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Steel structural design using nonlinear inelastic analysis

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ABSTRACT

With rapid improvement of computing technology, nonlinear inelastic analysis methods are commonplace and permitted in new design code versions of AISC-LRFD, AASHTO, etc. However, their applications on practical design of steel structures are still very limited due to excessive computational efforts. To overcome this problem, we develop a novel software, named as PAAP3D, in this study. PAAP3D is based on the plastic hinge approach that requires only one or two elements for modeling a frame member so computation time is efficiently reduced. The nonlinear inelastic truss and catenary elements are also implemented in PAAP3D that allows the use of this software for analysis of truss structures, cable-stayed bridges, suspension bridges, etc. In addition, the pre- and post-processors of PAAP3D are developed using C++ programming language with a user-friendly and easy-to-use interface. The generalized displacement control method (GDC) is employed for static analyses, and a time-history dynamic analysis is used for seismic analyses. Some examples of steel structures subjected to both static and seismic loads are presented.

1. INTRODUCTION

Steel structures have been used commonly in civil engineering because of their many advantages such as: (1) High reliability; (2) Light weight and high strength; (3) Speedy construction; (4) Uniformity in steel properties; (5) Flexibility and adaptability; (6) High sustainability; etc. However, steel structures contain many nonlinear inelastic behaviors should be addressed in analysis and design such as material and geometrical nonlinearities, nonlinear semi-rigid connections, buckling, etc. As a consequence, a significant effort has been dedicated to study practical advance analysis methods (PAAs) (see, for example, Chen and Kim 1997, Teh and Clarke 1999,

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1) Ph.D
2) Professor

Thai and Kim 2009, Truong and Kim 2017, Truong and Kim 2017, etc.). In PAAs, the ultimate strength and stability of whole structure are considered without a requirement of the separate member capacity checks as provided in the current design codes such as AISC-LRFD, AASHTO, Euro-Code, etc. PAAs are also known that they can produce an even lower size for structural members as opposed to elastic analysis, which is commonly used and well known to designers.

The PAAs, generally, can be divided into two categories such as: (1) the finite element and (2) beam-column types. In the finite element methods, the second-order effects are usually represented by using the interpolation functions, while the spread of plasticity is captured by using the fiber approach (refer: Teh and Clarke 1999, Pi and Trahair 1994, Izzuddin and Smith 1996, among other). Although these methods can be considered to be relatively accurate, they require a very refined discretisation of the structures that leads them to consume highly computational efforts. For this reason, the finite element methods are commonly used for research purposes. In the beam-column approaches, the second-order effects can be estimated by using the stability functions derived from the differential equilibrium equation, and the refined plastic hinge model can be used to account for the material nonlinearity. Only one or two elements per member are enough to accurately predict the structural nonlinear responses, so the computational time is significantly reduced. Based on the beam-column approaches, computer programs have been developed such as FRAME3D (2006), DRAIN-3DX (1993), and OpenSees (2005). However, the P-δ effect is not considered in those programs, hence they overestimate strength of a member subjected to significant axial force.

In this work, we develop a novel software based on the plastic hinge approach, named as PAAP3D. The nonlinear inelastic truss and catenary elements are implemented in PAAP3D, so trusses, cable-stayed and suspension bridges also can be analyzed by using PAAP3D. Furthermore, the pre- and post-processors of PAAP3D with a user-friendly and easy-to-use interface are developed using C++ programming language. The generalized displacement control method (GDC) is employed for static analyses, and a time-history dynamic analysis is used for seismic analyses. Some examples of steel structures subjected to both static and seismic loads are presented to demonstrate the robustness of the developed software.

2. PAAP3D INTERACTIVE GRAPHIC

PAAP3D software includes three parts such as: (1) the solver developed using FORTRAN, and (2) pre- and (3) post-processors are written using Visual C++ as presented in Fig. 1.

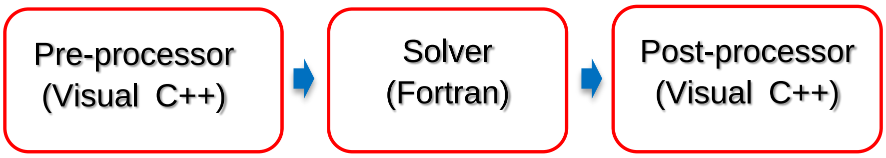

Fig. 1 PAAP3D flowchart

The main graphic user interface of the software is presented in Fig. 2 with four basic menus such as main, tree, icon, and result. This interface is designed very friendly and easy-to-use, even for users who are not familiar with using structural analysis software. As can be seen at the “Menu for view”, the model of structures can be presented in both plane or 3D perspective views. The software allows the use of two view windows at same time. Structures can be modeled by reading from a formatted input file or directly using the pre-processor. The structural information is then presented at the “Menu for Input”. Analysis of the structure is performed by using the Solver that is mentioned above. The results are shown in the view window. As can be seen at the “Menu for Result”, the software can show most of structural responses such as: buckling, element force, hinge, nodal displacement, and nodal reaction force, etc. The animations on deformed shape and progressive formation of plastic hinges also can be displayed and recorded as an AVI file.

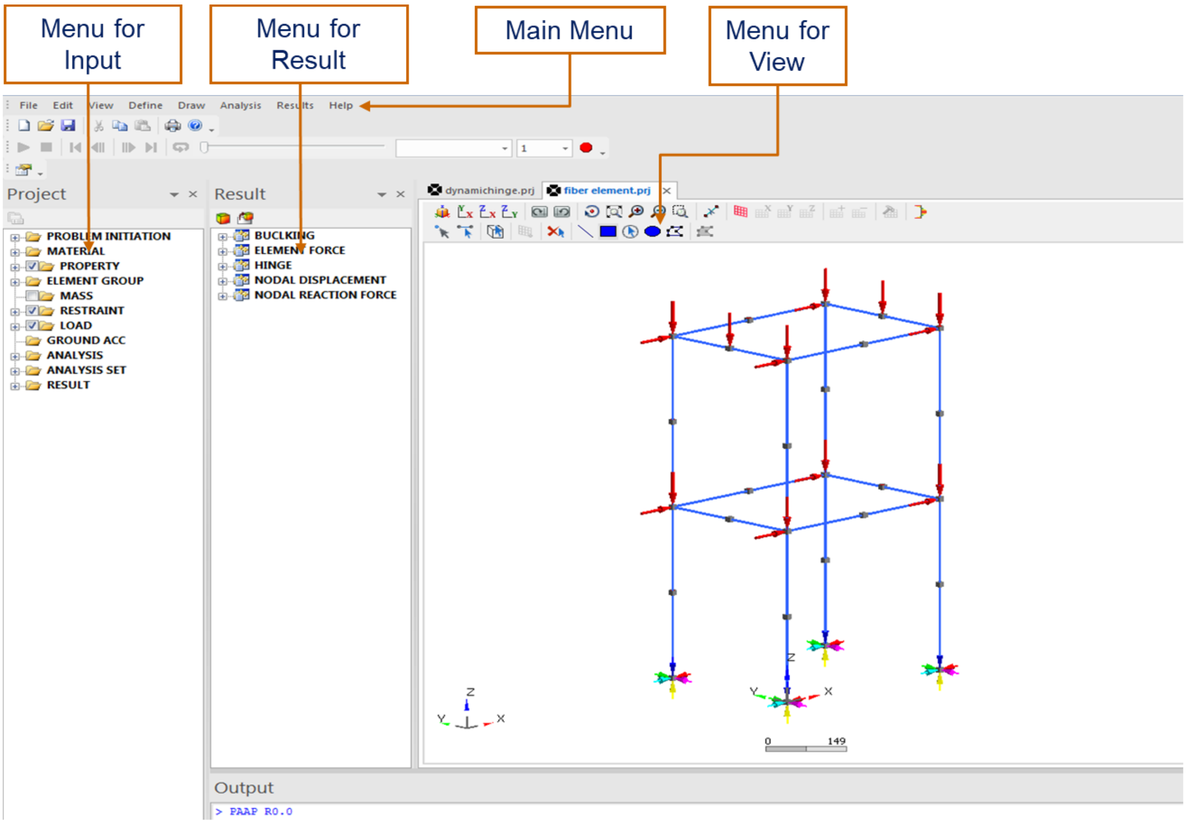

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Fig. 2 PAAP3D main graphic user interface

3. PRACTICAL ADVANCED ANALYSIS IN PAAP3D

3.1 Element library

PAAP3D consists of three basic nonlinear elements such as: truss element, catenary element, and plastic hinge beam-column element.

Catenary element model is used to model cable members of the structure. The realistic behaviors of a cable member, especially the sag effect due to the self-weight, is estimated from the exact analytical expressions of an elastic catenary (). Truss element model proposed by Thai and Kim () is used in PAAP3D since it is effective to capture the nonlinear inelastic behaviors of trusses considering several failure mechanisms such as yielding, buckling, reloading, and unloading. Regarding plastic hinge beam-column element, $P-\delta$ and $P-\Delta$ effects are captured by using the stability functions (Chen and Lui 1987), and initial geometric imperfection and residual stresses are estimated by using the column research council (CRC) tangent modulus concept (Chen and Lui 1992). the partial plastification effects of plastic hinges are predicted by using the Orbison's yield surface (Orbison et al. 1982). The detail of aforementioned elements can be found in Thai and Kim (2009) and Truong and Kim (2018).

3.2 Nonlinear Solution Procedure

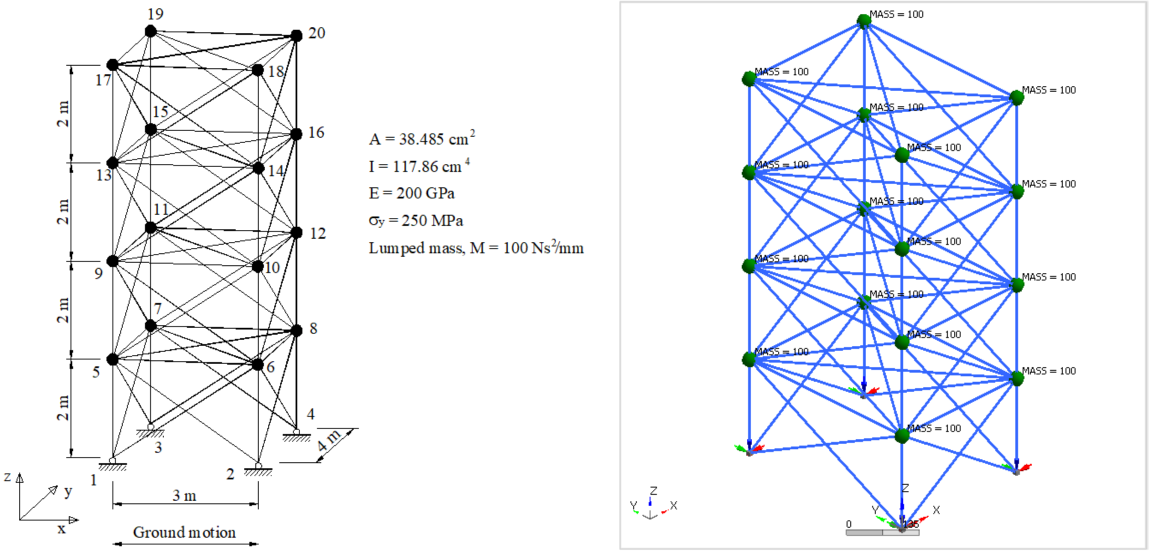
For static analysis, GDC method proposed by Yang and Shieh (1990) is used in this work since its advantages are (1) the step size is automatically adjusted, (2) it can self-adapt to the change of the loading direction, (3) and the analysis is relatively stable at the critical points.

For the time-history dynamic analysis, a static analysis is carried out first for predicting the structural responses under static loads, and then a time-history dynamic analysis is performed. Newmark family method (Newmark 1959) is employed for solving the equation of motion, and Newton-Raphson method is used to eliminate the residual forces in time steps.

4. CASE STUDIES

4.1 Space truss

A 72-member space truss which is taken from Thai and Kim (2011) is considered to demonstrate the capacity of PAAP3D for time-history dynamic analysis of steel truss structures. The geometric shape and data information of the truss are presented in Fig. 3a, while the structural model in PAAP3D is shown in Fig. 3b. The time-history dynamic analysis of the truss under El Centro earthquake is performed. It should be noted that the PAAP3D library provides many earthquake records such as Loma Prieta, El Centro, Imperial Valley, Kobe, etc. Furthermore, the users can input the earthquake record directly by themselves. Fig. 4 illustrates the time-history X-axis displacement of the node 17 of the truss.



a) Geometry of the truss b) Truss model in PAAP3D

Fig. 3 Space truss

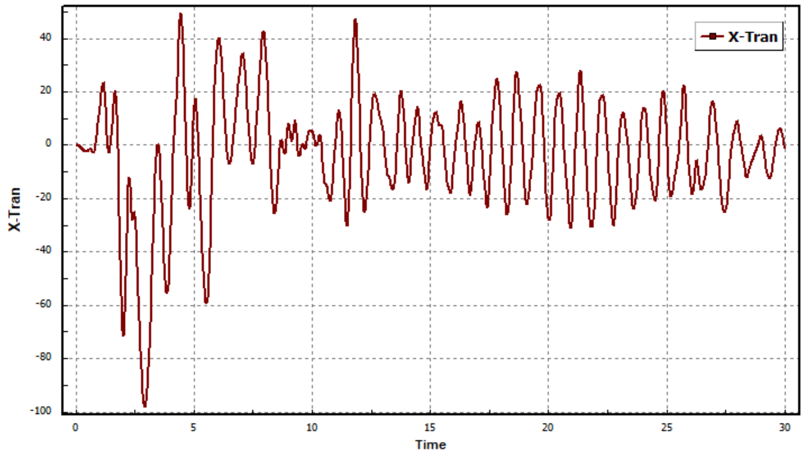


Fig. 4 Time-history Z-axis displacement of node 17

4.2 Suspension bridge

In the second case study, both static and dynamic analyses of a suspension bridge (Thai and Kim 2011) are presented. The geometry of the bridge is shown in Fig. 5. The total length of the bridge is 336m, while the height of the pylons is 35m. The pylons, girders and cross-beams are modeled as plastic hinge beam-column elements with only one element per member. The cables are modeled as catenary elements. There are total 65 beam-column elements and 69 catenary elements for modeling this bridge in PAAP3D. The Young's modulus and yield stress of beam-column members are 200 GPa and 248 MPa, respectively. The Young's modulus and yield stress of cable members are 165.5 GPa and 1,103 MPa, respectively. The weight per unit volume of the cable and beam-column members is 60.5 kN/m3 and 76.82 kN/m3, respectively.

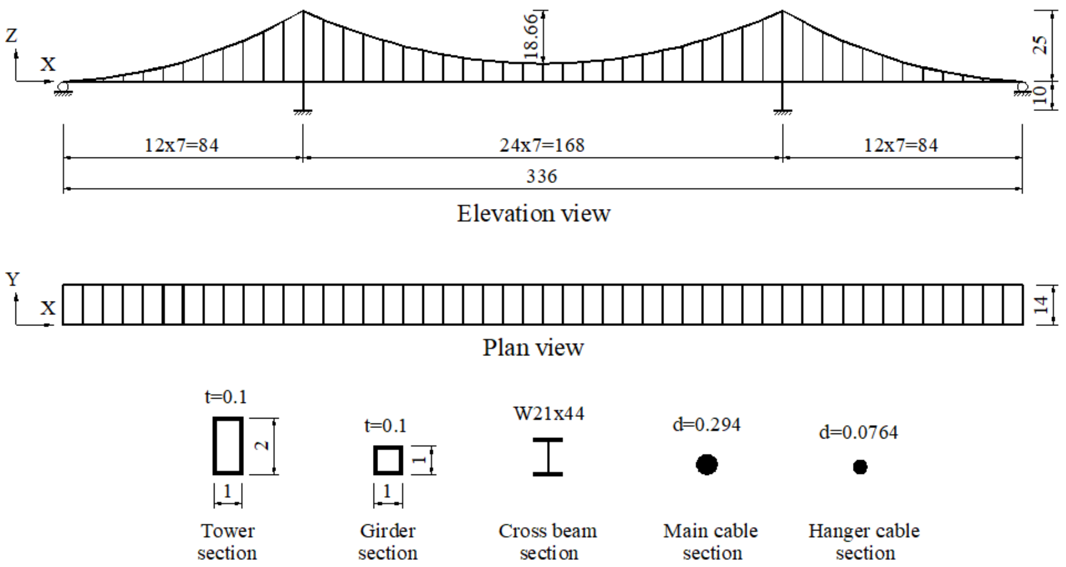


Fig. 5 Geometry and dimension of the bridge (unit: m)

The static analysis of the bridge is considered first with the load combination “Strength I”, (1.25DL+1.75LL) specified in AASHTO-LRFD. The dead load is taken as 2.3 kN/m^2 and the live load is equal to 3.1 kN/m^2. Fig. 6 presents the load-vertical deflection curve at the mid-span of the bridge presented in PAAP3D. As can been obtained from this figure, the ultimate load factor of the bridge is 2.26. Fig. 7 shows the plastic hinge deformation of the bridge at the ultimate load factor.

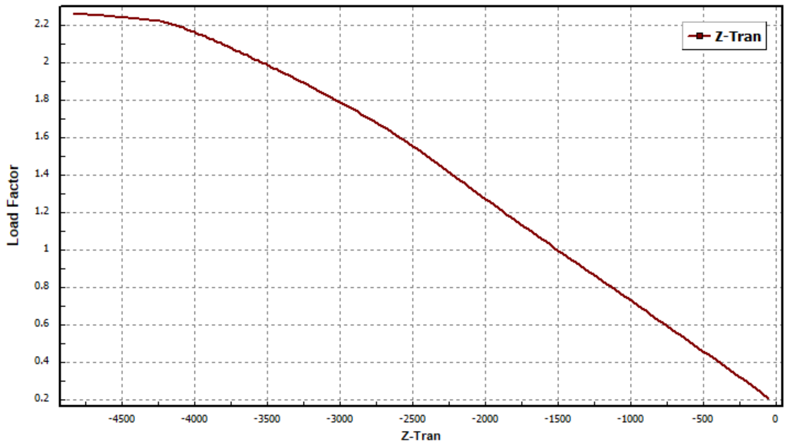


Fig. 6 Load-vertical deflection curve at the mid-span point

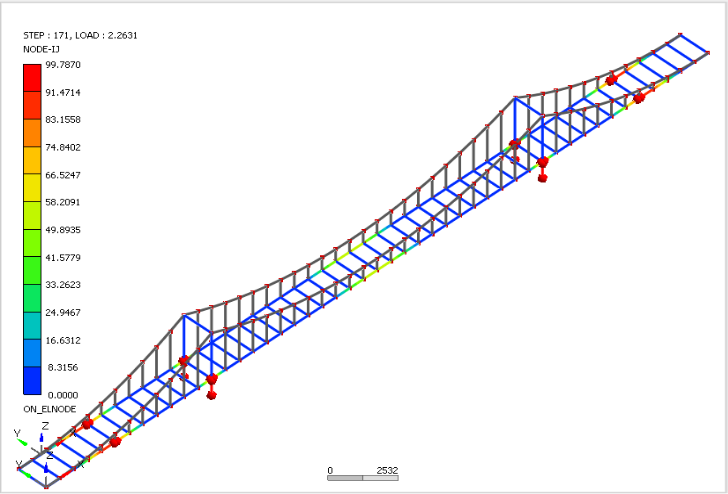


Fig. 7 Load-vertical deflection curve at the mid-span point

The behaviors of the bridge subjected to El Centro earthquake is now considered by using the time-history dynamic analysis. The structural responses under dead load (1.0DL) is analyzed first until the load factor of 1.0, and then the time-history dynamic analysis is performed from that structural deformation. The ground acceleration is scaled up by a factor of 2.5 to produce highly nonlinear inelastic behavior of the structure. Fig. 8 presents the model of the bridge in PAAP3D. Fig. 9 shows the time-history horizontal deflection of the pylon top under the dead load and earthquake.

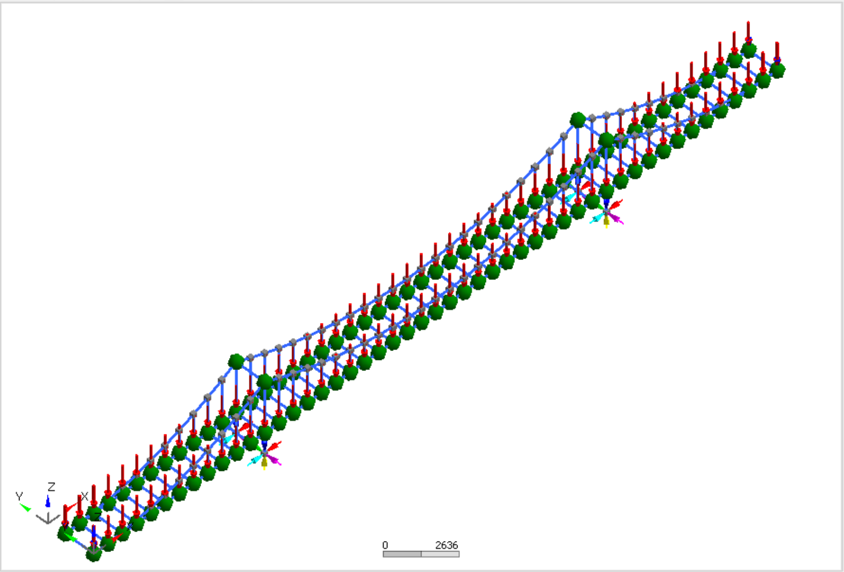


Fig. 8 Bridge model using PAAP3D

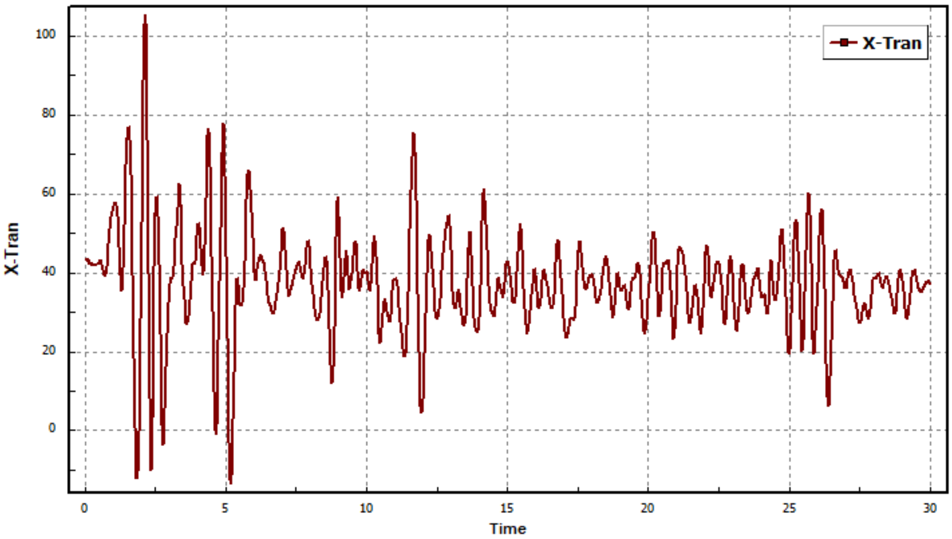


Fig. 9 Time-history X-axis deflection of the top point of the pylon

5. CONCLUSIONS

A robust software for nonlinear inelastic analysis of steel structures is presented. Both static and time-history dynamic analyses of steel structures are implemented in the proposed software. The pre- and post-processors of the proposed software are developed using C++ programming language with a user-friendly and easy-to-use interface. The numerical examples prove that the developed software is reliable and robust for practical design of steel structures.

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