MODELING OF THE PRECAST UNBONDED POST-TENSIONED SEGMENTAL BRIDGE COLUMN UNDER LATERAL LOAD

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ABSTRACT

Analytical models for a precast unbonded post-tensioned segmental bridge column system are presented. The conceptual design aspects of this system rely on the use of precast modular construction, unbonded post-tensioning tendon for enhanced lateral strength and re-centering ability of the column, and supplemental devices for energy dissipation. To develop this system, the accurate prediction of the lateral force-displacement (pushover) curve is important. In this paper, for design purpose, a simplified analytical model to predict this curve is presented and validated with 2D finite element model. To capture the stress and strain variation in the direction perpendicular to the loading direction, a 3D finite element model is also developed. Both results obtained from the analytical model and the 3D finite element model are compared with the available experimental results.

Keywords: Accelerated Bridge Construction, Precast, Unbonded Tendon, Segmental Column, Post-tensioning, Self-centering, Analytical Method, Finite Element Method (FEM).

INTRODUCTION

Over the past 20 years, the use of the precast modular construction for accelerated bridge construction has gained increasingly favorable attention in the United States. Most of the applications, however, have been in low-seismicity regions. In particular, there hasn't been any application of the precast segmental bridge column in moderate to high-seismicity regions such as the state of California (FHWA[1]). To investigate the use of segmental bridge columns in high-seismicity regions, a research project has been initiated by Federal Highway Administration (FHWA) and conducted at University at Buffalo.

A precast segmental bridge column typically consists of reinforced concrete segments combined with post-tensioning tendons. The tendon post-tensioning force and the gravity load from the superstructure are utilized to pre-compress the segments to develop the required lateral stiffness and strength. When the column is displaced laterally to a certain extent, the segmental interfaces will usually experience gap opening due to the decompression of the interfaces. The seismic design philosophy for conventional bridge columns requires a formation of the plastic hinges at the ends of a column to dissipate seismic energy. Thus, the greatest concern of the application of the precast segmental bridge columns in seismic regions has been whether the gap opening mechanism at the segmental interfaces will affect the formation of the plastic hinges and hence the seismic performance of the column.

Chang et al.[2,3] examined the seismic behavior of the precast segmental bridge column with rectangular hollow sections. Except for the first specimen, mild steel rebars across the segmental interfaces are provided for energy dissipation. The prestressing tendons were bonded with the surrounding concrete to increase the lateral strength of the columns. The resulting hysteretic loops show satisfactory energy dissipation and less residual displacement as compared with conventional columns. The testings also showed that the segmental interfaces did tend to prevent the formation of the plastic hinge in the segment between the interfaces. The segmental interfaces may have to be strengthened considerably to shift the damage from the interfaces to be in the segment body. Lee et al.[4] and Billington et al.[5] proposed an unbonded segmental bridge column system with the hinge segment made of fiber reinforced concrete to enhance the energy dissipation. Fine and well-distributed crackings were observed in the hinge segment at the end of the large-scale test. However, large localized damages were observed at the segmental interface.

In addition to the effort in applying the conventional seismic design concept using plastic hinge in the precast segmental bridge columns, some other researches utilize the damage avoidance design (DAD) or rocking column concept, which was developed by Mander[6]. DAD emphasizes the use of the rocking motion of a column and the protection of the rocking base was provided by a thick steel plate to achieve essentially no damage after earthquakes. The columns examined by Mander have only one interface at the column base. For percast segmental bridge columns, the application of the rocking column concept was examined in the first specimen in Chang et al.[3] with unbonded post-tensioning tendons and no rebar across the segmental interfaces. Little damage and energy dissipation were observed at the end of the test. Hewes et al.[7] investigated the cyclic behavior of the precast unbonded segmental bridge column with the base segment confined by a steel jacket. The use of the steel jacket minimized the spalling and crushing of the concrete and improved the ductility of the column. The residual displacements of the specimens were minimal at the end of the tests. However, the observed equivalent damping ratios were small with a maximum value of around 5%.

THE SEGMENTAL BRIDGE COLUMN SYSTEM BEING DEVELOPED AT UNIVERSITY AT BUFFALO

A precast unbonded post-tensioned segmental bridge column system using the concept of the self-centering system is now being developed at University at Buffalo. The use of the self-centering concept has been popular for building structures in beam-column connections, precast concrete shear walls and the masonry walls. For bridge structures, the concept of self-centering has already been implemented in South Rangitikei viaduct in New Zealand in 1981. However, relatively few research works can be found in the literature. An extensive review of the development of the self-centering systems can be found in Filiatraut et al.[8]

The concept of the design of a self-centering system usually includes three key components. The first component is the weakened interfaces in a structure to prevent the damage from occurring in the rest portion of the structure. The second one is a restoring force to re-center the structure. Because the weakened structure tends to have larger displacement response, thus the third one is to include the supplemental energy dissipation devices to reduce the displacement response to an acceptable level. In fact, a segmental bridge column normally already possesses the first two key components due to the need for accelerated bridge construction. For the third key component, instead of having the plastic hinges form in the segment body between interfaces, the energy dissipation in the bridge system being developed at University at Buffalo is achieved by taking advantages of the gap opening at the interfaces to activate the supplemental energy dissipation devices.

In developing of the self-centering segmental bridge columns, an analytical model is developed to predict the lateral force-displacement curve (pushover curve) for design purpose and is validated against 2D (loading plane) finite element model created by *ABAQUS*[9]. 3D finite element model is also developed to capture the stress and strain variation in the direction perpendicular to the loading direction. Both the results from the analytical model and the 3D finite element model will be compared with the experimental results obtained form the reference[7] at the end of this paper.

ANALYTICAL APPROACH PROPOSED

Hewes et al.[7] proposed an analytical approach to calculate the pushover curve of the unbonded segmental columns by assuming all the gap opening concentrated at the base segmental interface. In this paper, a more general analytical approach is proposed to take into account the gap opening in the interfaces other than the base interface.

When the segmental bridge column is displaced laterally, two important stages are identified. They are pre-decompression and post-decompression stages. The physical meaning underlying the derivation of the analytical model will be presented as follows.

PRE-DECOMPRESSION STAGE

Before a segmental bridge column is loaded laterally, under the gravity load from the superstructure and the compressive force from the prestressing tendon, the sections of the column is in the condition of uniform compression. After the lateral load such as the seismic load is applied to the top of the column, sections of the column start to rotate about the neutral axes. When the column is displaced laterally to a certain level, the compressive stress at the extreme fiber of the base section of the column will decrease to zero. If the base section is the segmental interface as the case shown herein, no tensile stress can be developed. Thus, the base section starts to have gap opening and lifts off. The stage before the decompression of the base interface of the column is called pre-decompression stage. The column behaves like a conventional fixed based one. The conventional beam theory can be applied to calculate the lateral force-displacement curve of the column.

At this stage, the materials used in the column are usually within the linear elastic range. A straight line can be drawn from the origin to the end of this stage to approximately represent the lateral force-displacement response of the column. As a result, only the force-displacement response at the end of this stage needs to be calculated. Due to the P-Δ effect, an iteration process is required in order to obtain the final lateral force and the top displacement of the column at the end of this stage.

POST-DECOMPRESSION STAGE

Reduced Section Assumption

After the decompression of the column base, the column enters another stage called post-decompression stage. Not only the base segmental interface but some of the rest of the interfaces will also have gap opening depending on how far the column is displaced laterally.

The loading condition for a segmental column in this stage is quite different from a conventional column. For example, at a certain drift ratio as shown in Fig. 1, all the sections in segment E and F are still in compression, so the curvature analysis can be applied to calculate the displacement response. However, for segment A to D, there are gap openings at the segmental interfaces. For segment D, the gap opening exists in the bottom interface while for segment A to C, gap openings exist both in the top and the bottom interfaces of each segment. For those interfaces that have gap openings, the strain compatibility exists in the portion of the interface that remains in contact. Curvature analysis is still applicable. However, for the sections inside the segment such as segment A, a boundary exists between two parts as shown in Fig. 1. The right hand portion is in compression while the left hand portion is in tension or with no stress. This boundary is difficult to be determined.

To apply the conventional curvature analysis, an assumption that no tension can be developed inside the segment is made. With this assumption, as a column deforms laterally, the effective width of the column reduces. The column base will have the smallest effective section. The effective section width increases from the base to the top of the column until a certain height called decompression height, h_d. The sections above decompression height have the effective section width equal to the width of the column. The reduced section width at any given drift for any section can be calculated using force equilibrium as will be presented later.

At this stage, the location of the prestressing tendon at the region with reduced sections will not be at the axis of bending. The tendon will be stretched and additional prestressing force will be induced. This additional force will push the column back to its undeformed position. Moreover, the P-Δ effect of the gravity load and the tendon prestressing force tend to further push the column laterally. As a result, an iteration process is required to obtain the final deformed shape of the column given an extreme fiber strain, ε_{cmb}, at the base section.

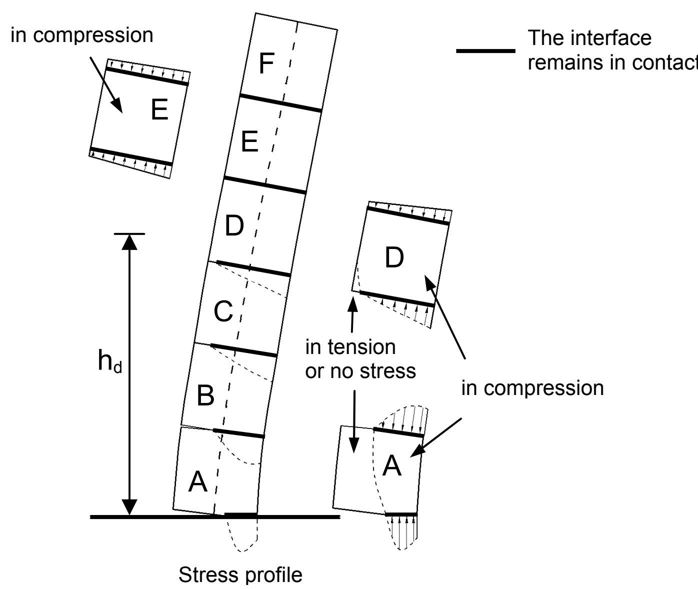

Fig. 1 The loading conditions of the segments

One can then increases ε_{cmb} to obtain the complete curve until failure of concrete material, which can be defined as

$$\varepsilon_{cmb} > \varepsilon_{cu} \tag{1}$$

ε_{cu} is the ultimate concrete compressive strain and can be defined at the fracture of the first hoop[10].

VALIDATION AGAINST THE 2D FINITE ELEMENT MODEL

An example segmental bridge column was created as shown in Fig. 2. The force-displacement response is obtained using the proposed analytical approach and is validated against the 2D FEM results by using *ABAQUS*. The compressive behavior is from the confined concrete model proposed by Mander[10]. The entire concrete column is assumed to be confined and the confinement ratio, ρ_{cc} is 0.039. The resulting confined compressive strength of the concrete, f'_{cc}, is 0.0819kN/mm^2 at a strain of 0.0088. The foundation is assumed to be rigid. The prestressing force after loss is 9092.4kN and the area of the tendon is 14409 mm^2. The design of the prestressing tendon and the initial prestressing force is such that the tendon will remain elastic up to the failure of the concrete in the base section of the column. Thus, the strength and re-centering ability of the segmental bridge column can be preserved after large lateral displacement. The amount of the sliding of the segmental interface is reported to be small as compared to the lateral displacement of the column caused by the gap openings at the interfaces[3], and hence is not considered in the modeling herein. The friction between the prestressing tendon and the duct can be minimized by lubricating the duct surface and hence not considered. More detail description of the modeling techniques will be presented later in the 3D finite element simulation.

The Reduced Section Assumption

Fig. 3 shows the analytical results of the reduced section curves at various drift ratios. By comparing the reduced section curve at the drift ratio of 0.26% from analytical results with the FEM result, shown in Fig. 4, it can be seen that the portion of the column that are on the left hand side of the reduced section curve in Fig. 3 has negligible vertical stress and hence can be ignored. This confirms the reduced section assumption used in the proposed analytical approach.

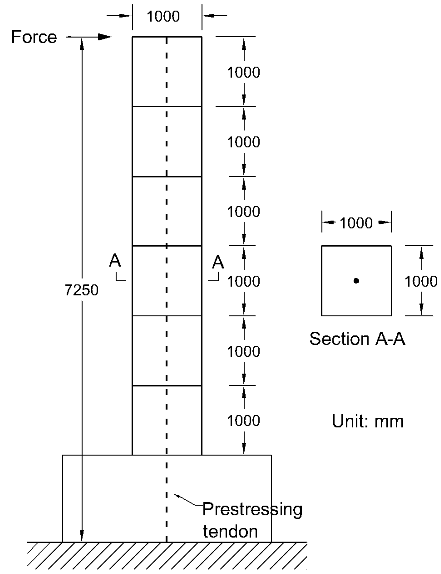

Fig. 2 Dimension of the example segmental column

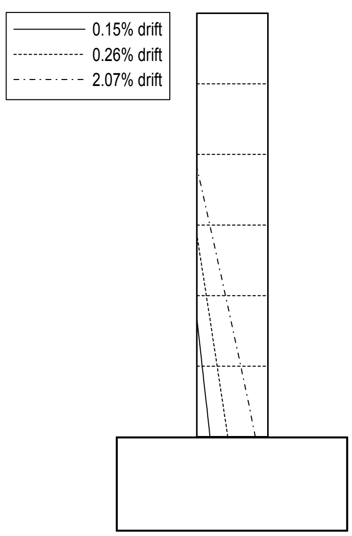

Fig. 3 Analytical results of the reduced section curves at various drift

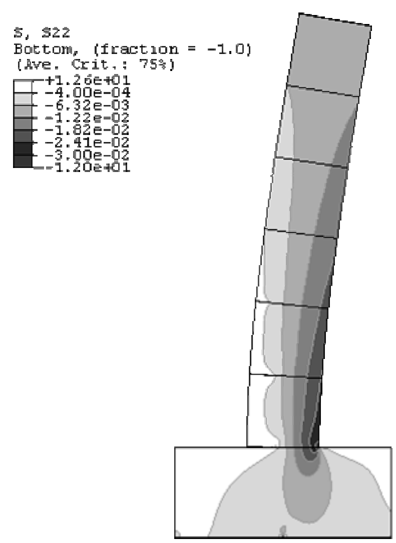

Fig. 4 Vertical stress results at 0.26% drift from FEM

The Crushing Length

A computer program was written following the concept of the proposed analytical approach. The column is discretized and the section curvature for each discrete element is calculated. It is observed that the plane section-remains-plane assumption agrees well with the results from FEM except for the corner of the base interface of the column when the drift ratio is below 1.5%. When the drift ratio is higher than 2%, the strain profiles at the sections near the column base deviate considerably from a straight line. As shown in Fig. 5, at the right hand corner of the base section, the longitudinal strain has a sudden increase due to the stress concentration. This phenomenon becomes more and more significant as the drift of the column increases. It is considered not practical trying to change the plane section-remains-plane assumption in the proposed analytical approach in order to model this phenomenon. Instead, an equivalent curvature for the base section is assumed such that the curvatures by analytical approach match those by FEM at the sections other than the base section. This is achieved by choosing a longer first discrete element, having a length called crushing length, Lcr[11]. As shown in Fig. 6, the crushing length of 500mm gives a desirable result, where the curvature of the section, for example, that at 500mm from the base by analytical approach agrees well with that by FEM. With the equivalent curvature at the base section, the force-displacement response can be calculated using the proposed analytical approach at high drift ratios.

A 500mm crushing length happens to be half of the section diameter, d/2, which is frequently used in estimating the plastic hinge length of the conventional fixed end column[12]. More FEM simulation or experimental work should be done to investigate the applicability of using d/2 to be the crushing length in predicting the pushover curve of the segmental column with different aspect ratios.

The Pushover Curve and the Elongation of the Tendon

The pushover results are shown in Fig. 7. The analytical result agrees well with FEM result. It can be observed that the proposed analytical approach tends to underestimate the strength obtained by FEM. This is because in the finite element model, the stress concentration at the corner of the base section as mentioned earlier causes the location of the resultant compressive force to be closer to the corner as compared with that predicted by using plane section-remains-plane assumption. The closer the resultant force is to the corner, the higher lateral force should be to push the column at a given displacement. The higher the drift is, the more the proposed analytical approach underestimates the strength of the column because of the more pronounced effect of the stress concentration at the corner. It will be shown later that 3D FEM model also exhibits the same phenomenon. Fig. 8 shows good agreement between the results of the elongation of the tendon predicted by the proposed analytical method and FEM.

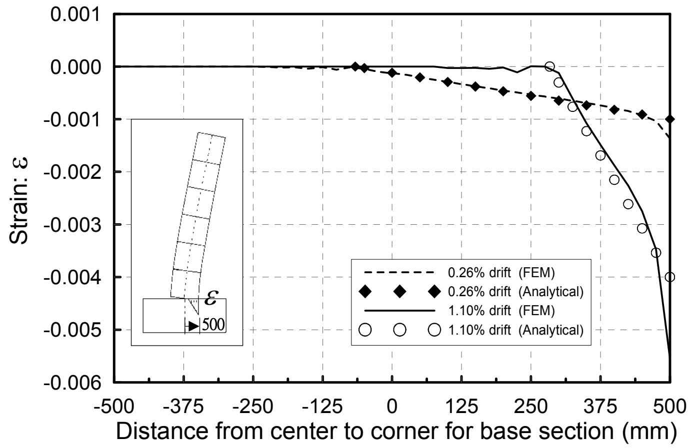

Fig. 5 Comparison of the strain profiles at the base section at low drift ratio

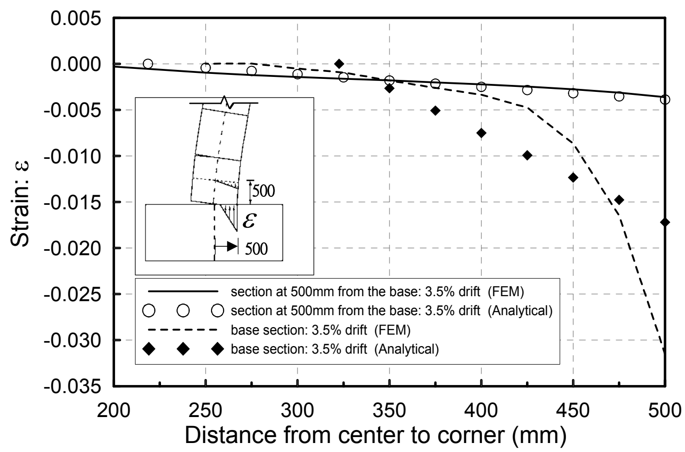

Fig. 6 Comparison of the strain profiles at 3.5% drift ratio ($L_{cr} = 500mm$)

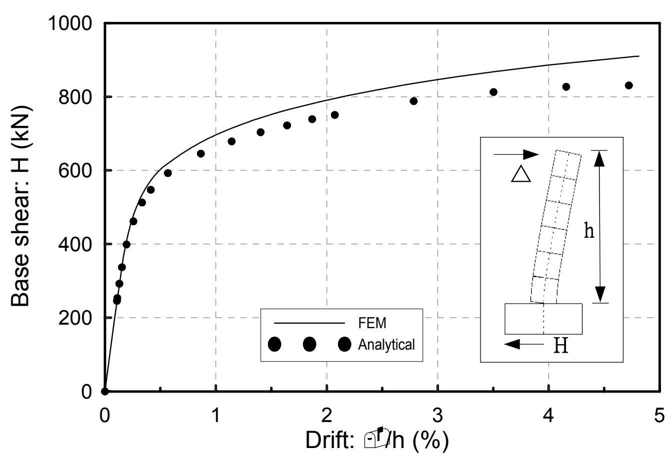

Fig. 7 Comparison of the pushover curves

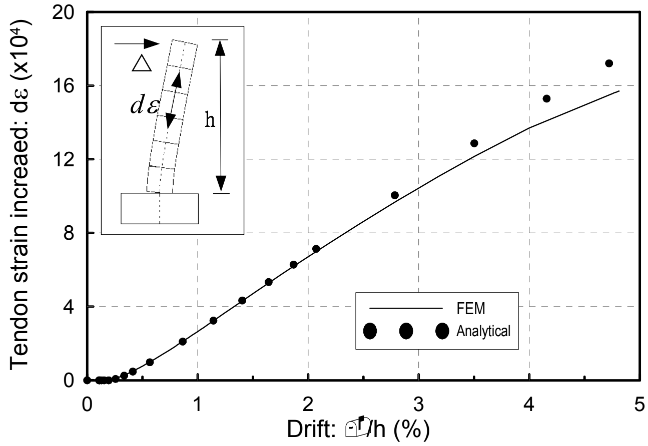

Fig. 8 Comparison of the tendon elongation versus drift curves

VALIDATION AGAINST THE EXPERIMENTAL RESULTS

Column JH1 in test one[7], as shown in Fig. 9, is used in this study for validation purpose. The first segment (S1) was steel-jacketed and rebars were located within the segments S2 to S4, without any rebar across the interfaces between segments. The steel jacket did not extend the full height of the bottom segment, but rather terminated approximately 25 mm above the interface between the column and footing. The testing was done cyclicly.

In the analytical model, the composite action between the steel jacket and the core concrete is not considered. This is because the strengthening of the steel jacket to the base section of the column, which normally decides the lateral strength of the column, is unknown due to the 25mm gap between the bottom of the steel jacket and the base section of the column. However, the confining effect by the steel jacket is considered.

The comparison between the results by proposed analytical and experiment is shown in Fig. 11, and will be explained later in the paragraph.

3D FINITE ELEMENT SIMULATION

3D finite element modeling in *ABAQUS* is also developed along with the analytical approach. In the 3D finite element model, the segmental interfaces are allowed to slide with coefficient of friction of 0.3. The concrete damaged plasticity model is used in modeling the behavior of the concrete. Based on the varying confining conditions in S1 and other segments, the appropriate concrete models for compressive behavior are used based on Mander confined concrete model[10]. The bonding between the steel jacket and the core concrete is not clearly stated in the reference[7]. Thus, full composite action is assumed between the steel jacket and the core concrete in the model. Fig. 10 shows a 3D finite element model of the specimen. For this particular problem, three-step analysis was employed and can be described as follows:

Step 1: Initiate contact
This step is required to initiate equilibrium condition for the problem. Unsupported elements need to be constrained to prevent any rigid body motion.

Step 2: Remove constraints
All constrained provided to the unsupported element must be removed after contacts were initiated.

Step 3: Apply load/displacement
Applied loads or displacements can be added to the problem. The analysis step should be done incrementally due to nonlinearity nature of gap opening and closing.

The Pushover Curve

Fig. 11 shows the comparisons of force-displacement response between finite element method (FEM), experiment, and the proposed analytical approach. The results obtained from FEM, proposed analytical method were based on the monotonic loading scheme, while the experimental results were obtained from an envelope of a cyclic response. The experimental results show more flexible behavior compared to FEM results because of some degradations due to cyclic loading. Besides, the steel jacket and the core concrete are more likely not to be fully composite in the real situation. Therefore, the FEM results provide an upper-bound solution while the proposed analytical solutions provide a lower-bound solution in this particular case. The results from the proposed analytical approach were developed considering the confining effect but without considering the composite action from the steel-jacket as mentioned earlier, which results in the more flexible post-yielding behavior.

The Strain Contour

Fig. 12 shows the vertical strain contour at 3% drift by 3D finite element simulation and the photo of the spalling of the concrete cover in the experiment. Hewes et al.[7] reported that during the second cycle push loading in 3% drift, it appeared as though the column was beginning to hinge about the top of the steel-jacketed segment, rather than about the column base. This observation agrees with the finite element simulation results, where the vertical strain is larger at the base of segment two than at the column base. This is undesirable because it will lead to large compressive straining of the compression toe at the base of segment two, which has much less confining effect and hence less ductility than that at column base.

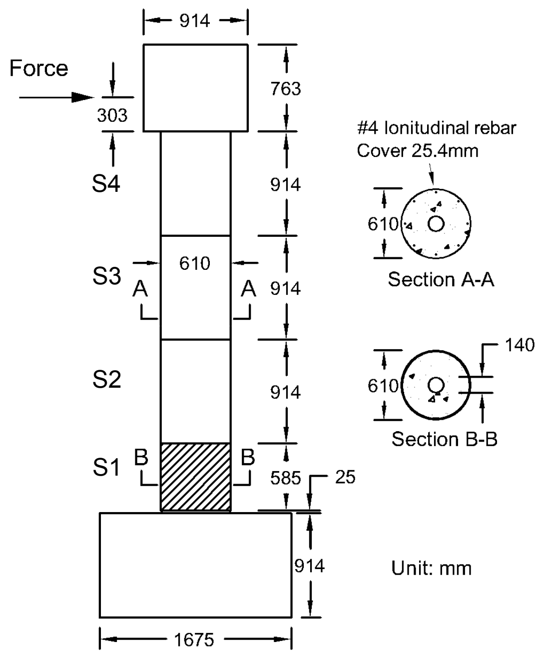

Fig. 9 Segmental prestressed column, JH1[7]

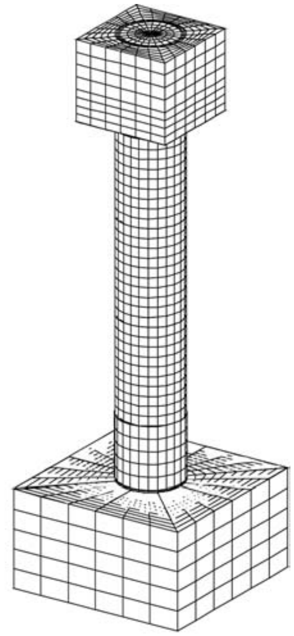

Figure 10 3D finite element model

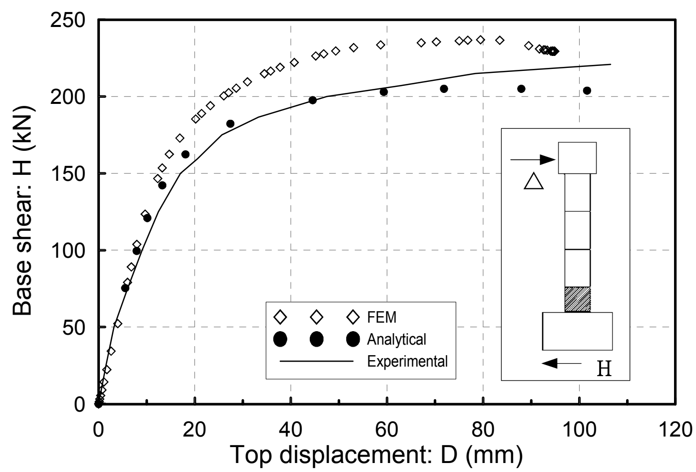

Fig. 11 Comparison of pushover curves for column JH1 in test one[7]

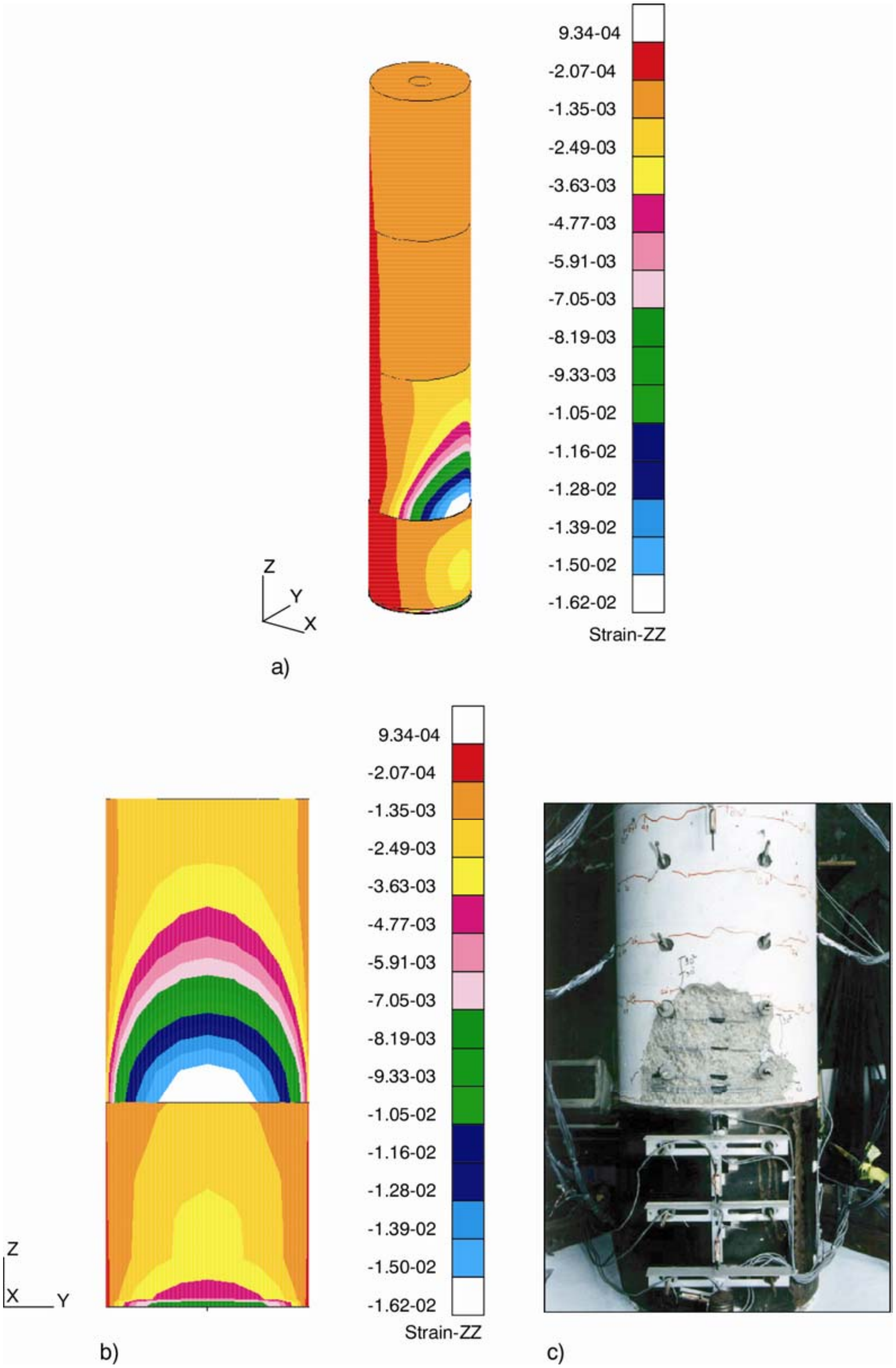

Fig. 12 Vertical strain at 2.8% drift – (a) Overall 3D strain contour, (b) 1st and 2nd segments, and (c) Concrete spalling in the experiment

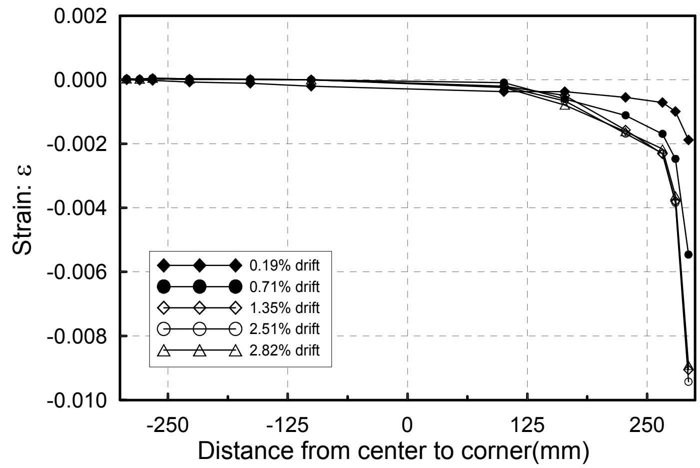

Fig. 13 Strain profiles at base-to-S1 interfaces at various drifts

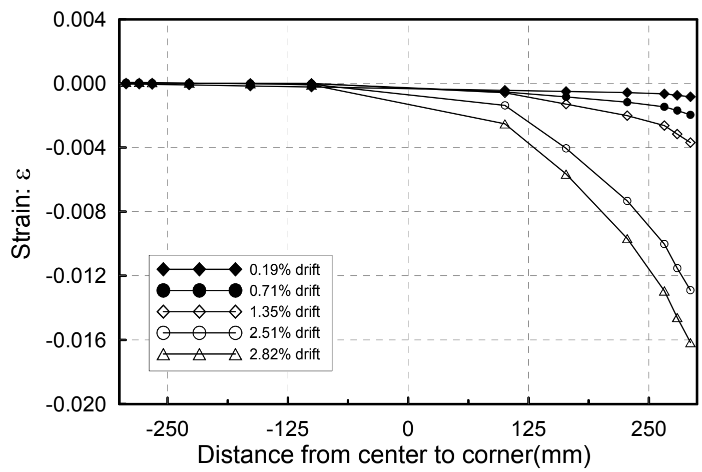

Fig. 14 Strain profiles at S1-to-S2 interfaces at various drifts

The Section Strain Profile

Fig. 13 and 14 show strain profiles at base-to-S1 and S1-to-S2 interfaces along the center line of the sections at different applied drift ratios. Plane section-remains-plane assumption is violated considerably at high drift ratios, say 2.51%. At low drift ratios, stress concentration at the corner is observed but it has little effect on the lateral strength of the column since the area at the corner of a circular column is small.

CONCLUSIONS

The comparisons between the analytical and FEM basically justify the use of the reduced section assumption in the segmental columns with similar segmental aspect ratio as those examined in this paper. More research work needs to be done to investigate the applicability of the reduced section assumption in other different segmental aspect ratios.

The shortening of the column due to the reduced section effect should be considered in calculating the tendon elongation. The elongation of the tendon predicted by proposed analytical method shows good agreement with the FEM results.

It is shown both in 2D and 3D finite simulations that, for segmental bridge columns, at high drift ratios, the plane section-remains-plane assumption is violated considerably in the sections near the critical segmental interfaces, which invalidates the conventional curvature analysis. A crushing length is proposed in this paper to solve this problem. The proposed crushing length, half of the column diameter, happened to be the same as the plastic length widely used in fixed end conventional column. The crushing length is chosen such that the curvatures calculated using proposed analytical approach match those by FEM except for the base section. However, before this crushing length can be widely used, more case studies should be performed.

The 3D finite element is able to model some particular details that are usually difficult for simplified analytical model to do, such as the strengthening effect of the steel jacket to the base section of the column while the jacket doesn't extend to the column base. Without accurate prediction of this effect can lead to undesired column behavior as shown in this paper.

ACKNOWLEDGEMENTS

This research is funded by a FHWA grant (No. DTSH61-98-C-00094) to the University at Buffalo. Dr. K. C. Chang and Dr. R. J. Wang of National Taiwan University provided their experimental results on precast segmental bridge columns. Their cooperation is sincerely appreciated.

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