distance between the beam/column-joint interface and the point of application of the transverse load.

Full design details and description of the experimentally-established behaviour of the external RC beam-column joint sub-assemblages forming the database developed can be found in the relevant publications [4,7,9,12–39] which describe most of the work carried out to date on the subject.

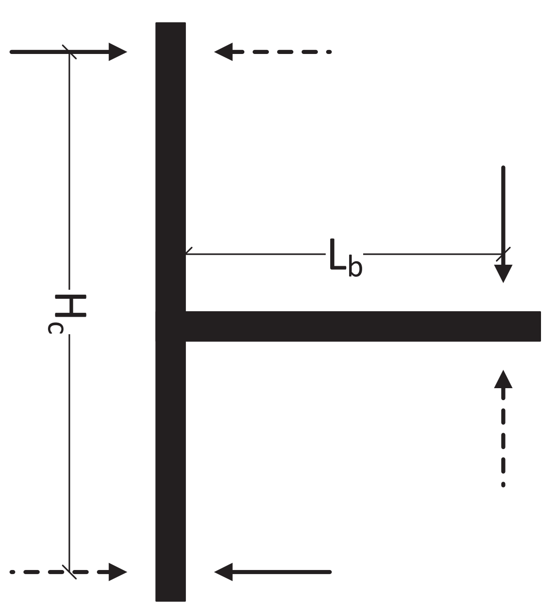

Fig. 1. Schematic representation of the structural forms investigated.

3. Development of artificial neural networks procedure

3.1. Background information

Artificial neural networks is a type of artificial intelligence technique that mimics the manner in which the human brain functions. ANNs are used to estimate or approximate functions depending on a large number of input parameters the effect of which is not clearly established or quantified. They have the ability to learn, generalize, categorize and predict values due to their adaptive nature and their ability to remember information introduced to them during their training. Over the last years they have been applied in various aspects of science and engineering; in the present work ANNs are used to predict the mode of failure and load-carrying capacity of external RC beam-column joint sub-assemblages, with the load-carrying capacity being also expressed in the form of the horizontal shear force developing at the joint mid height.

Free-forward multilayered networks (MLP), as shown in Fig. 2, are used in the present work. These ANNs consist of a number of layers (input, several hidden and output layers) organized strictly in one direction, each of them being a system of interconnected "neurons" (or otherwise referred to as nodes). Fig. 2 depicts a typical MLP ANN with one of its constituent neurons being shown in Fig. 3. From Fig. 2, it can be seen that the ANN consists of three layers – input, hidden and output layers – with the input layer comprising k neurons, the hidden layer three neurons and the output layer two neurons.

From Figs. 2 and 3, it can also be seen that the link forming between consecutive neurons is assigned a specific weight, which is multiplied with the input values generated by the neurons. The values obtained from all neurons of a specific layer are then transferred through the links and summed up with the bias (see Fig. 2). This latter sum is introduced into a predefined activation function representing the relationship between layers and is described as follows:

$$y_i = g_i = g\left(\sum_{j=1}^{k} W_{ji}x_j + \theta_i\right) \tag{1}$$

where y_i is the output from the ANN; x_j are the input values; w_{ji} are the weight coefficients; Θ_i is the bias value; and g is the activation function which is usually a sigmoid, a tan-sigmoid or a linear function. In the present work, sigmoid activation functions are used for the input and hidden layers and tan-sigmoid for the output layer.

3.2. Input and output data

The input and output/target data have been obtained from the database and organized in a tabular form. The selection of the parameters used as input data has been based on the commonly shared view that these parameters have a dominant effect on beam-column joint behaviour [1–3]. They are the following: the uniaxial cylinder compressive strength (f_c) of concrete; the cross-sectional beam width (b_b) and height (h_b); the cross-sectional column width (b_c) and height (h_c); the beam (M_{Rb}) and column (M_{Rc}) flexural capacities; column's longitudinal reinforcement ratio (ρ_c), the beam's tensile (ρ_{bt}) and compressive (ρ_{bc}) longitudinal reinforcement ratio; the product ($\rho_s f_{ys}$) of the yield stress (f_{ys}) and the reinforcement ratio (ρ_s) of the joint stirrups; the product ($\rho_d f_{yd}$) of the yield stress (f_{yd}) and the reinforcement ratio (ρ_d) of the horizontal component of the diagonal reinforcement of the joints; the vertical reinforcement ratio (ρ_{sv}) of the joints; the column height (H_c) (see Fig. 1); and the distance of the beam-joint interface from the point of application of the transverse load (L_b).

Since the code structural performance requirements for the beam-column joints are linked with their mode of failure and

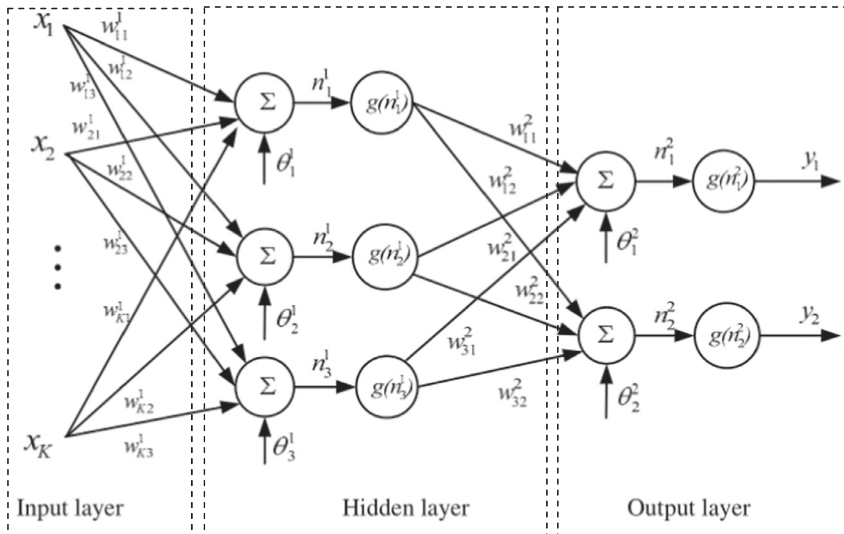

Fig. 2. A typical artificial neural network.

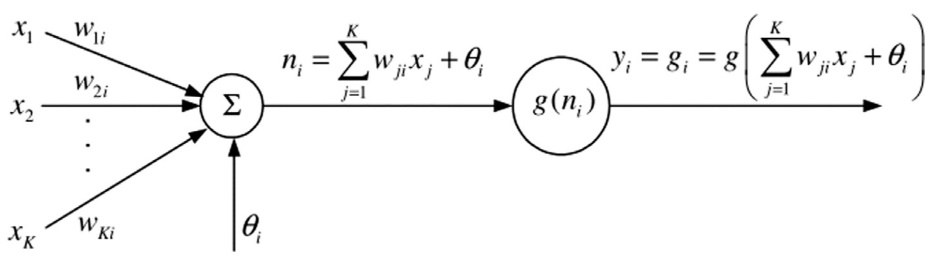

Fig. 3. A typical artificial neuron.

load-carrying capacity, these two parameters have been used as target data. The modes of failure (FM_{exp}) are classified as joint failure (JF) or beam failure (BF); the load-carrying capacity is represented by the transverse load (P_{max}) applied on the beam-column sub-assemblage and by the shear capacity (V_{jh}) of the horizontal mid-height cross section of the joint (see Appendix). The maximum and minimum values of the input and target values are shown in Table 1, whereas the values of all input parameters are shown in Table A1 in Appendix A. It should also be noted that, as discussed later, in order to minimize the likelihood of numerical instabilities and/or low convergence rates, the values of the input and target parameters have been normalized in the range [0,1] or [0.1,0.9].

Table 1
Maximum and minimum values of the input and target parameters.

Parameters/targets	Max value	Min value	Unit
f_c	93	18.09	MPa
h_c	500	200	mm
b_c	500	100	mm
ρ_c	0.0739	0.0058	–
M_{Rc}	733	13	MPa
h_b	610	200	mm
b_b	406	100	mm
M_{Rb}	488.2	16.5	MPa
ρ_{tb}	0.0287	0.0029	–
ρ_{cb}	0.0287	0.0022	–
$\rho_s f_{ys}$	6.526	0.000	MPa
$\rho_d f_{yd}$	3.303	0.000	MPa
ρ_{vs}	0.014	0.000	–
H_c	3581	800	mm
L_b	3048	600	mm
P_{max}	284	10.5	kN
V_{jh}	1316.4	65	kN
FM_{exp}	BF	JF	–

3.3. ANN procedure architecture

The number of neurons of the input layer is determined from the number of the parameters considered to have a significant effect on structural behaviour. In the present work, two sets of parameters are investigated: set 1 consisting of fifteen parameters, those in lines 1 to 15 in Table 1, and set 2 consisting of twelve parameters, those of set 1 except for parameters ρ_c, ρ_{tb} and ρ_{cb} in lines 4, 9 and 10 of Table 1, since these parameters are allowed for in the calculated values of the beam and column flexural capacities. Therefore, as regards the number k of the neurons in the input layer (see Fig. 1), two cases are investigated: $k = 15$ and $k = 12$.

The selection of the number of neurons comprising the hidden layers is usually based on the outcome of a parametric study. Such a parametric study carried out in previous work concerned with the use of ANNs for assessing the load-carrying capacity and mode of failure of RC beams has shown that the use of nine neurons produces very close predictions [11]. Therefore, the same number of neurons has been adopted in the present work.

As regards the output layer, this consists of one neuron, which is either the load-carrying capacity or the mode of failure. The load-carrying capacity is calculated in the form of the transverse load (P_{max}) applied on the beam-column sub-assemblage and of the shear capacity of the horizontal cross section at mid-height of the joint, whereas the output values for BF and JF are 1 and 2, respectively.

In view of the above, the ANNs models adopted for the present work are models 1 and 2 with the same number of neurons (9 and

1) in the hidden and output layers, but differing in the number of neurons (15 against 12) of the input layer. In order to investigate the effect of the use of the normalization equations on the ANNs predictions, each of the models 1 and 2 are subdivided into models 1(a) (ANN1) and 1(b) (ANN2) and models 2(a) (ANN3) and 2(b) (ANN4) in which the input data are normalized in the range [0,1] or [0.1,0.9], respectively.

3.4. Training, validation and testing of the ANNs

The process of training a neural network involves tuning the values of the weights and biases of the network, which are initially randomly assigned, to optimize network performance according to an iterative process. The default performance function for feed forward networks is the mean square error mse – the average squared error between the network outputs. It is defined as follows:

$$F = mse = \frac{1}{N}\sum_{i=1}^{N}(T_i - O_i)^2 \tag{2}$$

where T and O are the target and output values respectively.

The error of each output node is computed from the difference between the computed output and the desired output (target). To minimize the error obtained at each iteration, such as the output values of the ANN essentially agree with the target values, the back-error propagation algorithm (or Delta rule) is employed. This process is carried out from right to left of the ANN and makes use of the information provided from the database. According to this process, after the error is computed, the weights and biases are readjusted in order to obtain more accurate outputs and thus smaller errors. To enhance the performance and accurate predictions of the ANN, the normalized data (inputs and targets) is initially and randomly divided into three sub-sets for training, validation and testing purposes. In the present work 60% of the sets of inputs and target outputs is used for training, 20% for validation and 20% for testing.

Learning algorithms are classified as local or global algorithms; furthermore the methods used for dealing with the problem of weights and biases calibration may also be classified as deterministic or probabilistic. Global algorithms make use of knowledge regarding the state of the entire network, such as the direction of the overall weight update vector. In the widely used back-propagation global learning algorithm the gradient descent algorithm is used. As regards local adaptation strategies, these are based on specific information of the weight values such as the temporal behaviour of the partial derivative of the weights. The local approach is better related to the ANNs concept of distributed processing, where the computations are performed independently. Moreover, it appears that for many applications local strategies achieve faster and more reliable predictions than global techniques [40], this is why such a method was adopted in the current study of deterministic nature.

This iterative process, which can be schematically be seen in Fig. 4 is repeated until one of the following conditions is met:

I. The maximum number of 100 iterations (epochs) of training after which the algorithm terminates the training process
II. A maximum of 6 validation failures are exhibited. Validation failure occurs when the performance of the ANN during each iteration fails to improve or remains constant.
III. The value of performance goal becomes 10^{-6} expressing the difference between the target and output values and
IV. The minimum performance gradient becomes 10^{-10}.

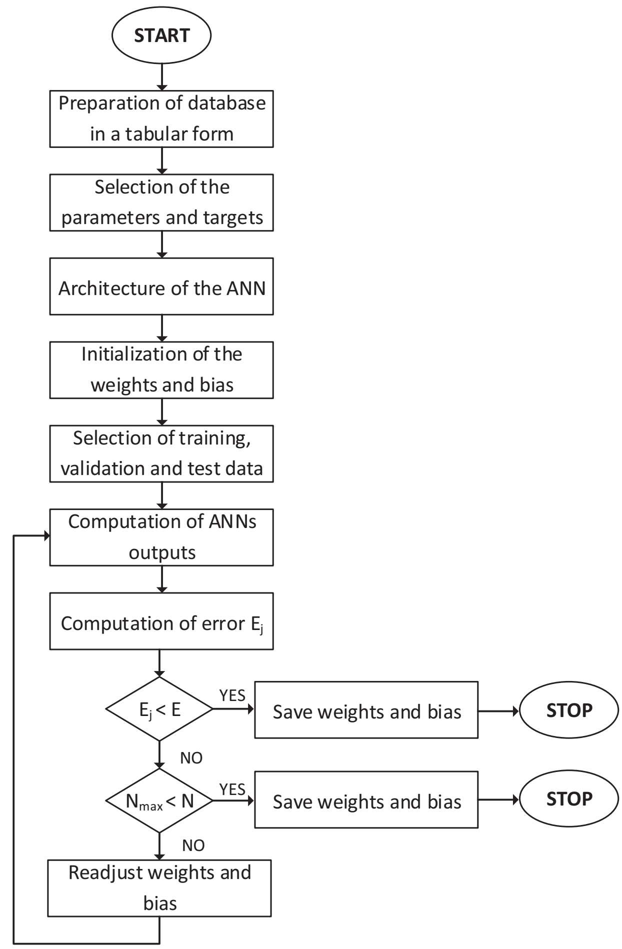

Fig. 4. Calibration procedure of the ANN model.

4. Comparative studies

The four ANN models investigated have been used to predict the transverse load-carrying capacities (P_{ANN1}, P_{ANN2}, P_{ANN3}, P_{ANN4}) of the beam-column sub-assemblages of the database developed in the present work. The mean values and standard deviations of the results obtained are summarized in a normalized form (resulting by dividing the calculated values of load-carrying capacity with their experimental counterparts P_{EXP}) in Table 2; the full results are presented in Table A2 in Appendix A.

From Table 2, it can be seen that both the number of neurons of the input layer and the expressions used for normalizing the input data investigated have a negligible for practical purposes effect on the models' predictions. However, in contrast with widely held views, normalization within the range [0,1], rather than within the range [0.1,0.9], resulted the smallest values of standard deviation. Therefore, in what follows, the ANNs predictions have been based on the use of Model 4.

The number of successful ANN predictions of the types of failure suffered by the structural forms investigated are shown in Table 3; detailed predictions are provided in Table A3. Both tables also include the predictions obtained from the methods incorporated in two widely used codes of practice, ACI 318 and EC2-EC8, together with those of the method proposed by Kotsovou & Mouzakis [41]. A concise description of the latter methods is provided in Appendix B. It should be noted that the code methods are calibrated through the use of values which form a safe envelope to the available experimental data and not mean values such

Table 2
Mean values and standard deviation of the load-carrying capacities calculated by the ANNs models investigated for the structural forms of the database developed.

Models:	1	2	3	4
Normalised load-carrying capacity:	P_{ANN1}/P_{EXP}	P_{ANN2}/P_{EXP}	P_{ANN3}/P_{EXP}	P_{ANN3}/P_{EXP}
Mean values:	1.019	1.027	1.002	0.994
Standard deviations:	0.194	0.182	0.176	0.150

Table 3
Number of successful predictions of the types of failure of the structural forms investigated obtained by ANNs and selected currently used methods.

Number of predictions								
Total (T)	Successful (S)							
	ANNs		ACI 318		EC2-EC8		Kotsovou & Mouzakis	
	S	S/T	S	S/T	S	S/T	S	S/T
153	147	0.96	87	0.57	105	0.69	138	0.90

as those of the database used in the present work for training and validating the ANN developed models. On the other hand, the Kotsovou & Mouzakis model has been developed without the need of calibration through the use of experimental information on the behaviour of beam-column joint elements. And yet, from Table 3, it can be seen that, in spite of the conservative nature (excluding the use of safety factors assumed to be equal to 1 for the purposes on the present work) of the code methods, the successful predictions of the type of failure suffered by the structural elements investigated are significantly fewer than those of the Kotsovou& Mouzakis method which exhibited a rather small deviation (of the order of 5%) from those of the ANNs, the latter providing the best predictions.

The methods used to predict the type of failure suffered by the structural elements contained in the database have also been used to predict the 'shear' capacity of the elements characterized by joint failure. From Table A3, it can be seen that 101 of the 153 elements of the database exhibited joint failure. The mean values and the standard deviations of the models' predictions are shown in Table 4which also includes the number of the predictions used to obtain the mean values and corresponding standard deviations. The detailed results are shown in Table A4 in Appendix A.

It should be noted that the values obtained through the use of the ACI 318 and EC2-EC8 methods are not predictions of 'shear' capacity, but maximum permissible values of the shear force developing at the joint mid height under the load applied to the beam-column joint sub-assemblages investigated. It is the specified stirrup reinforcement of the joint that is expected to delay joint failure until plastic hinge formation at the beam joint interface, but, unlike the Kotsovou & Mouzakis method, the codes do not provide any formula linking the amount of such reinforcement with the 'shear' capacity of the joint. Therefore, as regards the ACI 318 and EC2-EC8 methods, the values included in Tables 4 and A4 are the upper limits of 'shear' capacity calculated only for the structural elements with stirrup reinforcement in accordance with the code specifications. From the tables, it can be seen that the number of such elements is rather small.

Unlike the code specifications, the Kotsovou & Mouzakis method links the amount of stirrup reinforcement with the value of 'shear' force that should be sustained by the joint so as to prevent failure before the formation of plastic hinge formation at the beam-joint interface. From both the detailed results (Table A4) and their summary (Table 4), it can be seen that the method produces safe predictions of 'shear' capacity in all cases investigated.

Finally, ANNs produce the closest estimate of joint 'shear' capacity. However, it should be reminded that the method is empirical by nature and, therefore, it is only by implication that the predicted values refer to 'shear' capacity, since the method has been trained using values of 'shear' capacity. Moreover, the predicted values obtained are as valid as the experimental information used to train and validate the method.

5. Conclusions

The development of ANNs, which is based on a detailed mathematical approach allowing for all parameters found experimentally to affect joint behaviour but not considering any mechanism of load transfer such as those underlying most of the seismic design beam-column joints methods introduced to date, is found to produce predictions of the joint strength which correlate very closely with the experimentally-established values. It is also found capable of predicting the mode of failure of beam-column sub-assemblages in over 95% of the 153 cases investigated.

On the other hand, not only it is not possible to assess joint strength through the use of current code methods, but also these methods are found unable to predict the mode of failure of beam-column joint sub-assemblages, which is considered an indication of their inability to safeguard the code requirement for failure of the sub-assemblages due to the formation of a plastic hinge at the beam-column interface, before the joint suffering significant cracking. These findings confirm already reported similar findings.

In contrast with current code methods, the method proposed by Kotsovou & Mouzakis method, which unlike any other method proposed to date does not require calibration through the use of experimental data on joint behaviour, is found capable of predicting the mode of failure of external beam-column joint sub-

Table 4
Mean values and standard deviation of the shear capacities calculated by ANNs, ACI 318, EC2-EC8, and the Kotsovou & Mouzakis methods.

Methods:	ANNs	ACI 318	EC2-EC8	Kotsovou & Mouzakis
Normalised shear capacity:	V_{ANN1}/V_{EXP}	V_{ACI}/V_{EXP}	V_{EC}/V_{EXP}	$V_{K\&M}/V_{EXP}$
Number of predictions:	101	5	23	101
Mean values:	0.99	1.262	1.487	0.71
Standard deviations:	0.064	0.328	0.365	0.39

assemblages in over 90% of the 153 cases investigated and safe predictions of the joint load-carrying capacity.

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Appendix A. Results of comparative studies in table form

Table A1
Values of input parameters.

Spec.name	f_c MPa	h_c mm	b_c mm	ρ_{col} %	M_{Rc} kNm	h_b mm	b_b mm	ρ_t %	$\rho_{c\ (\%)}$ %	M_{fb} kNm	$\rho_s f_{yh}$ MPa	$\rho_d f_{yd}$ MPa	ρ_{sv} MPa	H_c mm	L_b mm
Hanson & Conner [12]															
I	39.4	381	381	6.50	733	508	305	1.86	0.93	384	2.14	0.00	1.40	3289	3048
I-A	36.7	381	381	7.04	727	508	305	1.86	0.93	356	1.34	0.00	1.40	3289	3048
II	41.1	381	381	7.39	678	508	305	1.86	0.93	360	2.52	0.00	1.40	3289	3048
V	37.4	381	381	6.42	710	508	305	1.86	0.93	379	0.00	0.00	1.40	3289	3048
Megget L.M. [13]															
Unit A	22.1	380	330	3.49	192	460	255	1.28	1.28	178	3.33	0.00	0.62	3000	1400
Uzumeri S.M. [14]															
6	36.2	381	381	3.54	450	508	381	1.14	0.76	297	3.81	0.00	0.89	3048	3048
7	30.7	381	381	3.32	416	508	381	1.14	0.76	293	1.95	0.00	0.89	3048	3048
8	26.3	381	381	3.13	403	508	381	1.51	1.14	377	3.89	0.00	0.89	3048	3048
Paulay & Scarpas [15]															
UNIT 1	22.6	457	457	2.58	292	610	356	0.94	0.94	302	2.12	0.00	0.60	3430	2235
UNIT 2	22.5	457	457	2.58	292	610	356	1.39	1.39	438	2.12	0.00	0.60	3430	2235
UNIT 3	26.9	457	457	2.58	302	610	356	0.94	0.94	304	1.07	0.00	0.60	3430	2235
Park & Milburn [16]															
Unit 3	38.2	406	305	1.46	211	457	229	1.90	1.90	215	2.17	0.00	0.51	3350	2667
Unit 4	38.9	406	305	1.46	213	457	229	2.57	2.57	286	2.71	0.00	0.51	3350	2667
Eshani & Wight [7]															
1B	33.6	300	300	3.68	143	480	259	1.81	1.81	271	2.67	0.00	0.63	2134	1524
2B	35	300	300	4.44	174	440	259	1.99	1.99	246	2.92	0.00	0.63	2134	1524
3B	40.9	300	300	3.68	152	480	259	1.81	1.81	275	4.01	0.00	0.63	2134	1524
4B	44.6	300	300	4.44	180	440	259	1.99	1.99	251	4.37	0.00	0.63	2134	1524
5B	24.3	340	340	5.99	304	480	300	1.80	1.80	297	2.36	0.00	0.88	2210	1067
6B	39.8	340	340	2.76	193	480	300	1.34	1.34	278	2.36	0.00	0.49	2210	1067
Eshani et al. [17]															
1	64.7	340	340	3.18	197	480	300	0.91	0.91	231	3.68	0.00	0.49	3454	1575
2	67.3	340	340	3.18	223	480	300	1.10	1.10	277	3.68	0.00	0.49	3454	1575
3	64.7	300	300	4.28	192	439	259	1.24	1.24	220	4.56	0.00	0.63	3454	1575
4	67.3	300	300	5.58	228	439	259	1.54	1.54	270	4.56	0.00	0.86	3454	1575
5	44.6	300	300	4.43	171	439	259	1.99	1.99	251	4.38	0.00	0.62	2134	1524
Kaku & Asakuka [18]															
1	31.7	220	220	1.81	51	220	160	1.59	1.59	39	1.17	0.00	0.00	1540	890
2	41.7	220	220	1.81	47	220	160	1.59	1.59	39	1.17	0.00	0.00	1540	890
3	41.7	220	220	1.81	28	220	160	1.59	1.59	39	1.17	0.00	0.00	1540	890
4	44.7	220	220	1.81	61	220	160	1.59	1.59	39	0.33	0.00	0.00	1540	890
5	36.7	220	220	1.81	43	220	160	1.59	1.59	39	0.33	0.00	0.00	1540	890
6	40.4	220	220	2.32	28	220	160	1.59	1.59	39	0.33	0.00	0.00	1540	890
7	32.2	220	220	2.47	53	220	160	1.59	1.59	39	1.17	0.00	0.59	1540	890
8	41.2	220	220	2.47	51	220	160	1.59	1.59	39	1.17	0.00	0.59	1540	890
9	40.6	220	220	2.47	37	220	160	1.59	1.59	39	1.17	0.00	0.59	1540	890
10	44.4	220	220	2.47	68	220	160	1.59	1.59	39	1.17	0.00	0.59	1540	890
11	41.9	220	220	2.47	51	220	160	1.59	1.59	39	1.17	0.00	0.59	1540	890
12	35.1	220	220	2.47	36	220	160	1.59	1.59	39	0.33	0.00	0.59	1540	890
13	46.4	220	220	2.47	27	220	160	1.59	1.59	39	1.17	0.00	0.59	1540	890
14	41	220	220	1.93	43	220	160	1.59	1.59	39	0.33	0.00	0.26	1540	890
15	39.7	220	220	2.08	45	220	160	1.59	1.59	39	0.33	0.00	0.29	1540	890
16	37.4	220	220	4.48	63	220	160	1.59	1.59	39	1.17	0.00	1.07	1540	890
17	39.7	220	220	1.42	20	220	160	1.59	1.59	39	1.17	0.00	0.26	1540	890
18	40.7	220	220	1.11		220	160	1.59	1.59	39	1.17	0.00	0.26	1540	890
Fuji & Morita [19]															
B1	30	220	220	2.58	41	250	160	2.87	2.87	81	0.90	0.00	0.59	1500	890
B2	30	220	220	2.58	41	250	160	2.87	2.87	81	0.90	0.00	0.59	1500	890
B3	30	220	220	2.58	41	250	160	2.87	2.87	81	0.90	0.00	0.59	1500	890
B4	30	220	220	2.58	41	250	160	2.87	2.87	81	2.39	0.00	0.59	1500	890

Table A1 (*continued*)

Spec.name	f_c MPa	h_c mm	b_c mm	ρ_{col} %	M_{Rc} kNm	h_b mm	b_b mm	ρ_t %	ρ_c (%) %	M_{fb} kNm	$\rho_s f_{yh}$ MPa	$\rho_d f_{yd}$ MPa	ρ_{sv} MPa	H_c mm	L_b mm
Eshani & Alameddine [20]															
LH8	55.8	356	356	4.00	275	508	318	1.48	1.48	397	5.88	0.00	0.61	3581	1600
HL8	55.8	356	356	5.48	352	508	318	1.88	1.88	488	3.92	0.00	1.20	3581	1600
HH8	55.8	356	356	5.48	352	508	318	1.88	1.88	488	5.88	0.00	1.20	3581	1600
LH11	73.8	356	356	4.00	283	508	318	1.48	1.48	411	5.88	0.00	0.61	3581	1600
LH14	93.8	356	356	4.00	287	508	318	1.48	1.48	424	5.88	0.00	0.61	3581	1600
Kurose Y. [21]															
S41	24.3	300	300	2.99	107	380	260	1.28	1.28	140	1.98	0.00	0.00	1500	750
S42	24.3	300	300	2.99	107	380	260	1.28	1.28	140	0.99	0.00	0.00	1500	750
U41L	26.7	300	300	2.99	107	380	260	1.28	1.28	140	1.98	0.00	0.00	1500	750
Ha et al. [22]															
Spec. 2	41.2	200	200	2.88	36	200	150	1.43	1.43	27	1.86	0.00	0.36	800	800
Spec. 4	68.6	200	200	2.88	39	200	150	1.43	1.43	28	1.86	0.00	0.36	800	800
Karayannis et al. [23]															
J2b	22.1	200	100	1.83	14	200	100	0.58	0.58	17	2.21	0.00	0.00	1700	1000
J0	20.8	200	100	1.83	13	200	100	0.58	0.58	17	0.00	0.00	0.00	1700	1000
J2b	26.2	200	100	1.83	14	200	100	0.87	0.87	25	2.21	0.00	0.00	1700	1000
JX2b	18.1	200	100	1.83	13	200	100	0.87	0.87	24	2.21	1.40	0.00	1700	1000
JX0	23.9	200	100	1.83	14	200	100	0.58	0.58	17	0.00	1.40	0.00	1700	1000
Chen & Chen [24]															
JC	20	500	500	2.27	372	500	300	1.60	1.60	344	2.23	0.00	0.41	2840	2250
Hakuto et al. [25]															
Unit O6	34	460	460	1.71	217	500	300	0.68	1.02	129	0.10	0.00	0.00	3200	1675
Clyde et al. [26]															
No.2	46.2	457	406	2.31	436	406	305	2.46	2.46	367	0.00	0.00	0.42	2570	1270
No.4	41	457	406	2.31	415	406	305	2.46	2.46	363	0.00	0.00	0.42	2570	1270
No.5	37	457	406	2.31	398	406	305	2.46	2.46	360	0.00	0.00	0.42	2570	1270
No.6	40.1	457	406	2.31	411	406	305	2.46	2.46	363	0.00	0.00	0.42	2570	1270
German M. [27]															
#3,#6	21	254	254	1.41	36	305	254	0.47	0.47	37	0.69	0.00	0.00	1219	864
El-Amoury & Ghobarah [28]															
T0	30.6	400	250	2.79	253	400	250	1.38	1.38	183	0.00	0.00	0.35	2850	1670
Pantelides et al. [29]															
Unit 5	31.7	406	406	2.90	380	406	406	1.85	1.85	368	0.00	0.00	0.00	3200	1524
Unit 6	31	406	406	2.90	476	406	406	1.85	1.85	368	0.00	0.00	0.00	3200	1524
Antonopoulos & Triantafilou [30]															
C1	19.4	200	200	1.87	30	300	200	0.87	0.87	66	0.00	0.00	0.00	1300	1000
C2	23.7	200	200	1.87	31	300	200	0.87	0.87	67	0.00	0.00	0.00	1300	1000
S-C	19.3	200	200	1.87	30	300	200	0.87	0.87	66	0.44	0.00	0.00	1300	1000
Atta et al. [31]															
G1-A	67	200	200	2.44	49	400	200	0.83	0.22	79	0.60	0.00	0.00	2400	600
G1-B	36	200	200	2.44	27	400	200	0.83	0.22	77	0.60	0.00	0.00	2400	600
G1-C	33	200	200	2.44	49	400	200	0.83	0.22	77	0.60	0.00	0.00	2400	600
G2-B	60	200	200	2.44	48	400	200	0.83	0.22	79	0.00	0.00	0.00	2400	600
G2-C	65	200	200	2.44	49	400	200	0.83	0.22	79	0.91	0.00	0.00	2400	600
G3-B	62	200	200	2.44	48	400	200	0.83	0.22	79	0.47	0.00	0.00	2400	600
G3-C	68	200	200	2.44	49	400	200	0.83	0.22	79	0.60	0.00	0.00	2400	600
G3-E	68	200	200	2.44	49	400	200	0.83	0.22	79	0.60	0.00	0.00	2400	600
G3-F	62	200	200	5.78	50	400	200	0.83	0.22	79	1.03	0.00	1.01	2400	600
Chutarat & Aboutaha [32]															
Spec. I	27.6	406	406	4.08	397	457	356	1.41	1.41	368	4.06	0.00	0.94	2438	2134
Spec. A	33.1	406	406	2.58	252	457	356	0.55	0.55	157	4.06	0.00	0.47	2438	2134
Hwang et al. [9]															
0T0	67.3	420	420	5.17	513	450	320	1.60	1.60	340	0.00	0.00	0.93	2700	1900
3T44	76.8	420	420	5.29	511	450	320	1.60	1.60	343	6.12	0.00	0.93	2700	1900
3T3	69	420	420	5.27	506	450	320	1.60	1.60	340	1.59	0.00	0.93	2700	1900
2T4	71	420	420	5.29	506	450	320	1.60	1.60	341	1.36	0.00	0.93	2700	1900
1T44	72.8	420	420	5.29	508	450	320	1.60	1.60	342	1.36	0.00	0.93	2700	1900
3T4	75.2	450	450	4.56	599	450	320	1.60	1.60	386	2.50	0.00	0.81	2700	1900
2T5	76.6	450	450	4.59	599	450	320	1.60	1.60	387	1.85	0.00	0.81	2700	1900
1T55	69.7	450	450	4.59	592	450	320	1.60	1.60	384	1.85	0.00	0.81	2700	1900
Shiohara & Kursuhaqra [33]															
B2	28.3	300	300	1.55	74	300	300	1.60	1.60	135	0.00	0.00	0.28	1470	1200

(*continued on next page*)

Table A1 (*continued*)

Spec.name	f_c MPa	h_c mm	b_c mm	ρ_{col} %	M_{Rc} kNm	h_b mm	b_b mm	ρ_t %	ρ_c (%) %	M_{fb} kNm	$\rho_s f_{yh}$ MPa	$\rho_d f_{yd}$ MPa	ρ_{sv} MPa	H_c mm	L_b mm
Tsonos A.G. [34]															
A1	35	200	200	2.21	40	300	200	0.58	0.58	42	4.35	0.00	0.39	1400	900
E1	22	200	200	4.05	55	300	200	0.86	0.86	58	4.35	0.00	0.77	1400	900
E2	35	200	200	4.31	60	300	200	0.57	0.57	41	4.35	0.00	0.77	1400	900
E3	20	200	200	2.90	48	300	200	0.84	0.84	66	4.35	0.00	0.57	1400	900
G1	22	200	200	4.05	55	300	200	0.86	0.86	58	3.55	0.00	0.77	1400	900
G2	20	200	200	2.90	48	300	200	0.84	0.84	66	3.55	0.00	0.57	1400	900
Karayannis et al. [35]															
J0	31.6	300	200	0.58	37	300	200	0.87	0.87	70	0.00	0.00	0.00	1500	1000
JS	31.6	286	186	0.62	35	300	200	0.87	0.87	70	0.98	0.00	0.00	1500	1000
JX10	31.6	300	200	1.15	59	300	200	0.87	0.87	70	0.00	1.68	0.00	1500	1000
JX12	31.6	300	200	1.41	69	300	200	0.87	0.87	70	0.00	3.30	0.00	1500	1000
Karayiannis et al. [36]															
A0	31.6	200	200	0.91	21	300	200	0.29	0.29	25	0.00	0.00	0.00	1500	1000
A1	31.6	200	200	0.91	21	300	200	0.29	0.29	25	0.98	0.00	0.00	1500	1000
A2	31.6	200	200	0.91	21	300	200	0.29	0.29	25	1.94	0.00	0.00	1500	1000
A3	31.6	200	200	0.91	21	300	200	0.29	0.29	25	2.92	0.00	0.00	1500	1000
B0	31.6	300	200	0.58	37	300	200	0.87	0.87	70	0.00	0.00	0.00	1500	1000
B1	31.6	300	200	0.58	37	300	200	0.87	0.87	70	0.98	0.00	0.00	1500	1000
C0	31.6	300	200	1.69	69	300	200	0.83	0.83	67	0.00	0.00	0.26	1500	1000
C2	31.6	300	200	1.69	69	300	200	0.83	0.83	67	1.94	0.00	0.26	1500	1000
C3	31.6	300	200	1.69	69	300	200	0.83	0.83	67	2.92	0.00	0.26	1500	1000
C5	31.6	300	200	1.69	69	300	200	0.83	0.83	67	4.86	0.00	0.26	1500	1000
Chalioris et al. [37]															
JA-0	34	300	200	1.69	70	300	200	0.83	0.83	67	0.00	0.00	0.26	1500	1000
JA-s5	34	300	200	1.69	70	300	200	0.83	0.83	67	4.86	0.00	0.26	1500	1000
JA-X12	34	300	200	2.52	101	300	200	0.83	0.83	67	0.00	2.42	0.26	1500	1000
JA-X14	34	300	200	2.82	112	300	200	0.83	0.83	67	0.00	3.30	0.26	1500	1000
JB-0	31.6	300	200	0.58	37	300	200	0.87	0.87	70	0.00	0.00	0.00	1500	1000
JB-s1	31.6	300	200	0.58	37	300	200	0.87	0.87	70	0.98	0.00	0.00	1500	1000
JB-X10	31.6	300	200	1.15	59	300	200	0.87	0.87	70	0.00	1.68	0.00	1500	1000
JB-X12	31.6	300	200	1.41	69	300	200	0.87	0.87	70	0.00	2.42	0.00	1500	1000
JCa-0	20.6	200	100	1.15	15	200	100	0.58	0.58	19	0.00	0.00	0.00	1500	1000
JCa-X10	20.6	200	100	2.31	25	200	100	0.58	0.58	19	0.00	3.30	0.00	1500	1000
Jca-s1	20.6	200	100	1.15	15	200	100	0.58	0.58	19	2.37	0.00	0.00	1500	1000
Jcas1X10	20.6	200	100	2.31	25	200	100	0.58	0.58	19	2.37	3.30	0.00	1500	1000
Jca-s2	20.6	200	100	1.15	15	200	100	0.58	0.58	19	4.72	0.00	0.00	1500	1000
Jcas2X10	20.6	200	100	2.31	25	200	100	0.58	0.58	19	4.72	3.30	0.00	1500	1000
JCb-0	23	200	100	1.15	15	200	100	0.87	0.87	28	0.00	0.00	0.00	1500	1000
JCb-X10	23	200	100	2.31	26	200	100	0.87	0.87	28	0.00	3.30	0.00	1500	1000
JCb-s1	23	200	100	1.15	15	200	100	0.87	0.87	28	2.37	0.00	0.00	1500	1000
JCbs1X10	23	200	100	2.31	26	200	100	0.87	0.87	28	2.37	3.30	0.00	1500	1000
JCb-s2	23	200	100	1.15	25	200	100	0.87	0.87	28	4.72	0.00	0.00	1500	1000
JCbs2X10	23	200	100	2.31	26	200	100	0.87	0.87	28	4.72	3.30	0.00	1500	1000
Wong & Kuang [38]															
BS-L-300	34.1	300	300	2.42	182	300	260	1.34	1.34	123	0.00	0.00	0.00	2695	1232
BS-L-450	30.9	300	300	2.42	176	450	260	0.86	0.86	196	0.00	0.00	0.00	2695	1232
BS-L-600	36.4	300	300	2.42	186	600	260	0.64	0.64	270	0.00	0.00	0.00	2695	1232
BS-L-V2	32.6	300	300	3.10	202	450	260	0.86	0.86	196	0.00	0.00	0.35	2695	1232
BS-L-V4	28.3	300	300	3.65	212	450	260	0.86	0.86	196	0.00	0.00	0.70	2695	1232
BS-L-H1	33.3	300	300	2.42	180	450	260	0.86	0.86	196	0.58	0.00	0.00	2695	1232
BS-L-H2	42.1	300	300	2.42	196	450	260	0.86	0.86	198	1.16	0.00	0.00	2695	1232
Ha & Cho [39]															
NJC	29.6	200	200	2.76	43	200	150	1.47	1.47	27	5.36	0.00	0.39	900	900
HJC	49.5	200	200	2.76	54	200	150	1.47	1.47	28	5.36	0.00	0.39	900	900
Kotsovou & Mouzakis [4]															
S1	35	300	300	3.88	166	450	300	0.99	0.99	264	6.53	0.00	0.70	3000	1050
S2	35	300	300	3.88	166	450	300	0.99	0.99	264	6.53	0.00	0.70	3000	1050
S2’	35	300	300	3.88	166	450	300	0.99	0.99	264	6.53	0.00	0.70	3000	1050
S3	35	300	300	3.88	166	450	300	0.99	0.99	264	4.89	0.00	0.70	3000	1050
S4	35	300	300	3.88	166	450	300	0.99	0.99	264	1.91	1.45	0.70	3000	1050
S5	35	300	300	4.05	187	450	300	0.99	0.99	264	1.91	1.59	0.75	3000	1050
Koutsovou & Mouzakis 11,40															
S6	35	400	400	1.86	239	450	300	0.99	0.99	264	1.41	2.56	0.28	3000	1050
S9	35	400	400	1.86	239	450	300	0.99	0.99	264	3.31	0.00	0.28	3000	1050
S10	35	300	300	3.21	151	450	300	0.50	0.50	140	1.61	1.59	0.75	3000	1050
S11	35	400	400	1.86	239	450	300	0.99	0.99	264	3.31	0.00	0.28	3000	1050

Table A2
Ann's predictions of the load-carrying capacity of the beam-column joint sub-assemblages of the database.

Specimen name	Experimental results	NNs result Model 1		NNs result Model 2		NNs result Model 3		NNs result Model 4	
	P_{EXP}	P_{NN1}	P_{NN1}/P_{EXP}	P_{NN2}	P_{NN2}/P_{EXP}	P_{NN3}	P_{NN3}/P_{EXP}	P_{NN4}	P_{NN4}/P_{EXP}
Hanson & Conner [12]									
I	126	103.9	0.825	123.1	0.977	103.2	0.819	124.4	0.987
I-A	102	85.7	0.841	103.1	1.011	91.2	0.894	105.2	1.032
II	117	116.6	0.996	128.0	1.094	117.5	1.004	128.4	1.098
V	90	93.6	1.040	100.9	1.121	91.9	1.021	75.3	0.837
Megget L.M [13]									
Unit A	166	211.2	1.273	157.4	0.948	162.3	0.978	170.1	1.025
Uzumeri S.M [14]									
6	115	123.2	1.071	130.4	1.134	116.9	1.017	114.8	0.998
7	115	114.1	0.992	96.6	0.840	113.5	0.987	113.4	0.986
8	166	135.3	0.815	154.4	0.930	116.1	0.699	109.4	0.659
Paulay & Scarpas [15]									
UNIT 1	160	158.6	0.991	136.0	0.850	158.6	0.991	128.4	0.803
UNIT 2	222	219.6	0.989	212.0	0.955	221.6	0.998	224.4	1.011
UNIT 3	170	177.1	1.041	128.1	0.754	173.5	1.021	152.6	0.898
Park &Milburn [16]									
Unit 3	100	106.9	1.069	98.0	0.980	99.2	0.992	106.1	1.061
Unit 4	100	102.1	1.021	105.2	1.052	123.6	1.236	130.7	1.307
Eshani & Wight [7]									
1B	148	157.4	1.063	152.2	1.028	150.8	1.019	92.9	0.628
2B	136	155.5	1.143	152.7	1.123	152.1	1.118	121.7	0.895
3B	184	163.3	0.887	173.5	0.943	156.0	0.848	148.8	0.809
4B	172	160.7	0.934	164.0	0.954	156.5	0.910	171.1	0.995
5B	167	176.3	1.056	148.6	0.890	171.9	1.030	163.3	0.978
6B	162	195.1	1.204	177.2	1.094	184.3	1.137	165.0	1.018
Eshani et al. [17]									
1	166	221.5	1.335	163.1	0.982	170.9	1.029	164.6	0.992
2	187	218.4	1.168	197.7	1.057	174.7	0.934	190.5	1.019
3	138	141.9	1.028	150.2	1.089	147.5	1.069	205.9	1.492
4	156	152.5	0.978	163.2	1.046	156.5	1.003	218.3	1.399
5	170	161.2	0.948	163.1	0.960	156.4	0.920	170.3	1.002
Kaku & Asakuka [18]									
1	54.1	52.6	0.973	46.6	0.861	48.7	0.900	47.9	0.886
2	54.6	57.3	1.049	55.3	1.012	53.6	0.982	47.0	0.860
3	47.4	59.7	1.260	49.9	1.053	54.3	1.146	44.7	0.943
4	52.2	52.3	1.002	60.4	1.157	52.1	0.998	47.6	0.912
5	48.2	49.5	1.027	49.5	1.027	45.7	0.947	45.9	0.952
6	45.7	62.2	1.362	48.1	1.052	51.9	1.137	43.8	0.958
7	54.3	40.7	0.750	49.5	0.912	41.4	0.763	50.1	0.922
8	53.2	47.1	0.885	49.1	0.923	48.1	0.904	47.8	0.899
9	51.5	48.8	0.948	45.7	0.888	48.1	0.934	46.1	0.895
10	53	47.0	0.887	52.1	0.984	50.7	0.956	49.6	0.935
11	50.4	47.6	0.945	48.9	0.971	48.7	0.967	47.7	0.947
12	45.3	42.1	0.929	40.6	0.897	40.7	0.899	45.3	0.999
13	45.7	54.6	1.196	43.7	0.957	53.3	1.167	43.5	0.953
14	49.3	49.7	1.008	45.2	0.916	49.5	1.004	45.6	0.925
15	50.3	49.9	0.992	44.4	0.883	48.6	0.967	46.1	0.916
16	54.8	38.9	0.711	58.4	1.065	44.6	0.814	53.0	0.968
17	38.5	48.2	1.252	41.2	1.069	49.7	1.292	44.1	1.144
18	26	46.4	1.784	37.9	1.457	49.3	1.896	41.6	1.601
Fuji & Morita [19]									
B1	59.8	62.2	1.040	66.4	1.110	60.7	1.016	62.6	1.046
B2	52	62.2	1.196	66.4	1.276	60.7	1.168	62.6	1.203
B3	66.7	62.2	0.933	66.4	0.995	60.7	0.911	62.6	0.938
B4	69.7	67.4	0.967	81.6	1.171	68.2	0.979	65.4	0.938
Eshani & Alameddine [20]									
LH8	240	252.5	1.052	271.6	1.132	251.9	1.050	261.5	1.089
HL8	262	250.0	0.954	264.0	1.008	261.4	0.998	263.7	1.007
HH8	264	252.8	0.958	265.2	1.004	268.5	1.017	269.8	1.022
LH11	284	234.0	0.824	269.1	0.948	232.1	0.817	269.1	0.947
LH14	267	185.1	0.693	264.7	0.991	188.9	0.707	273.9	1.026
Kurose Y [21]									
S41	199	185.9	0.934	190.1	0.955	200.8	1.009	195.4	0.982
S42	203	179.5	0.884	185.8	0.915	194.1	0.956	205.7	1.013
U41L	189	184.0	0.974	186.2	0.985	198.0	1.048	197.4	1.044

(*continued on next page*)

Table A2 (*continued*)

Specimen name	Experimental results	NNs result Model 1		NNs result Model 2		NNs result Model 3		NNs result Model 4	
	P_{EXP}	P_{NN1}	P_{NN1}/P_{EXP}	P_{NN2}	P_{NN2}/P_{EXP}	P_{NN3}	P_{NN3}/P_{EXP}	P_{NN4}	P_{NN4}/P_{EXP}
Ha et al. [22]									
Spec. 2	44	43.3	0.984	45.3	1.030	33.2	0.754	41.3	0.938
Spec. 4	47	45.5	0.968	31.1	0.661	46.5	0.990	42.3	0.901
Karayannis et al. [23]									
J2b	13	13.5	1.040	13.8	1.061	12.6	0.971	14.1	1.088
J0	13.5	13.1	0.969	16.3	1.211	12.2	0.901	14.5	1.074
J2b	16	14.8	0.922	14.7	0.921	15.0	0.936	14.7	0.921
JX2b	10.5	12.9	1.229	13.4	1.277	12.6	1.196	14.2	1.353
JX0	16	12.7	0.794	21.0	1.313	12.1	0.755	14.1	0.882
Chen & Chen [24]									
JC	160	103.2	0.645	167.3	1.046	149.4	0.934	87.7	0.548
Hakuto et al. [25]									
Unit O6	61	54.1	0.887	91.7	1.503	43.2	0.708	62.6	1.026
Clyde et al. [26]									
No.2	267	249.0	0.932	232.3	0.870	267.1	1.000	271.2	1.016
No.4	276	246.7	0.894	234.3	0.849	269.1	0.975	269.4	0.976
No.5	267	244.2	0.915	235.6	0.882	269.5	1.009	267.6	1.002
No.6	262	246.2	0.940	234.6	0.895	269.3	1.028	269.0	1.027
German M. [27]									
#3,#6	42	59.5	1.417	44.2	1.051	45.8	1.091	75.9	1.806
El-Amoury & Ghobarah [28]									
T0	86	199.0	2.313	87.1	1.012	186.8	2.173	114.5	1.332
Pantelides et al. [29]									
Unit 5	194	188.2	0.970	176.0	0.907	203.5	1.049	198.0	1.021
Unit 6	198	178.5	0.901	195.3	0.986	200.3	1.012	202.7	1.024
Antonopoulos & Triantafilou [30]									
C1	31	40.5	1.305	36.6	1.180	35.3	1.139	29.0	0.936
C2	31	42.5	1.373	38.2	1.231	37.8	1.218	29.0	0.936
S-C	33	44.4	1.345	33.8	1.023	39.7	1.204	33.2	1.007
Atta et al. [31]									
G1-A	128	124.5	0.973	113.5	0.887	118.9	0.929	130.6	1.020
G1-B	100	113.9	1.139	102.9	1.029	109.6	1.096	109.2	1.092
G1-C	118	111.9	0.948	97.3	0.825	111.9	0.949	113.2	0.959
G2-B	103	121.4	1.179	105.6	1.025	121.0	1.175	102.1	0.991
G2-C	127	124.6	0.981	119.6	0.942	117.5	0.925	139.0	1.095
G3-B	128	123.2	0.962	114.0	0.890	119.1	0.930	121.0	0.946
G3-C	124	124.6	1.005	112.7	0.909	118.7	0.958	131.6	1.061
G3-E	144	124.6	0.865	112.7	0.783	118.7	0.825	131.6	0.914
G3-F	168	147.8	0.880	37.0	0.220	139.8	0.832	117.3	0.698
Chutarat & Aboutaha [32]									
Spec. I	42	42.5	1.012	53.8	1.281	43.4	1.033	45.8	1.090
Spec. A	16	24.6	1.539	25.1	1.568	19.8	1.236	16.7	1.044
Hwang et al. [9]									
0T0	192	197.5	1.028	193.4	1.007	198.7	1.035	192.4	1.002
3T44	205	206.0	1.005	151.7	0.740	246.5	1.202	188.0	0.917
3T3	218	205.7	0.944	186.2	0.854	213.4	0.979	181.0	0.830
2T4	208	203.1	0.976	186.7	0.898	207.8	0.999	183.5	0.882
1T44	200	201.3	1.007	186.7	0.933	204.6	1.023	184.5	0.923
3T4	214	219.4	1.025	220.5	1.030	224.9	1.051	216.6	1.012
2T5	224	216.2	0.965	219.3	0.979	217.4	0.971	225.1	1.005
1T55	217	226.2	1.042	219.8	1.013	231.0	1.065	219.1	1.010
Shiohara & Kursuhaqra [33]									
B2	100.4	94.7	0.944	103.4	1.030	96.2	0.958	98.7	0.983
Tsonos A.G. [34]									
A1	54	62.8	1.163	52.2	0.967	56.2	1.040	52.9	0.979
E1	71	65.0	0.915	75.6	1.065	67.8	0.954	65.4	0.921
E2	53	58.5	1.103	56.3	1.063	55.5	1.046	57.7	1.088
E3	72.5	66.4	0.916	73.5	1.014	67.6	0.933	67.6	0.933
G1	63	59.1	0.939	74.0	1.174	62.5	0.992	62.9	0.999
G2	61	61.5	1.008	67.3	1.102	62.6	1.027	64.9	1.064
Karayannis et al. [35]									
J0	58	59.3	1.023	64.2	1.107	55.3	0.953	52.6	0.907
JS	64	63.8	0.997	57.0	0.890	61.9	0.968	52.7	0.823
JX10	70	77.0	1.100	75.9	1.084	73.9	1.056	65.3	0.933
JX12	73	50.7	0.695	70.6	0.968	40.3	0.552	68.7	0.941

Table A2 (*continued*)

Specimen name	Experimental results	NNs result Model 1		NNs result Model 2		NNs result Model 3		NNs result Model 4	
	P_{EXP}	P_{NN1}	P_{NN1}/P_{EXP}	P_{NN2}	P_{NN2}/P_{EXP}	P_{NN3}	P_{NN3}/P_{EXP}	P_{NN4}	P_{NN4}/P_{EXP}
Karayiannis et al. [36]									
A0	24	19.8	0.825	30.8	1.281	19.2	0.802	19.3	0.804
A1	24	23.0	0.960	30.0	1.252	21.6	0.900	24.0	1.001
A2	23	27.4	1.193	29.8	1.295	25.4	1.106	28.5	1.240
A3	26	32.9	1.267	30.1	1.159	31.0	1.191	32.1	1.234
B0	57.5	59.3	1.032	64.2	1.117	55.3	0.961	52.6	0.915
B1	65	71.9	1.106	64.1	0.986	66.8	1.028	60.0	0.922
C0	63	52.6	0.835	64.3	1.021	53.7	0.852	53.4	0.847
C2	63	67.9	1.078	68.9	1.094	66.3	1.053	61.9	0.983
C3	66	70.9	1.075	70.3	1.066	67.8	1.028	62.1	0.942
C5	63	63.2	1.003	70.4	1.118	59.5	0.945	62.0	0.984
Chalioris et al. [37]									
JA-0	63	55.5	0.880	63.7	1.012	58.6	0.930	53.9	0.856
JA-s5	62	66.4	1.071	67.2	1.083	63.3	1.020	62.4	1.006
JA-X12	63	94.2	1.496	81.1	1.287	108.5	1.722	62.5	0.991
JA-X14	63	63.5	1.008	78.0	1.238	65.4	1.037	64.3	1.021
JB-0	58	59.3	1.023	64.2	1.107	55.3	0.953	52.6	0.907
JB-s1	64	71.9	1.123	64.1	1.001	66.8	1.044	60.0	0.937
JB-X10	70	77.0	1.100	75.9	1.084	73.9	1.056	65.3	0.933
JB-X12	74	67.9	0.917	73.2	0.989	70.6	0.953	67.2	0.908
JCa-0	12	12.7	1.058	16.0	1.332	11.9	0.989	14.0	1.164
JCa-X10	11	14.1	1.278	18.0	1.633	11.7	1.068	13.6	1.238
Jca-s1	13	12.8	0.983	13.1	1.008	12.1	0.929	13.7	1.051
Jcas1X10	11	12.6	1.145	15.9	1.449	11.4	1.041	13.4	1.216
Jca-s2	13	11.9	0.919	11.8	0.910	12.6	0.968	13.4	1.029
Jcas2X10	12	11.4	0.948	17.7	1.471	11.9	0.992	13.1	1.092
JCb-0	15	13.4	0.890	16.7	1.114	12.6	0.838	14.6	0.974
JCb-X10	15	14.3	0.956	19.2	1.281	14.2	0.947	14.3	0.956
JCb-s1	17.5	13.6	0.776	13.4	0.767	13.4	0.767	14.3	0.818
JCbs1X10	16.5	12.9	0.780	17.2	1.044	13.5	0.821	14.1	0.853
JCb-s2	15.5	12.6	0.810	12.1	0.783	14.8	0.956	14.1	0.910
JCbs2X10	16.5	11.6	0.704	19.8	1.201	14.7	0.892	13.7	0.832
Wong & Kuang [38]									
BS-L-300	95.4	101.8	1.067	91.4	0.958	101.6	1.065	95.3	0.999
BS-L-450	100.9	100.1	0.992	112.0	1.110	96.9	0.960	104.0	1.031
BS-L-600	132.7	124.9	0.941	131.5	0.991	134.5	1.014	140.4	1.058
BS-L-V2	127	117.5	0.925	115.1	0.906	124.8	0.983	127.1	1.000
BS-L-V4	128.8	103.1	0.800	125.0	0.970	100.3	0.778	155.7	1.209
BS-L-H1	124.5	120.6	0.968	111.5	0.896	117.2	0.941	124.3	0.999
BS-L-H2	153.2	142.6	0.931	108.6	0.709	153.1	1.000	154.8	1.010
Ha & Cho [39]									
NJC	33	42.4	1.284	52.0	1.577	40.3	1.222	31.2	0.945
HJC	39	32.7	0.837	44.1	1.130	31.0	0.795	31.7	0.813
Kotsovou & Mouzakis [4]									
S1	230.5	224.6	0.974	231.2	1.003	233.4	1.013	230.9	1.002
S2	230.5	224.6	0.974	231.2	1.003	233.4	1.013	230.9	1.002
S2'	230.5	224.6	0.974	231.2	1.003	233.4	1.013	230.9	1.002
S3	230.5	224.1	0.972	229.0	0.994	227.7	0.988	223.0	0.967
S4	230.5	230.3	0.999	230.5	1.000	224.3	0.973	229.2	0.995
S5	230.5	232.0	1.007	232.2	1.007	227.5	0.987	229.7	0.997
Koutsovou & Mouzakis [11,40]									
S6	221.3	226.5	1.023	136.3	0.616	223.4	1.010	221.5	1.001
S9	221.3	219.7	0.993	193.4	0.874	223.3	1.009	221.6	1.001
S10	230.5	227.2	0.986	158.1	0.686	227.3	0.986	186.9	0.811
S11	221.3	219.7	0.993	193.4	0.874	223.3	1.009	221.6	1.001
Average/SD			1.019/0.194		1.027/0.182		1.002/0.176		0.994/0.150

Values of experimental load-carrying capacity – P_{EXP}.
ANN predictions of load-carrying capacity – P_{NNi}.

Table A3
Formulae's predictions of specimen's mode of failure.

Specimen name	Experimental			EC2-EC8			ACI			Kotsovou & Mouzakis				ANNs
	$V_{jh,EXP}$	As_{EXP}	FM	$V_{Rj,h}$	As_c	FM	$V_{Rj,h}$	As_c	FM	$F_{jmax,h}$	$F_{j,h}$	$V_{jR,h}$	FM	FM_{NN}
Hanson & Connor [12]														
I	978.1	1290	BF	408.8	2058	JF	1362	802	BF	1185.7	1507.6	1185.7	BF	BF
I-A	921.2	710	BF	*	1594	–	1314	658	BF	1109.1	946,2	946,2	BF	BF
II	915,8	1290	BF	1455,0	2265	JF	1391	710	BF	1063,9	1680,3	1063,9	BF	BF
V	1001,2	0	BF	230,9	–	JF	1327	–	JF	1131,3	0,0	377,1	JF	BF
Megget L.M. [13]														
Unit A	491,0	1592,8	JF	877,2	1721	JF	867	538	BF	460,3	1538,5	460,3	JF	BF
Uzumeri S.M. [14]														
6	695,2	2064	BF	692,8	1484	JF	1450	601	BF	1293,2	2475,8	1293,2	BF	BF
7	695,2	1032	BF	321,9	1311	JF	1335	997	BF	1078,4	1329,2	1078,4	BF	BF
8	913,4	2064	JF	*	1540	–	1236	427	BF	800,9	2796,2	800,9	JF	BF
Paulay & Scarpas [15]														
UNIT 1	554,6	1809,6	BF	1724,7	1972	JF	1466	572	BF	930,4	1701,8	930,4	BF	BF
UNIT 2	835,2	1809,6	BF	1717,9	2929	JF	1463	569	BF	950,6	1659,1	950,6	BF	BF
UNIT 3	547,5	942,5	BF	2013,6	2034	JF	1599	936	BF	1121,8	857,0	857,0	BF	BF
Park & Milburn [16]														
Unit 3	572,4	943	BF	1531,5	1886	JF	1112	763	BF	860,3	916,4	860,3	BF	BF
Unit 4	804,5	1178	JF	1554,1	2551	JF	1122	622	BF	1032,9	965,6	965,6	BF	JF
Eshani & Wight [7]														
1B	697,8	881	JF	848,6	1775	JF	807	1826	JF	482,1	1193,7	482,1	JF	JF
2B	707,2	881	JF	867,4	1757	JF	823	1743	JF	544,7	1159,2	544,7	JF	BF
3B	669,5	1321	JF	995,8	1773	JF	890	1482	JF	606,4	1781,8	606,4	JF	JF
4B	679,0	1321	BF	1029,4	1780	JF	**	1481	–	690,8	1717,4	690,8	BF	BF
5B	828,8	881	JF	865,6	1897	JF	890	873	BF	556,2	1184,9	556,2	JF	JF
6B	605,6	881	BF	1372,8	1509	JF	1139	1611	JF	826,8	1150,7	826,8	BF	BF
Eshani et al. [17]														
1	553,9	1321	BF	2099,3	1382	JF	**	1581	–	1660,2	1547,2	1547,2	BF	BF
2	680,8	1321	BF	2090,1	1645	JF	**	1644	–	1659,8	1601,1	1601,1	BF	BF
3	614,7	1321	BF	1483,2	1423	JF	**	1540	–	1110,0	1719,1	1110,0	BF	BF
4	774,4	1321	JF	1551,7	1793	JF	**	1565	–	1072,6	1804,6	1072,6	BF	JF
5	680,5	1321	BF	1071,9	1780	JF	**	1478	–	703,9	1707,9	703,9	BF	BF
Kaku & Asakuka [18]														
1	207,0	226,2	BF	499,4	839	JF	391	108	BF	293,2	163,5	163,5	JF	BF
2	206,7	226,2	BF	677,8	891	JF	448	142	BF	415,0	160,1	160,1	JF	BF
3	211,3	226,2	JF	754,4	968	JF	448	142	BF	447,9	156,0	156,0	JF	JF
4	208,2	56,5	JF	655,1	747	JF	**	135	–	411,7	46,1	137,2	JF	JF
5	210,8	56,5	JF	619,0	800	JF	420	111	JF	368,0	44,8	122,7	JF	JF
6	212,4	56,5	JF	713,0	862	JF	441	163	JF	433,8	43,8	144,6	JF	JF
7	206,8	226,2	BF	533,7	872	JF	394	110	BF	283,6	166,0	166,0	JF	JF
8	207,6	226,2	BF	687,0	906	JF	445	140	BF	398,2	161,6	161,6	JF	JF
9	208,7	226,2	JF	738,2	968	JF	442	138	BF	428,0	156,9	156,9	JF	JF
10	207,7	226,2	BF	650,8	839	JF	**	151	–	371,6	169,0	169,0	JF	BF
11	209,4	226,2	JF	697,3	907	JF	449	143	BF	406,1	161,5	161,5	JF	JF
12	212,7	56,5	JF	654,3	862	JF	411	106	JF	366,4	44,1	122,1	JF	JF
13	212,4	226,2	JF	856,4	1003	JF	**	158	–	509,7	154,9	169,9	JF	JF
14	210,1	56,5	JF	694,4	806	JF	444	105	JF	416,1	44,6	138,7	JF	JF
15	209,4	56,5	JF	674,8	804	JF	437	102	JF	395,4	44,9	131,8	JF	JF
16	206,5	226,2	BF	675,1	968	JF	424	108	BF	371,1	160,1	160,1	JF	BF
17	217,1	226,2	JF	724,8	968	JF	437	135	BF	437,3	154,5	154,5	JF	JF
18	225,2	226,2	JF	724,7	968	JF	443	169	BF	456,7	153,5	153,5	JF	JF
Fuji & Morita [18]														
B1	466,6	169,6	JF	458,6	1646	JF	380	388	JF	282,9	137,8	137,8	JF	JF
B2	471,8	169,6	JF	458,6	1646	JF	380	388	JF	282,9	137,8	137,8	JF	JF
B3	462,0	169,6	JF	458,6	1646	JF	380	388	JF	282,9	137,8	137,8	JF	JF
B4	460,0	452,4	JF	458,6	1646	JF	380	291	JF	282,9	367,6	282,9	JF	JF
Eshani & Alameddine [20]														
LH8	999,8	2322	BF	1868,6	2362	JF	**	1073	–	1375,2	2983,9	1375,2	BF	BF
HL8	1287,9	1548	JF	1804,1	2918	JF	**	1609	–	1172,7	2156,0	1172,7	JF	JF
HH8	1286,9	2322	JF	1804,1	2918	JF	**	1073	–	1172,7	3234,0	1172,7	JF	JF
LH11	978,0	2322	BF	2274,6	2386	JF	**	1419	–	1996,1	2780,9	1996,1	BF	BF
LH14	986,4	2322	BF	2603,7	2407	JF	**	1803	–	2715,6	2609,2	2609,2	BF	BF
Kurose Y. [21]														
S41	408,2	768	JF	775,2	1794	JF	687	284	BF	382,7	706,7	382,7	JF	JF
S42	405,8	384	JF	775,2	1794	JF	687	568	JF	382,7	353,4	353,4	JF	JF
U41L	414,2	768	JF	843,1	1794	JF	721	312	BF	423,9	705,5	423,9	BF	JF

Table A3 (*continued*)

Specimen name	Experimental			EC2-EC8			ACI			Kotsovou & Mouzakis				ANNs
	$V_{jh,EXP}$	As_{EXP}	FM	$V_{Rj,h}$	As_c	FM	$V_{Rj,h}$	As_c	FM	$F_{jmax,h}$	$F_{j,h}$	$V_{jR,h}$	FM	FM_{NN}
Ha et al. [22]														
Spec. 2	142,8	192	BF	579,0	488	JF	373	145	BF	351,1	203,2	203,2	BF	BF
Spec. 4	139,4	192	BF	839,3	488	JF	**	242	–	668,8	172,7	222,9	BF	BF
Karayannis et al. [23]														
J2b	66,9	201	BF	139,8	315	JF	156	846	JF	74,5	138,9	74,5	BF	JF
J0	66,6	0	JF	132,3	–	JF	151	–	JF	68,2	0,0	22,7	JF	JF
J2b	102,9	201	JF	162,7	474	JF	170	1004	JF	80,1	147,0	80,1	JF	JF
JX2b	106,5	201 157(d)	BF	116,6	474	JF	141	693	JF	52,2	275,0	52,2	JF	BF
JX0	65,0	0 157(d)	BF	150,2	–	JF	162	–	JF	83,4	125,6	83,4	BF	BF
Chen &Chen [24]														
JC	955,1	1645	JF	1761,1	3233	JF	1485	605	BF	1037,6	1445,4	1037,6	BF	JF
Hakuto et al. [25]														
Unit O6	273,5	57	BF	2475,3	840	JF	1692	3316	JF	1970,5	41,3	656,8	BF	BF
Clyde et al. [26]														
No.2	1249,9	0	JF	2469,5	–	JF	**	–	–	1808,1	0,0	602,7	JF	JF
No.4	1244,7	0	JF	2251,9	–	JF	1727	–	JF	1583,5	0,0	527,8	JF	JF
No.5	1249,9	0	JF	2074,1	–	JF	1640	–	JF	1417,8	0,0	472,6	JF	JF
No.6	1252,8	0	JF	2212,7	–	JF	1708	–	JF	1546,4	0,0	515,5	JF	JF
Gebman M. [27]														
#3,#6	131,7	128	JF	509,4	395	JF	491	270	JF	300,7	140,5	140,5	BF	JF
El-Amoury & Ghobarah [28]														
T0	584,1	0	JF	935,7	–	JF	918	–	JF	517,1	0,0	172,4	JF	JF
Pantelides et al. [29]														
Unit 5	1316,4	0	JF	1572,9	–	JF	1541	–	JF	994,8	0,0	331,6	JF	JF
Unit 6	1314,2	0	JF	1256,5	–	JF	1523	–	JF	1027,4	0,0	342,5	JF	JF
Antonopoulos & Triantafilou [30]														
C1	298,1	0	JF	242,3	–	JF	292	–	JF	107,2	0,0	35,7	JF	JF
C2	298,1	0	JF	293,5	–	JF	323	–	JF	136,3	0,0	45,4	JF	JF
S-C	296,4	101	JF	241,1	1188	JF	292	1241	JF	106,6	88,6	88,6	JF	JF
Atta et al. [31]														
G1-A	223,2	201	JS-BF	705,7	1072	JF	**	2936	–	410,1	164,7	164,7	JF	JF
G1-B	231,3	201	JS-BF	436,2	1061	JF	398	1578	JF	198,7	168,3	168,3	JF	JF
G1-C	226,1	201	JS-BF	404,4	1059	JF	381	1446	JF	191,4	167,7	167,7	JF	JF
G2-B	230,5	0	JS-BF	654,3	–	JF	**	–	–	363,6	0,0	121,2	JF	JF
G2-C	223,5	302	JS-BF	691,5	1072	JF	**	1899	–	396,5	247,6	247,6	BF	JF
G3-B	223,2	157	JS-BF	669,5	1071	JF	**	5434	–	376,6	128,8	128,8	JF	JF
G3-C	224,3	201	JS-BF	712,6	1073	JF	**	2980	–	416,5	164,7	164,7	JF	JF
G3-E	218,5	201	JS-BF	712,6	1073	JF	**	2980	–	416,5	164,7	164,7	JF	JF
G3-F	211,5	344	BF	669,5	1071	JF	**	2717	–	343,3	286,1	286,1	BF	BF
Chutarat & Aboutaha [32]														
Spec. I	1139,8	2064	JF	1630,6	3233	JF	1351	558	BF	762,9	2300,9	762,9	JF	JF
Spec. A	448,3	2064	BF	1908,9	1270	BF	1480	669	BF	1237,0	1822,1	1237,0	BF	BF
Hwang et al. [9]														
0T0	900,5	0	BF-JS	3457,4	–	JF	**	–	–	2649,4	0,0	883,1	JF	JF
3T44	890,4	2322	BF	3467,5	2085	BF	**	2291	–	3062,4	2777,6	2777,6	BF	BF
3T3	880,2	639	BF-JS	3307,6	2202	JF	**	1993	–	2683,6	745,8	894,5	BF	JF
2T4	888,0	516	BF-JS	3305,5	2083	JF	**	3178	–	2769,2	632,7	923,1	BF	JF
1T44	894,3	516	BF-JS	3357,6	2084	JF	**	6516	–	2859,2	627,8	953,1	BF	JF
3T4	1031,2	1161	BF	4028,4	2723	JF	**	2475	–	3465,5	1222,5	1222,5	BF	BF
2T5	1023,3	800	BF	4001,6	2532	JF	**	3819	–	3530,5	903,0	1176,8	BF	BF
1T55	1028,8	800	BF	3776,3	2529	JF	**	6950	–	3129,8	929,5	1043,3	BF	BF
Shiohara &Kursuhara [33]														
B2	602,7	0	JF	835,9	–	JF	795	–	JF	588,4	0,0	196,1	JF	JF
Tsonos A.G. [34]														
A1	149,8	483	BF	384,9	309	BF	393	181	BF	224,2	809,1	224,2	BF	BF
E1	223,7	483	JF	237,6	416	BF	311	101	BF	143,8	931,9	143,8	JF	JF
E2	145,1	483	BF	395,2	300	BF	393	160	BF	252,4	829,1	252,4	BF	BF
E3	265,5	483	JF	208,3	470	JF	297	98	BF	135,3	934,6	135,3	JF	JF
G1	229,4	344	JF	237,6	362	JF	311	219	BF	143,8	762,0	143,8	JF	JF
G2	273,7	344	JF	208,3	409	JF	297	212	BF	135,3	764,3	135,3	JF	JF

(*continued on next page*)

Table A3 (*continued*)

Specimen name	Experimental			EC2-EC8			ACI			Kotsovou & Mouzakis				ANNs
	$V_{jh,EXP}$	As_{EXP}	FM	$V_{Rj,h}$	As_c	FM	$V_{Rj,h}$	As_c	FM	$F_{jmax,h}$	$F_{j,h}$	$V_{jR,h}$	FM	FM_{NN}
Karayannis et al. [35]														
J0	283,3	0	JF	664,9	–	JF	560	–	JF	414,8	0,0	138,3	JF	JF
JS	279,0	101	JF	624,2	540	JF	496	818	JF	380,5	165,9	165,9	JF	JF
JX10	274,1	314 (d)	BF	664,9	–	JF	560	–	JF	398,6	364,2	364,2	BF	BF
JX12	271,8	616 (d)	BF	664,9	–	JF	560	–	JF	393,2	714,6	393,2	BF	BF
Karayannis et al. [36]														
A0	91,7	0	JF	403,1	–	JF	373	–	JF	268,4	0,0	89,5	JF	JF
A1	91,7	101	JF-BF	403,1	181	JF	373	673	JF	268,4	159,7	159,7	BF	JF
A2	92,4	201	JF-BF	403,1	181	BF	373	337	JF	268,4	317,8	268,4	BF	JF
A3	90,2	302	BF	403,1	181	BF	373	224	BF	268,4	477,4	268,4	BF	BF
B0	283,7	0	JF	664,9	–	JF	560	–	JF	414,8	0,0	138,3	JF	JF
B1	278,0	101	JF	664,9	543	JF	560	785	JF	414,8	161,1	161,1	JF	JF
C0	266,3	0	JF	664,9	–	JF	560	–	JF	377,0	0,0	125,7	JF	JF
C2	266,3	201	JF-BF	664,9	521	JF	560	393	JF	377,0	331,0	331,0	BF	JF
C3	264,0	302	BF	664,9	521	JF	560	262	BF	377,0	497,4	377,0	BF	JF
C5	266,3	503	BF	664,9	521	JF	560	157	BF	377,0	828,4	377,0	BF	BF
Chalioris et al. [37]														
JA-0	266,3	0	JF	707,4	–	JF	581	–	JF	413,4	0,0	137,8	JF	JF
JA-s5	267,1	503	BF	707,4	521	JF	581	169	BF	413,4	817,6	413,4	BF	BF
JA-X12	266,3	452(d)	JF-BF	707,4	–	JF	581	–	JF	397,0	524,3	397,0	BF	JF
JA-X14	266,3	616(d)	JF-BF	707,4	–	JF	581	–	JF	392,2	714,6	392,2	BF	JF
JB-0	283,3	0	JF	664,9	–	JF	560	–	JF	414,8	0,0	138,3	JF	JF
JB-s1	278,7	101	JF	664,9	543	JF	560	785	JF	414,8	161,1	161,1	JF	JF
JB-X10	274,1	0 314(d)	JF-BF	664,9	–	JF	560	–	JF	398,6	364,2	364,2	BF	BF
JB-X12	271,1	0 452(d)	JF-BF	664,9	–	JF	560	–	JF	393,2	524,3	393,2	BF	BF
JCa-0	79,7	0	JF	131,3	–	JF	151	–	JF	61,6	0,0	20,5	JF	JF
JCa-X10	80,5	0 314 (d)	JF-BF	131,3	–	JF	151	–	JF	56,6	295,2	56,6	JF	JF
Jca-s1	79,0	101	JF-BF	131,3	173	JF	151	739	JF	61,6	157,3	61,6	JF	JF
Jcas1X10	80,5	101 314 (d)	JF-BF	131,3	173	JF	151	739	JF	56,6	454,9	56,6	JF	JF
Jca-s2	79,0	201	JF-BF	131,3	173	BF	151	369	JF	61,6	313,0	61,6	JF	JF
Jcas2X10	79,7	201 314 (d)	BF	131,3	173	BF	151	369	JF	56,6	612,9	56,6	JF	JF
JCb-0	122,1	0	JF	145,0	–	JF	159	–	JF	65,8	0,0	21,9	JF	JF
JCb-X10	122,1	0 314 (d)	JF-BF	145,0	–	JF	159	–	JF	60,6	295,2	60,6	JF	JF
JCb-s1	120,3	101	JF	145,0	261	JF	159	825	JF	65,8	160,7	65,8	JF	JF
JCbs1X10	121,0	101 314 (d)	JF-BF	145,0	261	JF	159	825	JF	60,6	458,0	60,6	JF	JF
JCb-s2	121,7	201	JF	145,0	261	JF	159	413	JF	65,8	319,8	65,8	JF	JF
JCbs2X10	121,0	201 314 (d)	JF	145,0	261	JF	159	413	JF	60,6	619,2	60,6	JF	JF
Wong & Kuang [38]														
BS-L-300	538,9	0	JF	989,5	–	JF	814	–	JF	562,2	0,0	187,4	JF	JF
BS-L-450	536,1	0	JF	911,9	–	JF	775	–	JF	376,3	0,0	125,4	JF	JF
BS-L-600	519,8	0	JF	1043,3	–	JF	841	–	JF	347,8	0,0	115,9	JF	JF
BS-L-V2	522,7	0	JF	953,5	–	JF	796	–	JF	370,8	0,0	123,6	JF	JF
BS-L-V4	521,8	0	JF	846,6	–	JF	742	–	JF	332,3	0,0	110,8	JF	JF
BS-L-H1	524,0	157	JF	970,4	1035	JF	805	760	JF	407,2	269,7	269,7	JF	JF
BS-L-H2	509,2	314	JF	1169,5	1035	JF	**	480	–	520,7	539,1	520,7	BF	JF
Ha & Cho [39]														
NJC	155,6	471	BF	382,8	372	BF	316	88	BF	209,7	627,6	209,7	BF	BF
HJC	148,9	471	BF	573,7	372	BF	**	146	–	387,9	583,2	387,9	BF	BF
Kotsovou & Mouzakis [4]														
S1	725,3	1543	JF	1079,0	1458	BF	884	349	BF	552,5	2640,1	552,5	JF	JF
S2	728,3	1543	JF	1079,0	1458	BF	884	349	BF	552,5	2640,1	552,5	JF	JF
S2'	717,3	1543	JF	1079,0	1458	BF	884	349	BF	552,5	2640,1	552,5	JF	JF
S3	717,3	1157	JF	1079,0	1458	JF	884	465	BF	552,5	1979,7	552,5	JF	JF
S4	719,3	452 628(d)	JF	1079,0	1458	JF	884	698	JF	552,5	1476,7	552,5	JF	JF
S5	710,3	452 678(d)	JF	1079,0	1458	JF	884	698	JF	544,5	1550,8	544,5	JF	JF

Table A3 (*continued*)

Specimen name	Experimental			EC2-EC8			ACI			Kotsovou & Mouzakis				ANNs
	$V_{jh,EXP}$	As_{EXP}	FM	$V_{Rj,h}$	As_c	FM	$V_{Rj,h}$	As_c	FM	$F_{jmax,h}$	$F_{j,h}$	$V_{jR,h}$	FM	FM_{NN}
Kotsovou & Mouzakis [11,40]														
S6	714,3	402 1232(d)	BF	2038,0	1315	JF	1375	573	JF	1312,9	2004,1	1312,9	BF	BF
S9	712,3	942	BF	2038,0	1315	JF	1375	382	BF	1312,9	1445,5	1312,9	BF	BF
S10	352,2	344 678(d)	BF	1079,0	657	JF	884	630	JF	439,2	1520,4	439,2	BF	BF
S11	713,3	942	BF	2038,0	1315	JF	1375	382	BF	1312,9	1445,5	1312,9	BF	BF

Experimental established horizontal acting shear force – $V_{jh,EXP}$.
Experimental transverse reinforcement – As_{EXP}.
Horizontal joint strength – $V_{Rj,h}$.
Code specified transverse reinforcement – As_c.
Horizontal component of maximum sustained force by incline strut – $F_{jmax,h}$.
Horizontal component of compressive force corresponding to tensile force sustained by existing transverse reinforcement – $F_{j,h}$.
Joint failure – JF.
Beam failure – BF.
The joints specimens have no lateral reinforcement.
* The value of the axial load is greater.
** fc is larger than 42 MPa and the ACI equation is not valid.

Table A4
Comparison of predicted joint strength with published experimental data.

Specimen name	Experimental		EC2-EC8		ACI		Kotsovou & Mouzakis		ANNs	
	$V_{jh,EXP}$	FM	$V_{jR,h}$	$V_{jR,h}/V_{jh,EXP}$	$V_{Rj,h}$	$V_{jR,h}/V_{jh,EXP}$	$V_{jR,h}$	$V_{jR,h}/V_{jh,EXP}$	$V_{jR,h}$	$V_{jR,h}/V_{jh,EXP}$
Megget L.M. [13]										
Unit A	491,0	JF	1st	–	867	1,77	460,3	0,94	490,1	0,998
Uzumeri S.M. [14]										
8	913,4	JF	*	–	1236	1,35	800,9	0,88	913,1	1,000
Park & Milburn [16]										
Unit 4	804,5	JF	1st	–	1122	1,39	965,6	1,20	793,9	0,987
Eshani & Wight [7]										
1B	697,8	JF	1st	–	1st	–	482,1	0,69	696,9	0,999
2B	707,2	JF	1st	–	1st	–	544,7	0,77	706,3	0,999
3B	669,5	JF	1st	–	1st	–	606,4	0,91	668,8	0,999
5B	828,8	JF	1st	–	890		556,2	0,67	828,3	0,999
Eshani et al. [17]										
4	774,4	JF	1st	–	**	–	1072,6	1,39	773,4	0,999
Kaku & Asakuka [18]										
3	211,3	JF	1st	–	448	1,07	156,0	0,74	215,9	1,021
4	208,2	JF	1st	–	**	–	137,2	0,66	231,8	1,113
5	210,8	JF	1st	–	1st	–	122,7	0,58	209,3	0,993
6	212,4	JF	1st	–	1st	–	144,6	0,68	217,8	1,025
9	208,7	JF	1st	–	442	2,12	156,9	0,75	207,7	0,995
11	209,4	JF	1st	–	449	2,14	161,5	0,77	210,5	1,005
12	212,7	JF	1st	–	1st	–	122,1	0,57	210,8	0,991
13	212,4	JF	1st	–	**	–	169,9	0,80	210,3	0,990
14	210,1	JF	1st	–	1st	–	138,7	0,66	221,8	1,056
15	209,4	JF	1st	–	1st	–	131,8	0,63	217,2	1,037
17	217,1	JF	1st	–	437	2.01	154,5	0,71	217,1	1,000
18	225,2	JF	1st	–	443	1.97	153,5	0,68	223,4	0,992
Fuji & Morita [19]										
B1	466,6	JF	1st	–	1st	–	137,8	0,30	465,4	0,997
B2	471,8	JF	1st	–	1st	–	137,8	0,29	465,4	0,986
B3	462,0	JF	1st	–	1st	–	137,8	0,30	465,4	1,007
B4	460,0	JF	1st	–	380	0.83	282,9	0,61	458,6	0,997
Eshani & Alameddine [20]										
HL8	1287,9	JF	1st	–	**	–	1172,7	0,91	1288,5	1,000
HH8	1286,9	JF	1st	–	**	–	1172,7	0,91	1286,2	0,999
Kurose Y. [21]										
S41	408,2	JF	1st	–	687	1.68	382,7	0,94	411,9	1,009
S42	405,8	JF	1st	–	687	1.69	353,4	0,87	405,7	1,000
U41L	414,2	JF	1st	–	721	1.74	423,9	1,02	411,5	0,994

(*continued on next page*)

Table A4 (*continued*)

Specimen name	Experimental		EC2-EC8		ACI		Kotsovou & Mouzakis		ANNs	
	$V_{jh,EXP}$	FM	$V_{jR,h}$	$V_{jR,h}/V_{jh,EXP}$	$V_{Rj,h}$	$V_{jR,h}/V_{jh,EXP}$	$V_{jR,h}$	$V_{jR,h}/V_{jh,EXP}$	$V_{jR,h}$	$V_{jR,h}/V_{jh,EXP}$
Karayannis et al. [23]										
J0	66,6	JF	wtr	–	wtr	–	22,7	0,34	69,3	1,040
J2b	102,9	JF	1st	–	1st	–	80,1	0,78	100,7	0,979
Chen & Chen [24]										
JC	955,1	JF	1st	–	1485	1.55	1037,6	1,09	955,1	1,000
Clyde et al. [26]										
No.2	1249,9	JF	wtr	–	**	–	602,7	0,48	1217,0	0,974
No.4	1244,7	JF	wtr	–	wtr	1.77	527,8	0,42	1246,4	1,001
No.5	1249,9	JF	wtr	–	wtr	–	472,6	0,38	1264,6	1,012
No.6	1252,8	JF	wtr	–	wtr	–	515,5	0,41	1250,8	0,998
German M. [27]										
#3,#6	131,7	JF	1st	–	1st	–	140,5	1,07	171,6	1,303
El-Amoury & Ghobarah [28]										
T0	584,1	JF	wtr	–	wtr	–	172,4	0,30	587,6	1,006
Pantelides et al. [29]										
Unit 5	1316,4	JF	wtr	–	wtr	–	331,6	0,25	1313,3	0,998
Unit 6	1314,2	JF	wtr	–	wtr	–	342,5	0,26	1313,6	1,000
Antonopoulos & Triantafilou [30]										
C1	298,1	JF	wtr	–	wtr	–	35,7	0,12	298,9	1,003
C2	298,1	JF	wtr	–	wtr	–	45,4	0,15	297,3	0,997
S–C	296,4	JF	1st	–	1st	–	88,6	0,30	294,4	0,993
Atta et al. [31]										
G1-A	223,2	JS-BF	1st	–	**	–	164,7	0,74	220,9	0,990
G1-B	231,3	JS-BF	1st	–	1st	–	168,3	0,73	224,3	0,970
G1-C	226,1	JS-BF	1st	–	1st	–	167,7	0,74	224,7	0,994
G2-B	230,5	JS-BF	wtr	–	**	–	121,2	0,53	227,9	0,989
G2-C	223,5	JS-BF	1st	–	**	–	247,6	1,11	220,6	0,987
G3-B	223,2	JS-BF	1st	–	**	–	128,8	0,58	223,7	1,002
G3-C	224,3	JS-BF	1st	–	**	–	164,7	0,73	220,4	0,982
G3-E	218,5	JS-BF	1st	–	**	–	164,7	0,75	220,4	1,009
Chutarat & Aboutaha [32]										
Spec. I	1139,8	JF	1st	–	1351	1.18	762,9	0,67	842,2	0,739
Hwang et al. [9]										
0T0	900,5	BF-JS	wtr	–	**	–	883,1	0,98	900,8	1,000
3T3	880,2	BF-JS	1st	–	**	–	894,5	1,04	880,6	1,000
2T4	888,0	BF-JS	1st	–	**	–	923,1	1,07	887,8	1,000
1T44	894,3	BF-JS	1st	–	**	–	953,1	0,98	894,6	1,000
Shiohara & Kursuhara [33]										
B2	602,7	JF	wtr	–	wtr	–	196,1	0,33	494,9	0,821
Tsonos A.G. [34]										
E1	223,7	JF	237,6	1,06	311	1.39	143,8	0,64	176,3	0,788
E3	265,5	JF	208,3	0.78	297	1.18	135,3	0,51	212,1	0,799
G1	229,4	JF	1st	–	311	1.39	143,8	0,63	181,3	0,790
G2	273,7	JF	1st	–	297	1.08	135,3	0,49	214,2	0,782
Karayannis et al. [35]										
J0	283,3	JF	wtr	–	wtr	–	138,3	0,49	282,0	0,995
JS	279,0	JF	1st	–	1st	–	165,9	0,59	287,4	1,030
Karayannis et al. [36]										
A0	91,7	JF	wtr	–	wtr	–	89,5	0,98	90,0	0,982
A1	91,7	JF-BF	1st	–	1st	–	159,7	1,74	90,4	0,986
A2	92,4	JF-BF	403,1	–	1st	–	268,4	2,91	91,5	0,991
B0	283,7	JF	wtr	–	wtr	–	138,3	0,49	282,0	0,994
B1	278,0	JF	1st	–	1st	–	161,1	0,58	277,1	0,997
C0	266,3	JF	wtr	–	wtr	–	125,7	0,47	264,6	0,994
C2	266,3	JF-BF	1st	–	1st	–	331,0	1,24	264,9	0,995
Chalioris et al. [37]										
JA-0	266,3	JF	wtr	–	wtr	–	137,8	0,52	265,0	0,995
JA-X12	266,3	JF-BF	wtr	–	wtr	–	397,0	1,49	257,8	0,968
JA-X14	266,3	JF-BF	wtr	–	wtr	–	392,2	1,47	288,1	1,082
JB-0	283,3	JF	wtr	–	wtr	–	138,3	0,49	282,0	0,995
JB-s1	278,7	JF	1st	–	1st	–	161,1	0,58	277,1	0,994
JB-X10	274,1	JF-BF	wtr	–	wtr	–	364,2	1,33	273,0	0,996
JB-X12	271,1	JF-BF	wtr	–	wtr	–	393,2	1,45	270,0	0,996
JCa-0	79,7	JF	wtr	–	wtr	–	20,5	0,26	73,7	0,924
JCa-X10	80,5	JF-BF	wtr	–	wtr	–	56,6	0,70	86,4	1,073
Jca-s1	79,0	JF-BF	1st	–	1st	–	61,6	0,78	75,1	0,951
Jcas1X10	80,5	JF-BF	1st	–	1st	–	56,6	0,70	79,4	0,987

Table A4 (*continued*)

Specimen name	Experimental		EC2-EC8		ACI		Kotsovou & Mouzakis		ANNs	
	$V_{jh,EXP}$	FM	$V_{jR,h}$	$V_{jR,h}/V_{jh,EXP}$	$V_{Rj,h}$	$V_{jR,h}/V_{jh,EXP}$	$V_{jR,h}$	$V_{jR,h}/V_{jh,EXP}$	$V_{jR,h}$	$V_{jR,h}/V_{jh,EXP}$
Jca-s2	79,0	JF-BF	131,3		1st	–	61,6	0,78	78,2	0,990
JCb-0	122,1	JF	wtr	–	wtr	–	21,9	0,18	120,8	0,990
JCb-X10	122,1	JF-BF	wtr	–	wtr	–	60,6	0,50	125,7	1,030
JCb-s1	120,3	JF	1st	–	11st	–	65,8	0,55	120,9	1,005
JCbs1X10	121,0	JF-BF	1st	–	1st	–	60,6	0,50	119,6	0,988
JCb-s2	121,7	JF	1st	–	1st	–	65,8	0,54	120,7	0,992
JCbs2X10	121,0	JF	145,0		1st	–	60,6	0,50	120,2	0,994
Wong & Kuang [38]										
BS-L-300	538,9	JF	wtr	–	wtr	–	187,4	0,35	537,9	0,998
BS-L-450	536,1	JF	wtr	–	wtr	–	125,4	0,23	529,2	0,987
BS-L-600	519,8	JF	wtr	–	wtr	–	115,9	0,22	546,3	1,051
BS-L-V2	522,7	JF	wtr	–	wtr	–	123,6	0,24	521,7	0,998
BS-L-V4	521,8	JF	wtr	–	wtr	–	110,8	0,21	520,8	0,998
BS-L-H1	524,0	JF	1st	–	1st	–	269,7	0,51	523,0	0,998
BS-L-H2	509,2	JF	1st	–	**	–	520,7	1,02	515,5	1,012
Kotsovou & Mouzakis [4]										
S1	725,3	JF	1079,0	1,49	884	1,22	552,5	0,76	723,4	0,997
S2	728,3	JF	1079,0	1,48	884	1,21	552,5	0,76	723,4	0,993
S2'	717,3	JF	1079,0	1,5	884	1,23	552,5	0,77	723,4	1,008
S3	717,3	JF	1st	–	884	1,23	552,5	0,77	716,6	0,999
S4	719,3	JF	1st	–	1st	–	552,5	0,77	701,5	0,975
S5	710,3	JF	1st	–	1st	–	544,5	0,77	709,6	0,999
Mean value/SD								0.71/0.39		0.99/0.064

Horizontal joint strength – $V_{jR,h}$.
Experimental established joint strength –$V_{jh,exp}$.
Lack of specific transverse reinforcement, 1st.
Without transverse reinforcement, wtr.

Appendix B. Design methods investigated

B.1. Acting shear force

The horizontal shear force (V_{jh}) acting at the joint mid height is obtained from:

$$V_{jh} = T - V_c = 1.2A_{sl,b}f_y - V_c \quad \text{(B1)}$$

where $A_{sl,b}$ is the total area of the beam compressive longitudinal reinforcement, V_c is the value of the shear force at the upper column-joint interface corresponding to the formation of a plastic hinge at the beam-joint interface, and f_y the yield stress of the reinforcement.

B.2. ACI 318 requirements

From clause 21.5.3.1,

$$V_{jh} \geqslant V_n = 20\sqrt{f'_c}b_jh \quad \text{(B2)}$$

where b_j is the joint width; $b_j = b_c$ when $b_b \geqslant b_c$ or $b_j = \frac{b_b+b_c}{2} \leqslant b_b + \frac{h_c}{2}$ when $b_b < b_c$ (where b_b and b_c are the widths of the beam and column, respectively), h is the height of the column cross section, and f'_c is the concrete compressive strength ≤6000 psi (42 MPa).

The total cross-sectional area (in Imperial units) of the rectangular hoop reinforcement is obtained from (expressions 21.3 and 21.4 in clause 21.4.4.1):

$$A_{sh} = 0.3\frac{sh_cf'_c}{f_{yh}}(A_g/A_c - 1) \quad \text{(B3a)}$$

$$A_{sh} = 0.09\frac{sh_cf'_c}{f_{yh}} \quad \text{(B3b)}$$

where s is the stirrup spacing, h_c is the height of the portion of the beam cross section enclosed by the stirrup center line, f_{yh} is the characteristic yield stress of the reinforcement, A_g is the gross column cross sectional area and A_c is to confined cross sectional area.

B.3. EC2-EC8 requirements

From in clause 5.5.3.3(2) (expression (5.33)):

$$V_{Jh} \geqslant V_{jR,h} = nf_{cd}\sqrt{1 - \frac{v_d}{n}}b_jh_{jc} \quad \text{(B4)}$$

where $n = 0.6\left(1 - \frac{f_{ck}}{250}\right)$, f_{cd} is the concrete design strength, $b_j = \min\{b_c; (b_w + 0.5h_c)\}$ for $b_c > b_w$, or, $b_j = \min\{b_w; (b_c + 0.5h_c)\}$ for $b_c < b_w$, (where b_c is column cross-sectional width, b_w the width of the beam web, and h_c the cross sectional column depth in the direction of interest), h_{jc} is the distance between extreme layers of column reinforcement.

The total amount of transverse reinforcement is obtained from expression B5(a) (expression (5.35) in clause 5.5.3.3(3)) or alternatively from expression (B5b) (expression (5.36b) in clause 5.5.3.3 (4)), with the latter one being used in the present work, since the former was found to lead to reinforcement congestion.

$$A_{sh} \geqslant \left(\frac{\left(\frac{V_{jhd}}{b_jh_{jc}}\right)^2}{f_{ctm} + v_df_{cd}} - f_{ctd}\right)\frac{b_jh_{jw}}{f_{yd}} \quad \text{(B5a)}$$

$$A_{sh} \geqslant \frac{\gamma_{Rd}A_{s1}f_{yd}(1 - 0.8v_d)}{f_{yd}} \quad \text{(B5b)}$$

where A_{sh} is the total area of horizontal hoops, V_{jhd} is the design joint shear force, h_{jw} is the distance between the top and bottom beam reinforcement, and v_d is the normalized axial force of the column above.

B.4. Kotsovou & Mouzakis method

$$V_{jh} \leqslant F_{Rjmax} sina = \frac{z_c}{3} w_j f_c sina \quad \text{(B6)}$$

where h_c is the column cross section height, x_c the depth of the column compressive zone depth, $z_c = h_c - x_c$, when $x_c > z_c/3$, then $z_c/3$ is replaced with x_c, w_j the joint width, and α is the inclination of the joint diagonal

The total amount of stirrup reinforcement is obtained from:

$$As_{j,h} \leqslant \frac{T_j}{f_y cosa} \quad \text{(B7)}$$

where $T_j = F_j tanb = \frac{V_{jh}}{sina} tanb$ and $tanb = \frac{z_c}{4\sqrt{z_b^2 + z_c^2}}$

The shear force $F_{js,h}$ that can be sustained at the joint mid height when the transverse reinforcement is at yield is obtained from

$$F_{js,h} = \frac{T_j}{tanb} sina \leqslant \frac{z_c}{3} w_j f_c sina \quad \text{(B8)}$$

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