



## **FLEXURAL BEHAVIOUR OF REINFORCED CONCRETE BEAM-COLUMN JOINTS EXTERNALLY REINFORCED WITH SHAPE MEMORY ALLOY BARS**

Elbahy, Yamen I.<sup>1,2</sup>, and Youssef, Maged A.<sup>1</sup>

<sup>1</sup> Western University, Canada

<sup>2</sup> [yelbahy@uwo.ca](mailto:yelbahy@uwo.ca)

**Abstract:** One of the problems for existing reinforced concrete (RC) structures designed per older standards (pre 1970s) is the inadequate anchorage for the beam reinforcement in the joint area. For newly built structures, Beam-column joints (BCJs) may need to be retrofitted to accommodate changes in the structure use or an increase in the applied loads. Shape Memory Alloys (SMAs) have unique properties that motivated researchers to use them as reinforcing bars in RC structures. They can undergo large deformations and return to their undeformed shape upon unloading. This unique property can be utilized in RC structures subjected to seismic loads to limit residual deformations. In this study, the applicability of using external unbonded SMA bars to retrofit RC BCJs is investigated. A finite element (FE) model is first developed and validated. A simplified model is then proposed and used to conduct a parametric study to investigate the behaviour of SMA retrofitted RC BCJs.

### **1 INTRODUCTION**

It is acceptable to assume that pre-1970s Reinforced Concrete (RC) structures are deficient under seismic loads. These structures are not designed for ductile behaviour. Insufficient anchorage of the beam reinforcement into the joint area of the beam-column joint (BCJ) can be considered a main deficiency of these structures. Thus there is an urgent need to retrofit these structures to ensure safety of the occupants.

Newly built structures may also need to be retrofitted to accommodate a change in the purpose of structure or increase in the applied load levels. Different retrofitting materials and techniques are suggested in the literature to retrofit RC BCJs. Adding additional external reinforcement is a one of these techniques. The type of reinforcement may vary depending on the purpose and condition of the structures. Although steel is a commonly used material, it has a major disadvantage, which is the large permanent seismic deformations. This disadvantage can be eliminated if steel is replaced with a smart material such as Shape Memory Alloys (SMAs).

Superelastic SMAs can undergo large strains and return to their undeformed shape upon unloading. The flag shape hysteresis stress-strain of SMAs gives them adequate damping ability. Also, SMAs have excellent fatigue properties and high corrosion resistance. All of these unique properties make SMAs potential candidate for retrofitting RC BCJs (Janke et al. 2005, Alam et al. 2007).

In this study, the applicability of retrofitting RC BCJs using external unbonded SMA bars is investigated. First, a Finite Element (FE) model is developed and validated using available experimental results. After validating the model, a simplified model is suggested and validated using the FE model. An extensive parametric study is then carried out to investigate the behaviour of retrofitted RC BCJs. Results of the parametric study are then used in multiple linear regression analysis to develop equations that address the change in the behaviour of the retrofitted BCJs.

## 2 FINITE ELEMENT SIMULATION

Three-dimensional FE models are developed to investigate the behaviour of RC BCJs retrofitted using external SMA bars during the loading/unloading stages. Analysis is performed using the commercial FE program ABAQUS Version 6.9 (ABAQUS 2018). 8-node hexahedral isoparametric linear solid elements with reduced integration (C3D8R) are used in the modelling process of the concrete, internal and external reinforcement, and external angles. Different element sizes are first considered to determine the appropriate mesh size. The concrete damage plasticity model is used to model the concrete behaviour. The SMA is defined using the implemented one-dimensional model in ABAQUS.

## 3 EXPERIMENTAL VALIDATION

Results of the experimental work performed by Youssef et al. (2008) are used to validate the accuracy of the developed FE model. Two large scale BCJs are constructed and tested under reversed-cyclic loading applied at the free beam tip. The two joints are identical in dimensions and reinforcement details except the type of reinforcement. In the plastic hinge region, one joint (BCJ1) is reinforced with regular steel bars, while the second (BCJ2) is reinforced with superelastic SMA bars.

The beams of the two joints have a length of 1830 mm, 400 mm cross-section height, and 250 mm cross-section width. Amounts and arrangements of transverse reinforcement are also identical for the two beams. Stirrups are 10M in diameter and are spaced at 80 mm for 800 mm length adjacent to the column and spaced at 120 mm elsewhere. The type of longitudinal reinforcement in the plastic hinge regions of the two beams is different. Two superelastic SMAs bars (20.6 mm diameter) are used at the top and bottom of the plastic hinge region of BCJ2 beam, while 2-20M steel bars are used at the top and bottom of BCJ1 beam. Regular 2-20M steel bars are used outside the plastic hinge region of BCJ2 beam. Steel couplers are used to connect the SMAs bars to the steel bars.

Average concrete compressive strength is found to be 53.50 MPa for BCJ1 and 53.70 MPa for BCJ2. Average split cylinder tensile strength is found to be 3.50 MPa for the BCJ1 and 2.80 MPa for BCJ2. Steel Reinforcing bars of BCJ1 have yield strength of 520 MPa, ultimate strength of 653 MPa, and a modulus of elasticity of 198 GPa. Steel reinforcing bars of BCJ2 have yield strength of 450 MPa, ultimate strength 650 MPa, and a modulus of elasticity of 193 GPa. Stirrups have a yield strength of 422 MPa and ultimate strength of 682 MPa.

Youssef et al. (2008) determined the mechanical properties of the superelastic SMA bars by experimentally testing them under cyclic loading. It is reported that the SMA bars critical stress is 401 MPa at a critical strain of 0.75%. The modulus of elasticity is evaluated as 62.5 GPa. The residual deformation is determined as 0.73%, when the SMA bar was loaded up to 6.0% strain. As shown in Figure 1, good agreement between the experimental and analytical results can be observed for the two BCJs.

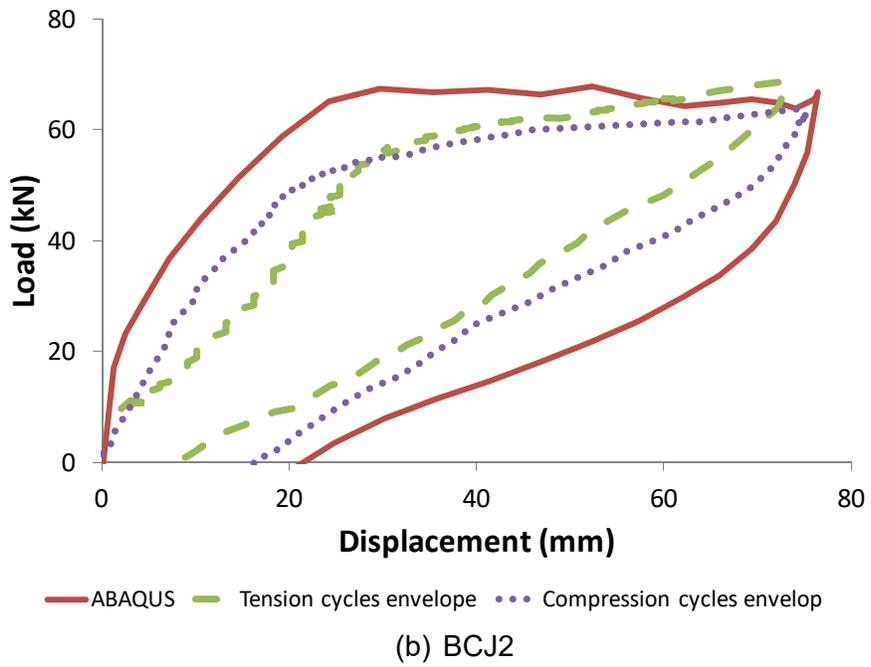
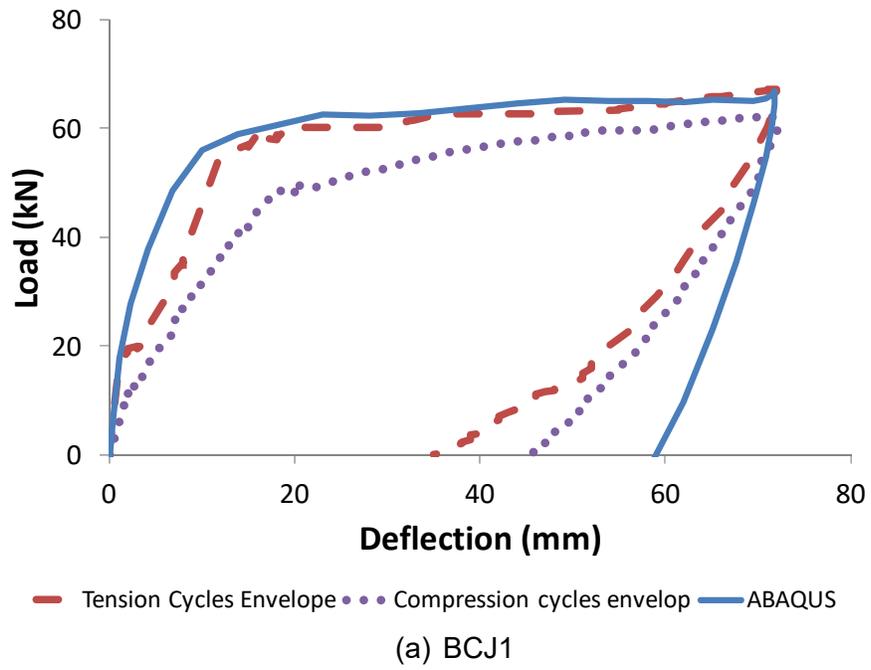


Figure 1: Experimental vs. FE load-displacement results for the BCJs tested by Youssef et al. (2008); (a) BCJ1; and (b) BCJ2

#### 4 SUGGESTED RETROFITTING TECHNIQUE

The idea of the proposed retrofitting technique is based on attaching external SMA bars to the RC BCJ. As shown in Figure 2, the bars are attached to the BCJ using external steel angles. The steel angles are attached to the BCJ using steel bolts. One angle is attached to the BCJ joint area, while the second angle is attached to the beam. Hold down plates can be used for big lengths of the SMA bars to enforce the bars to deform with the beam.

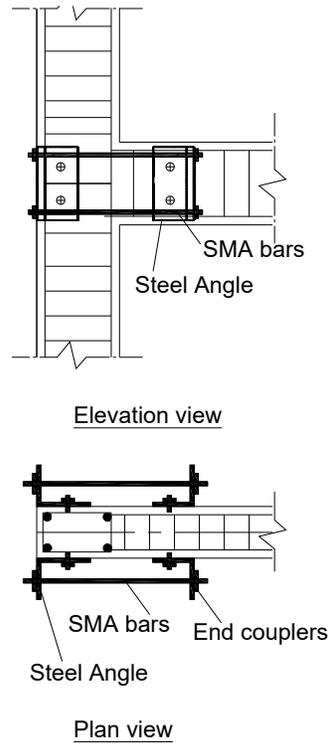


Figure 2: Proposed retrofitting technique

The modulus of elasticity of SMA is much lower ( $1/5$  to  $1/3$ ) than that of the regular steel. Thus, attaching a small to moderate ratio of SMA will improve the strength and the stiffness of the BCJ, but it is not expected to reduce the residual deformations at complete unloading. Thus, it is proposed to cut the internal steel bars of the beam at the face of the column. To overcome any change in the BCJ stiffness or strength, additional external SMA bars should be added. This ensures that the BCJ behaviour is governed by the external SMA bars rather than the internal steel bars, and thus minimum residual deformations are expected at complete unloading.

A RC BCJ is assumed for the analysis in this section. The beam of the BCJ has a cross-section of 250x400 mm and a span of 1830 mm. The column has similar cross-section dimensions to the beam and is 1200 mm in height. The BCJ is supported using top and bottom plates representing roller and hinge supports, respectively. The plates have dimensions equal to 250x400x100. The external angles have dimensions equal to 200x90x80x20 mm and is attached to the BCJ using 8 bolts. The bolts are assumed to be 71 mm in length and 12.7 mm in diameter. The external SMA bars are attached to the external angles using end couplers. The ratio of the added external SMA is equal to the ratio of the internal steel reinforcement.

FE analysis is performed for the retrofitted BCJ. Figure 3 shows the FE model of the retrofitted BCJ. Figure 4 shows the load-displacement relationship of the retrofitted beam vs. the original beam. The maximum moment capacity of the beam increased from 70 kN to 85 kN due to retrofitting. The initial stiffness of the

beam is almost not affected by retrofitting. This is attributed to the big difference in the modulus of elasticity value between steel and SMA. The amount of residual displacement is reduced from 72 mm to 60 mm. Amount of dissipated energy is increased.

It is clear from Figure 4 that adding external SMA bars reduced the amount of residual displacement by 17% only. This small effect is attributed to the low modulus of elasticity for the SMA bars. To improve the contribution of the SMA bars, it is proposed to cut the internal steel reinforcement at the face of the column.

FE analysis is performed again for the BCJ assuming cutting the internal steel reinforcement. Analysis of the results is illustrated in Figure 5. As shown in the figure, significant reduction in the amount of residual displacement (98%) is observed in this case. On the other hand, the total moment capacity of the beam is reduced by 31% due to the cut of the internal steel bars. Initial stiffness of the beam is also significantly reduced. These disadvantages can be overcome by increasing the amount of the external SMA bars as will be investigated in the following sections.

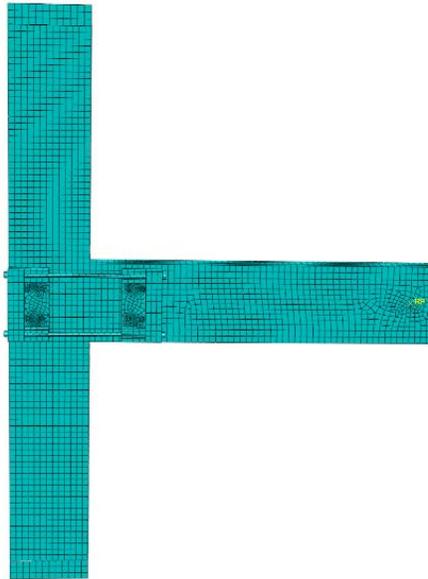


Figure 3: FE Model of the retrofitted BCJ

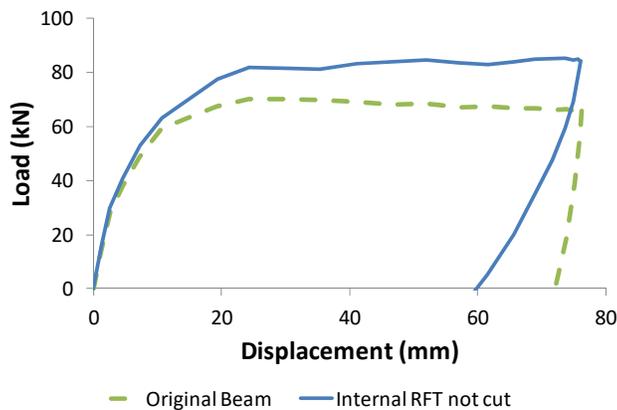


Figure 4: FE load-displacement relationship for the original BCJ vs. the retrofitted BCJ

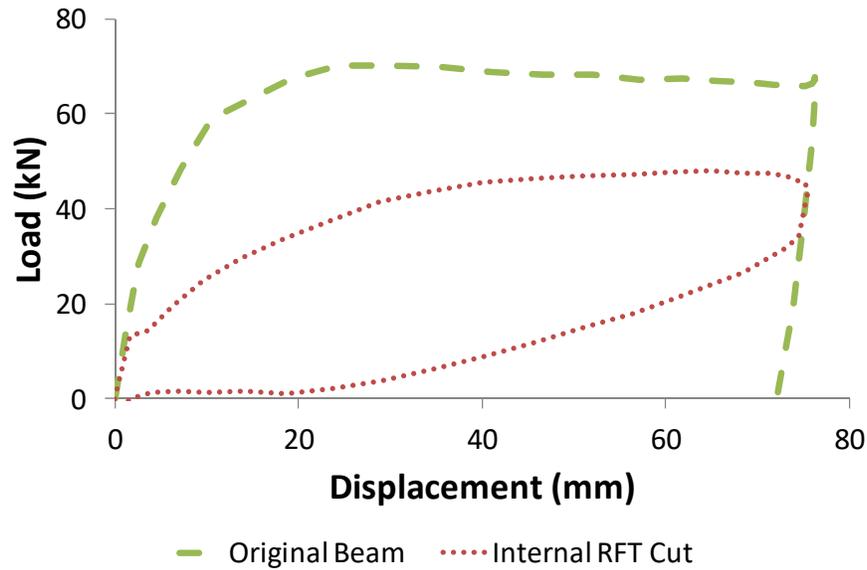


Figure 5: FE load-displacement relationship for the original BCJ vs. the retrofitted BCJ with internal steel bars are cut

## 5 SIMPLIFIED MODEL

Modelling the retrofitted BCJ using ABAQUS software is a complex process. Thus, a simplified model for the retrofitted BCJ is proposed in this section. The simplified model is developed using Seismostruct software v.6 (Seismostruct 2018). The special technique used to model the connection include: (i) modelling the SMA bars using inelastic truss elements; (ii) modelling the superelastic behaviour of the SMA bars using the uniaxial material model proposed by Auricchio and Sacco (1997); (iii) modelling the concrete beam and column using displacement based inelastic frame elements; and (iv) modelling the external angles that supports the SMA bars using rigid arms connected to the concrete beam and column.

As shown in Figure 6, the beam and the column of the BCJ are modelled using frame elements. Two rigid arms are connected to the beam near the face of the column representing the angle supported in the joint area. Another two rigid arms are connected to the beam at a distance equal to the length of the required SMA bars. The SMA bars are connected between the rigid arms and are modelled using truss elements. The reinforcement in the beam element is cut in between the rigid arms to eliminate any contribution from it to the strength, stiffness and residual deformation of the joint.

To validate the assumed simplified model, a comparison between the load-displacement results of the simplified model developed using Seismostruct software and the actual model developed using ABAQUS is shown in Figure 6. Very good agreement between the two results is achieved.

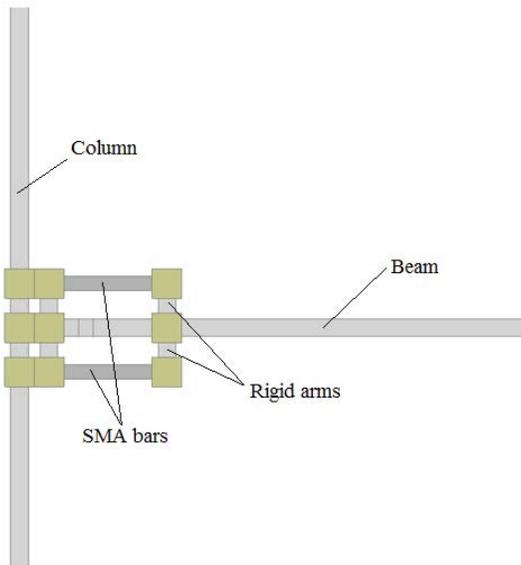


Figure 6: Sketch of the simplified model

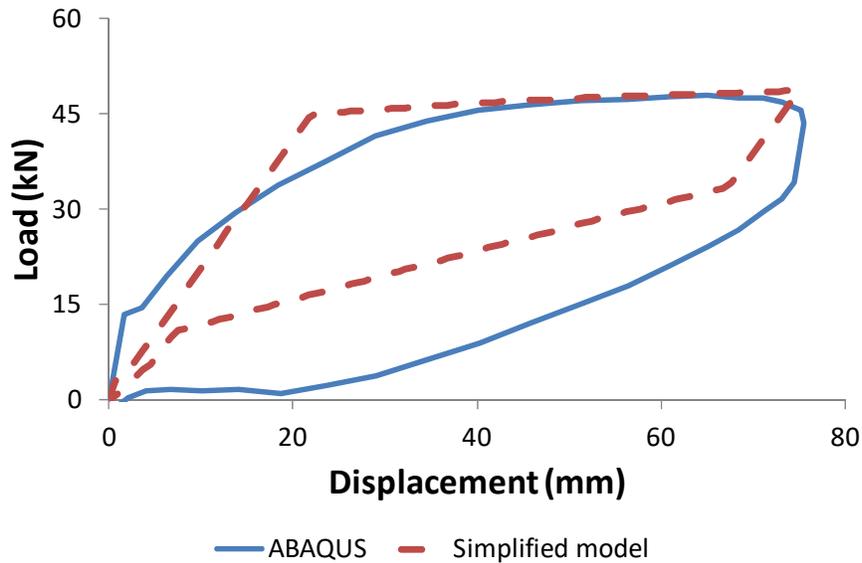


Figure 7: Load-displacement results of the ABAQUS model vs. the simplified Seismostruct model

## 6 PARAMETRIC STUDY

A parametric study is carried out in this section to further investigate the behaviour of RC BCJs retrofitted using external SMA bars. The analysis is performed using the developed simplified model for both loading and unloading stages. Three different parameters are investigated in this study: (i) the ratio between the

added external SMA reinforcement to the amount of internal steel reinforcement in the beam ( $A_{SMA}/A_s$ ); (ii) ratio between the length of the used SMA bars to the length of the beam ( $L_{SMA}/L$ ); and (iii) drift ratio ( $\delta_{max}/L$ ).

The parametric study is performed on BCJs with geometrical dimensions similar to that presented in the Finite Element Simulation section. The beams are loaded/unloaded using a point load applied at the cantilever tip. For each of the studied parameters, the parameter under investigation is varied within the desired range while keeping all other parameters constant during the analysis. Four different outputs are used to compare the results of the parametric study. These outputs are: (i) the ratio between the amount of residual displacement upon complete unloading ( $\delta_r$ ) and the maximum displacement applied to the beam tip ( $\delta_{max}$ ); (ii) the ratio between the maximum moment capacity of the retrofitted BCJ ( $M_{rt}$ ) to the moment capacity of the original BCJ ( $M_{org}$ ); (iii) the ratio between the secant stiffness of the retrofitted BCJ ( $ST_{rt}$ ) to the secant stiffness of the original BCJ ( $ST_{org}$ ); and (iv) the amount of dissipated energy by the retrofitted BCJ ( $EN_{rt}$ ) to the amount of dissipated energy by the original BCJ ( $EN_{org}$ ). It should be noted that the amount of dissipated energy using the simplified model is slightly smaller than that obtained using the ABAQUS model. Internal steel reinforcement is assumed to be cut in all of the studied BCJs. Detailed results of the parametric study are introduced in the following section.

## 7 CHOICE OF SMA BARS

After performing the parametric study, the results are then arranged in a database format with all records of the study. Multiple linear regression analysis is performed using STATA software V. 12 to determine the relationships between the inputs and outputs. Numerous number of models based on different transformations (i.e. linear transformations, quadratic power transformation, and logarithmic transformation) are first tried. The best models that relate the parametric study inputs to outputs are then chosen and reported in this study. A total of seven models for the four outputs are reported.

A total of 524 data sets are used in establishing the statistical models. These data represents all the data obtained from the parametric study. All inputs and outputs of this study are kept dimensionless. The inputs of the models are: (i) internal reinforcement status (bars are cut or not cut); (ii)  $A_{SMA}/A_s$  ratio; (iii)  $L_{SMA}/L$  ratio; and (iv) load level. The outputs of the parametric study are:  $\delta_r/\delta_{max}$ ,  $M_{rt}/M_{org}$ ,  $ST_{rt}/ST_{org}$ , and  $EN_{rt}/EN_{org}$ .

Correlation analysis is first used with the data to determine the correlation between each pair of the variables and noting the highly correlated ones and their signs. The correlation matrix is presented in Table 3. Table 4 shows the final regression model for  $\delta_r/\delta_{max}$  as an example. The adjusted R-squared value is found to be: 0.725 for  $\delta_r/\delta_{max}$ ; 0.93 for  $M_{rt}/M_{org}$ ; 0.98 for  $ST_{rt}/ST_{org}$ ; 0.85 for  $EN_{rt}/EN_{org}$ .

Table 3: Correlation coefficients between all variables

	RFT Status	$\delta_{max}/L$	$L_{SMA}/L$	$A_{SMA}/A_s$	$\delta_r/\delta_{max}$	$M_{rt}/M_{org}$	$ST_{rt}/ST_{org}$	$EN_{rt}/EN_{org}$
RFT Status	1							
$\delta_{max}/L$	0.02	1						
$L_{SMA}/L$	0.03	-0.01	1					
$A_{SMA}/A_s$	0.00	-0.01	-0.01	1				
$\delta_r/\delta_{max}$	-0.76	0.31	-0.14	0.07	1			
$M_{rt}/M_{org}$	-0.48	0.21	-0.22	0.66	0.47	1		
$ST_{rt}/ST_{org}$	-0.83	-0.02	-0.16	0.40	0.74	0.79	1	
$EN_{rt}/EN_{org}$	-0.75	0.35	-0.22	0.30	0.90	0.71	0.85	1

Table 4: Regression model for  $\delta_r/\delta_{max}$ 

Source	SS	df	MS	Number of obs	=	524
Model	311799.6	6	51966.6	F( 6, 517)	=	230.77
				Prob > F	=	0
Residual	116419.6	517	225.183	R-squared	=	0.7281
				Adj R-squared	=	0.725
Total	428219.2	523	818.7748	Root MSE	=	15.006

$\delta_r/\delta_{max}$	Coef.	Std. Err.	t	P>t	[95% Conf. Interval]	
RFT Status	-43.8554	1.312181	-33.42	0	-46.4333	-41.2775
$(\delta_{max}/L)^2$	-3.05824	0.743889	-4.11	0	-4.51965	-1.59682
$(\delta_{max}/L)$	24.97149	4.095759	6.1	0	16.92511	33.01787
$(L_{SMA_s}/L)^2$	48.73263	9.739459	5	0	29.59885	67.86641
$(L_{SMA_s}/L)$	-63.5142	10.60582	-5.99	0	-84.35	-42.6784
$(A_{SMA}/A_s)^2$	0.299076	0.081117	3.69	0	0.139717	0.458436
Constant	23.85597	5.454152	4.37	0	13.14094	34.57099

Equations [1-4] represent the summary of the final statistical models for the four outputs.

$$[1] (\delta_r/\delta_{max}) = -43.8554 \times (\text{Reinforcement status}) - 3.05824 \times (\delta_{max}/L)^2 + 24.97149 \times (\delta_{max}/L) + 48.73263 \times (L_{SMA_s}/L)^2 - 63.5142 \times (L_{SMA_s}/L) + 0.299076 \times (A_{SMA}/A_s)^2 + 23.85597$$

$$[2] \ln(M_{rt}/M_{org}) = 0.351534 \times (\delta_{max}/L) - 0.03753 \times (\delta_{max}/L)^2 - 0.70269 \times (L_{SMA_s}/L)^2 + 0.736527 \times \ln(A_{SMA}/A_s) + 3.829082$$

$$[3] (ST_{rt}/ST_{org}) = 63.86686 \times (L_{SMA_s}/L) + 24.46517 \times (L_{SMA_s}/L)^2 - 1.92955 \times (A_{SMA_s}/A_s)^2 + 56.02788$$

$$[4] \ln(EN_{rt}/EN_{org}) = 2.085338 \times (\delta_{max}/L) - 0.25739 \times (\delta_{max}/L)^2 - 4.36291 \times (L_{SMA_s}/L) + 0.985633 \times (L_{SMA_s}/L)^2 + 1.194 \times \ln(A_{SMA_s}/A_s) + 0.415448$$

## 8 CONCLUSIONS

Retrofitting RC BCJs using external unbonded SMA bars is investigated in this study. A FE model is first developed and validated using available experimental results. Experimental results included RC BCJs internally reinforced with steel and SMA bars. Good agreement between experimental and analytical results is observed. A simplified model using the Seismostruct software is then developed to capture the behaviour of RC BCJs externally reinforced with SMA bars. Results of the simplified model are first validated using the results of the FE model.

After validating the simplified model results, it is then used to carry out an extensive parametric study to investigate the behaviour of RC BCJs retrofitted using external SMA bars. Three parameters are investigated in this study. These parameters are: (i) ratio between the external SMA reinforcement to the internal steel reinforcement ( $A_{SMA}/A_s$ ); (ii) ratio between the length of the SMA bars and the full length of the beam ( $L_{SMA_s}/L$ ), and applied drift ratio ( $\delta_{max}/L$ ). Four outputs are used in the parametric study to capture the change happening in the behaviour due to varying of the parameters. These outputs are:  $(\delta_r/\delta_{max})$ ,  $(M_{rt}/M_{org})$ ,  $(ST_{rt}/ST_{org})$ , and  $(EN_{rt}/EN_{org})$ .

Results of the parametric study are then used to perform multiple linear regression analysis. Different models with different transformations of the inputs are developed for the four outputs. Results of the

regression analysis are then summarized in the form of simple equations to determine the optimum amount and length of the used SMA bars.

## 9 REFERENCES

- ABAQUS, F.E. A. (2018) "ABAQUS Analysis user's manual." Dassault Systemes, Vélizy Villacoublay, France.
- Alam, M.S., Youssef, M.A., and Nehdi, M. 2007. Utilizing Shape Memory Alloys to Enhance the Performance and Safety of Civil Infrastructure: a Review." *Canadian Journal of Civil Engineering*, **34**(9), 1075-1086.
- Auricchio, F, and Sacco, E. (1997) "Superelastic shape-memory-alloy beam model." *Journal of Intelligent Material Systems and Structures*, **8**(6), 489-501.
- Janke, L., Czaderski, C., Motavalli, M., and Ruth, J. 2005. Applications of Shape Memory Alloys in Civil Engineering Structures - Overview, Limits and New Ideas. *Materials and Structures*, **338**(279), 578-592.
- SeismoSoft. 2018. SeismoStruct - A computer program for static and dynamic nonlinear analysis of structures. Available from URL: <http://www.seismosoft.com>.
- Youssef, M.A., Alam, M.S. and Nehdi M. 2008. Experimental investigation on the seismic behaviour of beam-column joints reinforced with superelastic shape memory alloys. *Journal of Earthquake Engineering* **12**(7), 1205-1222.