Numerical analysis of dynamic behavior of pre-stressed shape memory alloy concrete beam-column joints

S Yan¹, Z F Xiao¹, M Y Lin¹ and J Niu¹,²

¹. School of Civil Engineering, Shenyang Jianzhu University, Shenyang Liaoning, 110 168, China.
² Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian Liaoning, 116024, China.
Corresponding author email: syan1962@163.com

Abstract. Beam-column joints are important parts of a main frame structure. Mechanical properties of beam-column joints have a great influence on dynamic performances of the frame structure. Shape memory alloy (SMA) as a new type of intelligent metal materials has wide applications in civil engineering. The paper aims at proposing a novel beam-column joint reinforced with pre-stressed SMA tendons to increase its dynamic performance. Based on the finite element analysis (FEA) software ABAQUS, a numerical simulation for 6 beam-column scaled models considering different SMA reinforcement ratios and pre-stress levels was performed, focusing on bearing capacities, energy-dissipation and self-centering capacities, etc. These models were numerically tested under a pseudo-static load on the beam end, companying a constant vertical compressive load on the top of the column. The numerical results show that the proposed SMA-reinforced joint has a significantly increased bearing capacity and a good self-centering capability after unloading even though the energy-dissipation capacity becomes smaller due the less residual deformation. The concept and mechanism of the novel joint can be used as an important reference for civil engineering applications.

1. Introduction

Reinforced concrete (RC) beam-column joints are dominant parts of a RC structure, which plays an important role in high-rise structures. Under a dynamic environment such as an earthquake, the well dynamic performance is important to ensure the reliability of the structure. The main dynamic performances are including the bearing capacity, deformation capacity, energy-dissipation capacity, etc. One of the traditional design criteria is meeting requirements of enough bearing capacity and well deformation capacity to dissipate more energy and the structural stability during a dynamic loading. However, a traditional RC structure might have an observable residual deformation after unloading which could greatly influence the vertical stability of the structure even inducing severe damages or collapse. Self-centering capacity of a structure is a kind of new but important concept which represents a recovery capacity to its original or balance position by its own ability [1-3]. Smart materials are usually used to design the self-centering devices or resembled into structures to make them having the self-centering function [4].

Shape memory alloy (SMA) is a new type of smart metal material. SMA has obviously superior shape memory effect (SME) and superelasticity (SE) characteristics which has both sensing and driving functions [5]. The SE effect of SMA is a process of stress-induced martensitic transformation after loading of $A_s-A_f$, a process of austenite transformation after unloading, and the material is completely...
restored to the original shape. The SE type SMA has a unique hysteresis characteristic which can consume large amounts of energy in the material without causing residual strain or deformation. The SE of SMA can also effectively improve the bearing capacity, residual deformation and energy dissipation capacity of beam-column joints [6-8].

Based on the SE of SMA, a novel RC beam-column joint reinforced with SMA tendons for part instead of traditional reinforcement is proposed in the paper, aiming at improving the self-centering performance under dynamic loading. A finite element model is established by finite element analysis (FEA) software (ABAQUS) to analyze dynamic behaviors of the proposed novel joints.

2. Mechanical properties of SMA

In the SMA excellent properties, the most significant features are SME and SE. The SMA elastic strain is up to 5% -20% but the elastic strain for an ordinary metal material elastic strain is generally not more than 0.5% [9]. In a cycle of loading and unloading, the stress-strain curve of the superelastic SMA will form a complete hysteresis loop, thus providing good energy dissipation and self-centering capability. The SE of SMA is affected by alloy composition and heat treatment method, ambient temperature, strain rate, strain amplitude, cyclic loading, pre-strain and other factors. Huang [10] treated Ti-49.8at% Ni alloy wire with cold drawing and intermediate annealing process. The results show that the material can obtain complete nonlinear ultra-linearity after large cold deformation and medium temperature annealing elasticity. When the Ni content is more than 50%, the material obtain good superelasticity after heat treatment, such as Ti-50.8at% Ni alloy wire at 400℃ for 30 min after quenching to obtain better superelasticity. Strain amplitude has a great influence on the energy dissipation of materials [11-12]. With increase of the strain amplitude, the martensitic transformation of SMA is more obvious and the energy consumption increases, but the change of critical stress is small. The equivalent damping ratio increases linearly in the range of medium and low strain amplitude (1% -5%). Since the martensitic elastic deformation occurs after the normal phase transition, the equivalent damping ratio is higher than that at high strain (5% -10%). When the SMA performance is not stable, the residual strain increases with increase of the strain amplitude. Ip[13] predicted the energy dissipation of SMA wire under bending load, and the results show that pre-strain can improve the damping capacity of SMA. In the beam repair performance test, SMA tendons was loaded in the effective pre-strain with the greater strain, the fracture recovery rate was better [14].

3. Finite element model

3.1. Model description

The numerical simulation model is selected as a typical member of a multi-layer and high-rise frame RC structure under a horizontal load, and the model scale is 1:2. In this paper, two types of beam-column joints are designed. One is the ordinary beam-column concrete joint and the other is reinforced with pre-stressed SMA tendons. The geometrical dimensions of the beam members are 770mm × 120mm × 240mm (length × width × height), and the column member geometry is 1500mm × 200mm × 200mm (length × width × height). The ordinary beam is reinforced by 4 longitudinal reinforcement of HRB400Φ10, stirrup of HRB400Φ10 @ 80mm, and the protective layer thickness of 20 mm. The column is installed by 4 longitudinal reinforcements of HRB400Φ16, stirrup of HRB400Φ10 @ 80mm, and the protective layer thickness of 20 mm. Specific specimen cross-section size and reinforcement situation are shown in Figure 1. The specimen design parameters are shown in Table 1.
Figure 1. The model size and reinforcement. (a) The model dimension and reinforcement. (b) Reinforcements in cross-sections.

Table 1. The model design parameters

| Specimen number | Column reinforcement | Reinforcement of beam members | SMA tendons |
|-----------------|----------------------|-----------------------------|-------------|
|                 | Longitudinal tendons (mm) | Stirrups (mm) | Longitudinal tendons (mm) | Reinforcement ratio(%) | Pre-strain(%) |
| XJD-1           | 4Φ16                | Φ10@80                    | 4Φ10 Ordinary tendons | 0                   | 0             |
| YJD-1           | 4Φ16                | Φ10@80                    | 4Φ10 SMA tendons    | 0.65                | 4             |
| YJD-2           | 4Φ16                | Φ10@80                    | 4Φ10 SMA tendons    | 0.65                | 5             |
| YJD-3           | 4Φ16                | Φ10@80                    | 4Φ10 SMA tendons    | 0.65                | 6             |
| YJD-4           | 4Φ16                | Φ10@80                    | 4Φ12 SMA tendons    | 0.94                | 6             |
| YJD-5           | 4Φ16                | Φ10@80                    | 4Φ14 SMA tendons    | 1.19                | 6             |

3.2. Constitutive model of concrete
The constitutive model of CONTRETE02 [15] in OPSEES platform is used in simulation analysis. The compression skeleton curve is used by Kent and Park, and Scott [16] modified the Kent-Park model. The hysteresis rules of constitutive relation of concrete: from the unloading point D on the skeleton curve, the straight line DE with the slope of the initial tangential stiffness is unloaded to a certain extent and then unloaded to the residual plastic strain point H by a straight line EH with a slope of half of the reload slope, the reload line is a straight line connecting the plastic strain point H to the unloading point D and is loaded back along the skeleton line back to the skeleton line. Residual plastic strain depends on unloading strain and reloading stiffness. The slope of the reload is determined by defining the point R, where all the reload lines extend in the opposite direction. The slope of the reload line can be obtained from the unload point and the R point. That is as shown in Figure 2.

Figure 2. The hysteresis rules of constitutive relation of concrete.

Figure 3. The tensile part of the concrete skeleton curve.
The tension part is proposed by Yassin [17]. The skeleton line is divided into two straight lines. The first one is linearly loaded to the tensile peak stress, and then along the straight line from the tensile peak stress point goes down to stress zero. The tension loading and unloading lines overlap, being pulled into the starting point of the linear plastic strain residual tension by unloading point. The model takes into account the stiffness degradation during the unloading process of concrete and the hysteretic energy dissipation of the loading and unloading process. That is shown in Figure 3.

3.3. Reinforcement constitutive model

The constitutive model of USTEEL02 [18] in PQ-fiber platform is used in the simulation analysis. Its main feature does not immediately point to the history of the largest point, but first by unloading stiffness loaded to the maximum point of the corresponding stress of 0.2 times, that is, 0.2f_{max}, and then point to the largest point in history in the reverse reload. The specific process is shown in Figure 4.

![Figure 4. The hysteresis rules of constitutive relation of concrete.](image1)

![Figure 5. The tensile part of the concrete skeleton curve.](image2)

In this model, the degradation and decline of the yield strength of steel skeleton curve considers not only the deterioration of the steel itself, but the effect of reflecting the integrated bond slip degradation of reinforced concrete and concrete interface peeling caused by a protective layer.

3.4. The constitutive model of SMA

The model is based on the SMA thermodynamic model framework derived from Lagoudas [19] et al. It is based on the concept of free energy and dissipation. The model assumes that the loading and unloading phases of each SMA stress and strain are linear, and a multi-linear model is proposed and simplified, greatly reducing the computation time and being more convenient in engineering applications. Figure 5 is the schematic diagram of the superelastic SMA multi-linear constitutive model. C_M and C_A are the critical stress-temperature conversion coefficients of martensitic transformation and reverse phase transformation, respectively. The $\varepsilon_L$ is the maximum phase transition strain, and T is the ambient temperature.

3.5. Unit selection and model establishing

The numerical analysis is based on the ABAQUS platform. According to characteristics of RC beam-column joints, a modeling fiber unit is taken [20]. The slip between the reinforcement and the concrete is ignored. In the model analysis, the boundary conditions and loads are imposed by setting two analysis steps. The specific processes are: (1) constraining column bottom three directional displacements, an axial pressure is applied on the column top plate. Then, constraining X and Y directional displacements on the top of the column to prevent the component tilt and beam end force. (2) In the second analysis step, the Z-direction vertical load and the line displacement are applied to both ends of the beam to realize the quasi-static test.

3.6. Loading scheme
In the FEA simulation, the loading system is used, shown in Figure 6. Each cycle includes a forward loading-unloading and a reverse loading-unloading two stages. At start, three cycles are controlled by the vertical load, and the control value is typically 30%, 50% and 70% of the maximum vertical load, respectively. The fourth cycle is changed to the vertical displacement control when the model reaches the yield load. Then the displacement control is used until the model fails.

4. Finite element analysis results
Based on the above modeling method, the simulation results show that the hysteresis performance and the self-centering performance of the pre-stressed beam-column joints of YJD-1, YJD-2, YJD-3, YJD-4, YJD-5 and the ordinary beam-column of XJD-1 are compared.

4.1. Hysteresis curves
After post-processing, beam-force-displacement hysteresis curves of YJD-1 and XJD-1 models are obtained by extracting peak displacements in the last hysteresis, shown in Figure 7. The maximum reaction force and residual deformation at the beam end after unloading equivalent are shown in Table 2.

![Figure 6. Quasi-static loading scheme.](image)

![Figure 7. Comparison of YJD-1 and XJD-1 hysteresis curves and residual deformation. (a) Force-displacement curves. (b) Residual deformation-displacement curves.](image)
Table 2. Comparison of maximum and residual deformation of models.

| Specimen number | Maximum deformation (mm) | Maximum reaction force (kN) | Residual deformation (mm) | Residual deformation rate (%) |
|-----------------|--------------------------|-----------------------------|---------------------------|-------------------------------|
| XJD-1           | 38.83                    | 21.49                       | 24.28                     | 62.53                         |
| YJD-1           | 39.65                    | 22.83                       | 4.07                      | 10.26                         |
| YJD-2           | 39.61                    | 23.62                       | 3.55                      | 8.96                          |
| YJD-3           | 39.68                    | 24.33                       | 2.95                      | 7.43                          |
| YJD-4           | 39.73                    | 26.90                       | 1.41                      | 3.55                          |
| YJD-5           | 39.71                    | 30.27                       | 0.76                      | 1.91                          |

(1) It can be seen from Figure 7(a) that the vertical reaction-displacement curve is almost linear at the beginning of loading and the hysteresis curve loop area is very small. This is because the initial stiffness of the joint is large and the structure is in the elastic phase. As continuing loading, concrete reaches the ultimate bearing capacity, and the longitudinal reinforcement tends to carry the main load until the steel reaches yield strength. The ultimate load of the model cannot be able to maintain, and the beam bending failure happens in the end.

(2) It can be seen from Figure 7(a) and (b) that the normal joint and the pre-stressed SMA joints have good energy dissipation capacity. The hysteresis curve of the common beam-column joint shows a long quadrilateral, and the residual deformation is larger after unloading. The hysteresis curve of pre-stressed SMA tendons is round and full, showing a "double flag" curve with typical self-centering characteristics. It can be seen from Table 2 that the residual deformation of the common beam-column joint increases with the loading of the load, and the residual deformation rate is 62.53% in the last loading and unloading stage. In each loading and unloading stage, the residual deformation of the pre-stressed SMA tendons does not change much, and the residual deformation rate is only 10.26% during the last loading and unloading phase, showing good self-centering performance.

4.2. Skeleton curves

In this paper, the envelope curve formed by connecting these points is the skeleton curve of the reciprocating load of the model. The skeleton curves of the XJD-1 and YJD-1 models shown in Figure 8.

![Figure 8. The comparison of skeleton curves between XJD-1 and YJD-1 models.](image)

It can be seen from Figure 8 that the skeleton curves of the two joints generally show "S" shape, which has experienced the elastic stage and the elastoplastic stage. Throughout the process, the beam reaction force of the YJD-1 model is larger than that of the XJD-1 one. With increase of the loading displacement, the two curves separate to form two curves, and both curves have downward trend. When loading to the maximum displacement, two loading capacities are different.
4.3. Performance analysis of hysteretic curve under different influencing factors

4.3.1. The SMA pre-stress level influences. The SMA pre-stress level has an influence on the dynamic performance of the joint. Models of YJD-1, YJD-2 and YJD-3 are respectively subjected to different pre-stress levels by using the cooling method in the FEA model, and other parameters are the same. The hysteretic curves of the beam-side reaction-displacement are obtained, shown in Figure 9.

![Figure 9](image)

**Figure 9.** The comparison of YJD-1, YJD-2 and YJD-3. (a) The hysteresis curves. (b) The residual deformation.

It can be seen from Figure 9 (a) that the magnitude of the initial pre-stress has a significant effect on the joint stiffness but small effect on bearing carrying capacities. Three sets of models are smooth "double flag" shape curves with a high degree of similarity. With increase of loading, SMA tendons are gradually elongated, and the SMA stress on initial stage continues increasing. At each unloading, the SMA tendons pull the beam back to original position due to the superelasticity, and the cracks in the concrete beam become self-closing.

It can be seen from Figure 9 (a), (b) and Table 2 that the initial pre-stress of the SMA tendon is large and the residual deformation of the specimen is small after unloading. As the load continuing increasing, the residual deformation after unloading at each stage gradually decreases as the pre-stress of the SMA tendons increases. It is shown that the pre-stress level tendon has some influences on the reset performance of joints.

4.3.2. The SMA diameter influences. The SMA diameter also has an effect on the dynamic performance of the joint. By changing the diameter of SMA tendons in YJD-3, YJD-4 and YJD-5, retaining the same parameters, the hysteretic displacement hysteresis curves of the beam end are obtained, shown in Figure 10.

![Figure 10](image)

**Figure 10.** The comparison of YJD-3, YJD-4 and YJD-5. (a) The hysteresis curves. (b) The residual deformation.
It can be seen from Figure 10(a) that with increase of the SMA diameter, the joint stiffness and bearing capacities of beam-column joints are gradually increased. When the load gradually increases, the SMA tendons are gradually elongated. When the load increases to a certain extent, the main bending stiffness of the model comes from the SMA tendon.

It can be seen from Figure 10(a) and (b) and Table 2 that the residual deformation gradually decreases with increase of the SMA tendon diameter, that is, the self-repairing performance of the joints is getting better.

4.4. Performance analysis of skeleton curves under different influencing factors

The peak points of the beam-side responses are extracted in each cycle of the hysteresis curve in each series, and the envelope curves are formed by connecting these points together, shown in Figure 11. The skeleton curves have the following properties:

- The trend of skeleton curves of joints is basically the same as the typical "S" shape. The development trend of the model is from steep to slow. The bearing capacities of the models are gradually increased.
- It can be seen from Figure 11(a) that the beam end magnitude in descending order is YJD-3, YJD-2 and YJD-1 in the loading process. It is shown that with the increase of pre-stress level, the reaction force of the beam is gradually increasing.
- It can be seen from Figure 11(b) that the skeleton curve increases with increase of SMA tendon diameter. Therefore, the SMA tendon diameter has a significant effect on the bearing capacity of the joint.

![Figure 11](image_url)

**Figure 11.** The skeleton curve comparison for different pre-stress levels and diameters. (a) YJD-1 (4%), YJD-2 (5%) and YJD-3 (6%). (b) YJD-3 (10 mm), YJD-4 (12 mm) and YJD-5 (14 mm).

5. Conclusions

In this paper, by means of finite element method, the hysteretic characteristics, bearing capacity and self-centering ability of the RC beam-column joint reinforced with pre-stressed SMA tendons are analyzed. The main conclusions are as follows:

- The pre-stressed SMA tendons can not only improve the bearing capacity of the joints, but also the self-centering performance of the joints due to the superelastic effect of SMA material.
- The larger the initial pre-stressed of the SMA in the beam-column joints, the better the self-centering ability of the joints, the greater the bearing capacity, and the smaller the residual deformation after unloading.
- In the beam-column joints, with the increase of the SMA diameter, the better the self-centering ability of the joints, the seismic bearing capacity of the joints is obviously improved, and the residual deformation is smaller after unloading.
6. References

[1] Farmani M A and Ghassemieh M 2016 Shape memory alloy-based moment connections with superior self-centering properties. *Smart Materials and Structures* **25** 075028

[2] Shajil N, Srinivasan S M and Santhanam M 2016 An experimental study on self-centering and ductility of pseudo-elastic shape memory alloy (PESMA) fiber reinforced beam and beam-column joint specimens. *Materials and Structures* **49** 783-793

[3] Wang W, Chan T M, Shao H and Chen Y Y 2015 Cyclic behavior of connections equipped with NiTi shape memory alloy and steel tendons between H-shaped beam to CHS column. *Engineering Structures* **88** 37-50

[4] Song L L, Guo T, Gu Y and Cao Z L 2015 Experimental study of a self-centering prestressed concrete frame subassembly. *Engineering Structures* **88** 176-188

[5] Qian H, Li H N, Song G B 2008 Energy dissipation system of structures with shape memory alloy damper. *Journal of Vibration & Shock* **27** 42-47 (in Chinese)

[6] Moradi S and Alam M S 2015 Feasibility study of utilizing superelastic shape memory alloy plates in steel beam–column connections for improved seismic performance. *Journal of Intelligent Material Systems and Structures* **26** 463-475

[7] Wang W, Yan S, Song G B and Jiao L 2009 An improved two-dimensional constitutive law for shape memory alloys. *Key Engineering Materials* **410-411** 429-437

[8] Yan S, Niu J, Mao P, Song G B and Wang W 2013 Experimental research on passive control of steel frame structure using SMA wires. *Mathematical Problems in Engineering* Article ID: 416828

[9] Ren W, Li H, Song G 2007 Phenomenological modeling of the cyclic behavior of superelastic shape memory alloys. *Smart Materials and Structures* **16** 1083

[10] Huang B, Cai W, Zhao W, et al. 1997 The effect of heat-treatment and cold deformation on non-linear superelasticity of Ti-Ni alloy. *Aerospace Materials & Technology* **6** 51-54 (in Chinese)

[11] Piedboeuf M C, Gauvin R, Thomas M 1998 Damping behaviour of shape memory alloys: strain amplitude, frequency and temperature effects. *Journal of Sound & Vibration* **214** 885-901

[12] Dolce M, Cardone D 2001 Mechanical behavior of shape memory alloys for seismic applications II, austenite NiTi wires subjected to tension. *International Journal of Mechanical Sciences* **43** 2657-2677

[13] Ip K H 2000 Energy dissipation in shape memory alloy wires under cyclic bending. *Smart Materials and Structures* **9** 653-659

[14] Sakai Y, Kitagawa Y, Fukuta T, Iiba M 2003 Experimental study on enhancement of self-restoration of concrete beams using SMA wire. *International Society for Optics and Photonics* **5057** 178-186

[15] Chen W 2012 Applicability of hysteretic constitutive models of concrete in structural analysis based on development of OpenSees. Chongqing University, Chongqing, China (in Chinese)

[16] Scott B D, Park R, Priestley M J N 1989 Stress-strain behavior of concrete confined by overlapping hoops at low and high strain ratio Rates. Doctoral Thesis, Lulea University of Technology, Lulea, Sweden

[17] Yassion M H M 1995 Nonlinear analysis of prestressed concrete structures under monotonic and cyclic loads. Ph. D. University of California of Berkeley

[18] Gao X, Zhang Y 2014 Nonlinear analysis of a RC column under cycling loads. *Structural Engineers* **30** 56-63 (in Chinese)

[19] Lagoudas D C, Bo Z, Qidwai M A, et al. 2003 SMA um: user material subroutine for thermomechanical constitutive model of shape memory alloys. Texas A & M University, College Station, Texas, USA

[20] Ge D, Wan J, Pan P, et al. 2013 Comparative study on simulation methods of steel bar in fiber beam element model. *Building Structure* **43** 60-62 (in Chinese)
Acknowledgements
This work was partially funded by the Natural Science Foundation of Liaoning Province of China grant 2015020595; the Liaoning Provincial Department of Education Science Research Project grant LJZ2016029; the National Natural Science Foundation of China grant 51278313.