

# Nonlinear finite element analysis of PC segmental bridge columns subjected to quasi-static loading

Ehsan Nikbakht, Khalim Rashid, Farzad Hejazi, Siti Aminah Osman, Iman Mohseni

Dept. Civil and Structural Engineering  
Universiti Kebangsaan Malaysia (UKM)  
43600 Bangi, Malaysia

**Abstract**— This study analytically investigates the seismic behaviour of post-tensioned precast segmental columns comparing with conventional monolithic bridge columns. For this purpose, 3D nonlinear finite element ANSYS software is employed. In this study, the numerical results of quasi-static analysis are compared and validated with the experimental results. Then, the behavior of the column samples of monolithic conventional and precast segmental are compared under lateral cyclic loading. The nonlinear-static analysis shows that the precast segmental bridge sample compared to the monolithic column has higher stiffness with negligible residual displacement.

**Keywords**— Hybrid precast bridge columns, monolithic conventional; post-tensioning; cyclic loading; pseudo-dynamic loading; nonlinear finite element

## I. Introduction

Precast segmental bridge piers have shown an appropriate performance against earthquake loading. In recent years, the hybrid post-tensioned precast segmental bridge columns have been interest of many researchers. In this system, mild steel reinforcement dissipates the seismic energy while post-tensioning strands, has the restoration capability which returns the columns to the original place when severe earthquake occurs [1]. In seismic regions precast segmental bridge columns behavior has to be emulated with conventional monolithic bridge columns [2]. In Hybrid post-tensioned piers, the combination of mild steel reinforcement and post-tensioning strands causes less residual displacement or permanent cracks, higher ductility and acceptable energy dissipation. The precast segmental post-tensioned bridge columns were examined experimentally and analytically [3-9].

## II. Finite element analysis

In this work, in order to investigate the effect of post-tensioning forces on the behaviour of precast segmental bridge columns under real earthquake loading, the results obtained by the nonlinear finite element method are firstly compared and validated with experimental work done by Hewes and Pristley [4]. Then, precast PT samples and emulative conventional

monolithic bridge columns are analysed under nonlinear-static. 3D finite element program ANSYS [10] has been utilized. The details of the geometry, properties of the experimented precast segmental column sample, post-tensioning and loading program, boundary conditions and failure criteria are described below.

## III. Loading procedure

There are three types of loading; posttensioning, axial and lateral cyclic which are imposed at three stages as below. The footing is fixed at the bottom in all stages.

- Post-tensioning of prestressed strands at the centre of the column. A 2230 kN equivalent of 40% of the tension yielding capacity of 27 prestressing strands with 12.7 mm diameter has been applied in this stage.
- Applying an axial force of 890 kN at the top of the column, representing the weight of the bridge deck, which is equivalent to  $0.08 f_c A_g$ .
- Lateral cyclic loading at the loading point of 303mm above the column at the loading head. The cyclic loading history is shown in Fig. 3. The loading is imposed as 0.6%, 0.9%, 1.2%, 1.6%, 2.2%, 3% and 4% drift displacement, and for each drift level three cycles of loading are repeated.

## IV. Specimen description

There are four segments and a footing foundation which are connected together by unbonded continuous strands. The dimensions and geometry of the sample is shown in Fig. 1. There is a steel tube jacketing with thickness of 6 mm around the first segment. 27 D12.7 mm strands are placed in the hollow duct with 140 mm diameter at the centre of the column. The longitudinal reinforcement is discontinuous at the joint of the segments. There are transverse spirals which are spaced at 75 mm.

The material properties for the concrete, transverse and longitudinal reinforcement, steel tube jacketing and PT strands are shown in Table 1.

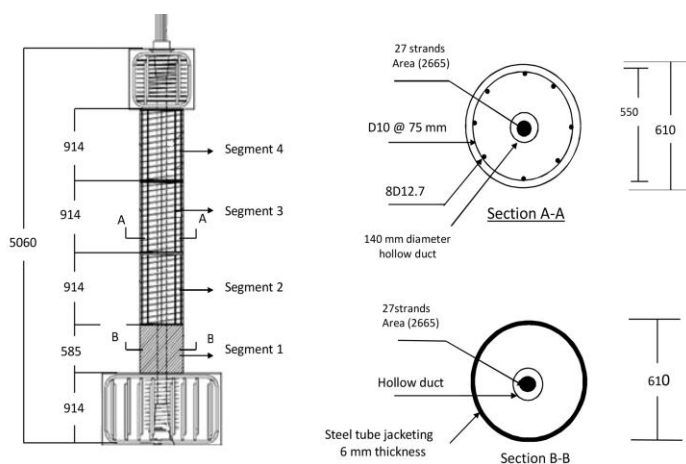


Figure 1. Unbonded precast segmental bridge column sample (Hewes and Pristley [4])

TABLE I. MATERIAL PROPERTIES OF THE SAMPLE

Specimen	Segmental column	
<b>Prestressing steel</b>	Material	27 D12.7
	Yielding stress (MPa)	1890
	Initial stress (MPa)	756
<b>Longitudinal reinforcement</b>	Material	8 D12.7
	Yielding stress (MPa)	410
<b>Transverse reinforcement</b>	Material	D10@75
	Yielding stress (MPa)	410
<b>Steel tube jacketing</b>	Thickness (mm)	6
	Yielding stress (MPa)	317
<b>Strength of concrete</b>	(MPa)	41.4
<b>Nominal shear strength</b>	(kN)	265

### A. Types of elements

Solid65 element is used for the modeling of the concrete. This element is defined with 8 nodes and three degrees of freedom at each node. This element has the capability of cracking in tension, crushing, and nonlinear plastic deformation. The compressive stress-strain of concrete is

obtained using Eqs. (1-4)[11]. For accurate modelling, the tensile stress-strain of concrete should be defined by specifying the modulus of rupture of concrete through the Eq. 4.

$$(1) \quad f = \frac{E_C \varepsilon}{1 + \left(\frac{\varepsilon}{\varepsilon_0}\right)^2}$$

$$(2) \quad \varepsilon_0 = \frac{2f'_c}{E_C}$$

$$(3) \quad E_C = 4700\sqrt{f'_c}$$

$$(4) \quad f_r = 0.62\sqrt{f'_c}$$

where;  $\varepsilon_0$  is the strain at the ultimate compressive strength of concrete;  $E_C$  is elastic modulus of the concrete (MPa) up to 30% of the compressive strength of the concrete.

The Link8 element is used for longitudinal and transverse spirals mild steel reinforcement. It has the capability of plasticity, swelling, stress defining and large deflection.

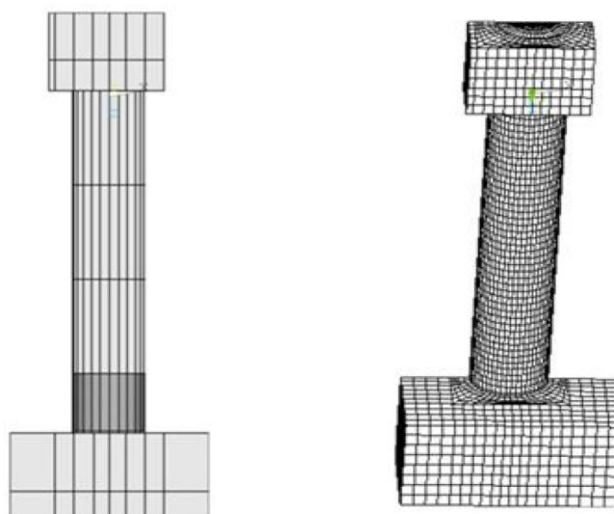


Figure 2. Finite element details for a) four segments with steel tube jacketing around the first segment;b) finite element meshes of the samples

Shell181 is used for the steel tube jacketing. The Contact174 and Target170 with unilateral flexible surface to surface and penalty method contact algorithm are selected to model the contact between the segments. A coefficient of friction of 0.5 is used for the friction between the surfaces of two adjacent segments. For modeling the contact between the unbonded PT strands and hollow duct, surface to surface Contact and Target elements have been implemented.

Solid185 element is used for the post-tensioning strands. This element has the capability of large deflection, plasticity and large strain, and the Prets179 element is used for distributing the pretension force in the tendon. This element is an element with one degree of freedom in one translational direction. It

acts between meshed solid elements (in this case solid185) and by creating a section at the middle of element specified, spreading pretension force through the coincident nodes. Bilinear elastic-perfectly plastic stress-strain has been assumed for the longitudinal, transverse and post-tensioning strands.

### v. Bonded segmental and monolithic conventional columns

The bonded precast PT segmental column has been analysed to investigate the effect of interaction of concrete and strands on the energy dissipation, strength and stiffness of the sample described in the previous sections. The emulative monolithic conventional column has also been analysed to assess the overall performance of the precast segmental columns under nonlinear-static and earthquake loading. All conditions for the loading and concrete properties of these samples are the same as the unbonded sample, except that there is interaction between the concrete and strands in the bonded samples. The comparison of these types of bridge columns is discussed in section VII.

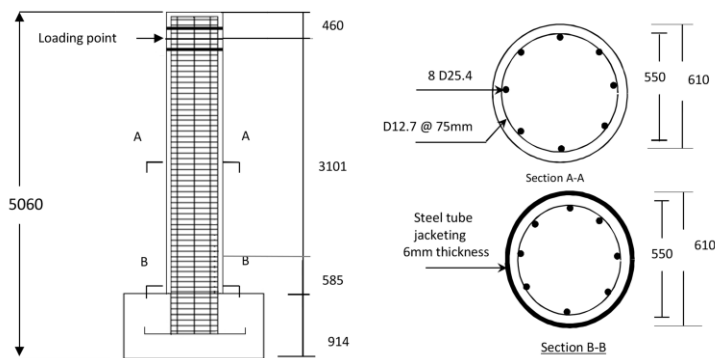


Figure3. Monolithic sample dimension and reinforcement configuration

### VI. Unbonded and bonded columns

The performance of bonded and unbonded PT segmental samples under cyclic loading is investigated. Compared to the bonded PT segmental column, the unbonded system is advantageous for delaying the yielding of the PT strands because in this system the post-tensioning force is distributed throughout the height of the strands. Fig. 4(a) shows the comparison of cyclic lateral force-displacement and energy dissipation in bonded and unbonded samples up to 3% drift (108.9 mm). The analysis shows that the cumulative energy dissipation of the bonded system is higher than the unbonded system (Fig. 4(b)).

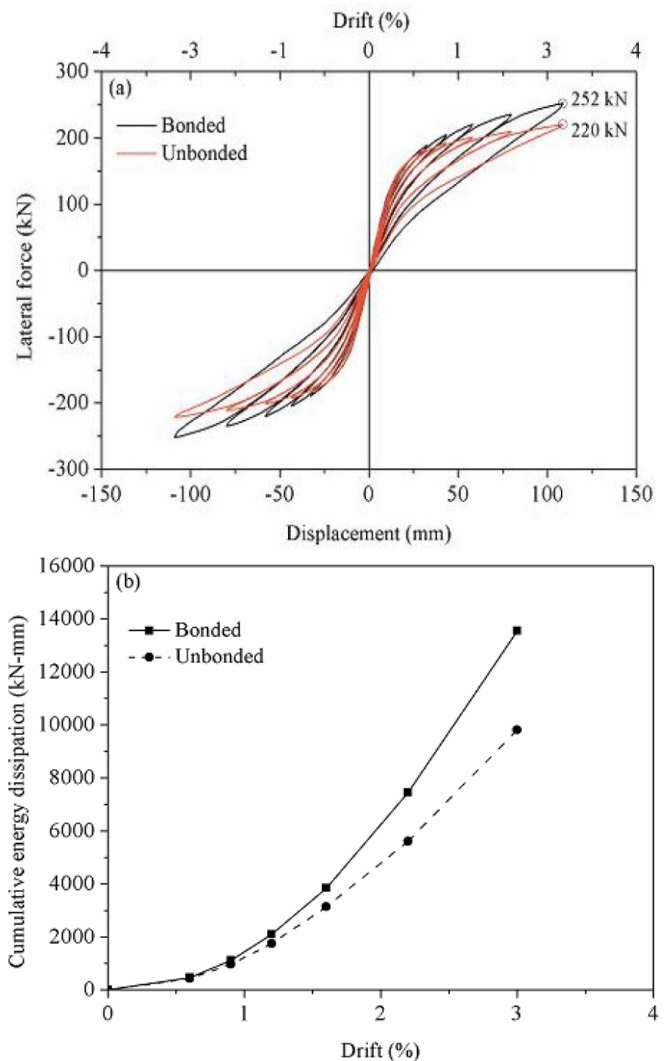


Figure 4. Comparison of bonded and unbonded system a) lateral Load-deflection, b) Cumulative energy dissipation of bonded and unbonded samples

### VII. Results and discussion

The comparison between the lateral cyclic loading-displacement of samples is shown in Fig. 5. All samples are analysed up to 4% drift (150 mm lateral displacement) except for the monolithic column due to it exceeding 1% drift residual displacement which is stopped at 3% drift displacement (108.9 mm). In contrast, the residual displacement of the precast segmental columns is negligible due to the restoration capability of the strands that return the column to its intact position in the unloading stages. As it is apparent in this figure, the samples with a higher initial stress have a higher initial stiffness and strength over the 4% drift. The BS70 sample has the highest strength with 295 kN, and BS40 and BS25 have 263 kN and 228 kN respectively (Fig. 5(a)). In Fig.5(b) the strength of the monolithic sample with 267 kN strength over the 3% drift has been compared with the precast segmental columns.

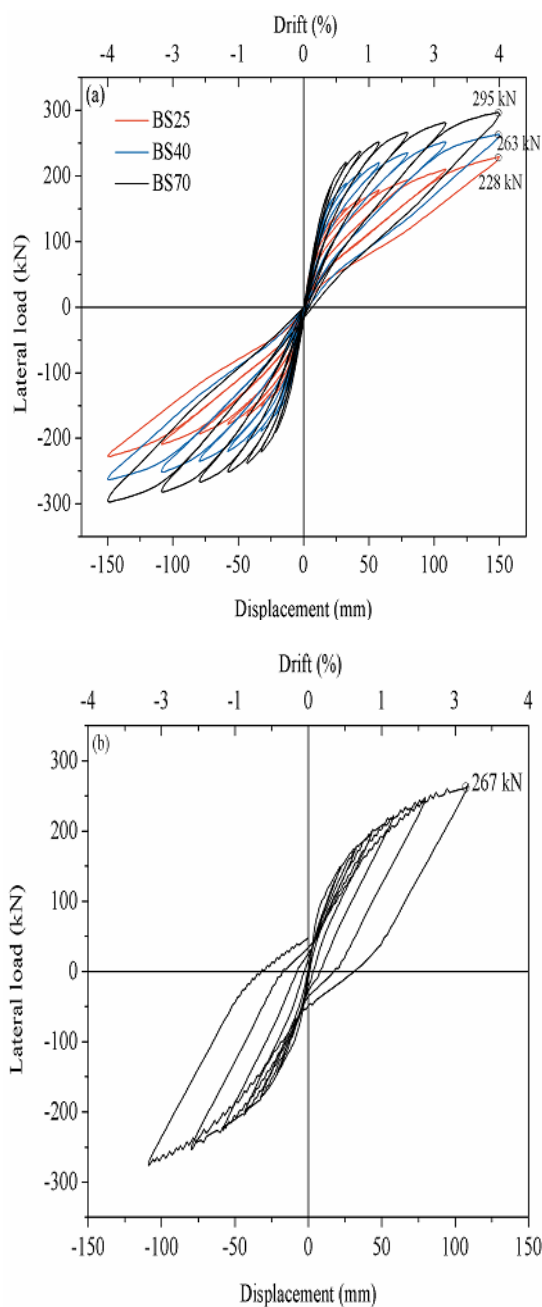


Figure. 5 Lateral cyclic load-deflection of a) precast segmental columns and b) Monolithic column

segmental bridge columns under nonlinear-static analysis. The results indicate that bonded post-tensioned bridge column

## VIII. Conclusions

This study analytically investigated the effect of prestressing strand initial stress on the behaviour of PT precast

exhibited higher strength and energy dissipation compared to unbonded systems. Bonded segmental columns with a higher initial stress level demonstrated higher stiffness and strength over the 4% drift displacement. The precast segmental column samples exhibited low energy dissipation, i.e. (4-14% equivalent viscous damping). The higher strength and greater number of induced cracks around the strands in samples at higher initial stress levels leads to more equivalent viscous damping. The quasi-static analysis showed that the stiffness of the BS25 sample was lower than the monolithic column while the stiffness of the BS40 sample was similar and the BS60 and BS70 samples had higher initial stiffnesses.

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