EFFECT OF PLASTICITY MODELS ON THE PREDICTION OF CYCLIC BEHAVIOR OF BRACES

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ABSTRACT

In this paper, the effect of using different plasticity models on the theoretical predictions of the strength and cyclic behavior of braces is studied. Various geometrical parameters of braces, on both global and local levels, are considered. The finite element method is utilized considering both geometrical and material non-linearity. The difficulty in numerical calculations arising from occurring the snap-backs during the cyclic deformation is overcome through incorporating the arc-length technique in the finite element program. The results are closely examined with respect to both the ultimate strength and energy dissipation capacity.

Keywords: *Finite Element, Plasticity Models, Cyclic Behavior, Braces.*

INTRODUCTION

Bracing members are used commonly in space trusses and offshore structures. These structures which are subjected to extreme environmental loadings such as earthquake, wave and wind are normally designed considering their ultimate strength. In nature, these loadings are repetitive, therefore, the structures and their individual members must have a sufficient strength and ductility under cyclic loadings. To predict the performance under extreme seismic loading conditions, it is necessary to investigate the inelastic cyclic behavior of the structures as well as their individual members. In many instances, the use of experimental testing to evaluate the performance of structures under these severe conditions is either expensive or practically impossible. Therefore in these cases, analytical means must be employed. This has been the subject of intensive investigations in recent years [1-15].

The application of finite element method to treat the nonlinear behavior of structures has reached such a stage that the results obtained from these analyses can be accepted with high level of reliability. Also, the recent advances in computer technology have resulted in greater computer storage capacity and high computational speed. As a result, non-linear analysis may be performed at a reasonable cost.

On the other hand, one of the major factors that affect the numerical simulations of cyclic behavior of a structural member is the choice of the cyclic plasticity model which would simulate the real material behavior under deformation. In this study, three plasticity models of structural steel material are investigated, considering several factors such as the strain hardening, Bauschinger effect and the cyclic hardening of the material, namely, elastic-perfectly plastic model, kinematic model with strain hardening and combined isotropic-kinematic hardening model.

The structural member investigated in this study is a pin-ended circular tubular brace with several geometrical parameters, under cyclic axial load. The numerical results are analyzed on the bases of the ultimate strength and energy dissipation capacity.

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METHOD OF COMPUTATION

In this research, the finite element program **CYNAPSS1**[13-15] is employed. The features of this finite element program are summarized as follows:

1) A simple four nodes quadrilateral isoparametric flat shell element is used. The formulation of this element is based on the assumed displacement field approach. The stiffness matrix of this element is composed of bending and in-plane stiffness. The bending stiffness matrix is formulated based on the Mindlin plate theory, in which the transverse shear deformations are considered. Selective reduced integration scheme, i.e. the integration of the different strain terms with different orders of integration, is adopted to prevent the transverse shear and membrane locking [16].
2) Large rotation and small strain are considered on the bases of Total Lagrangian formulation which uses the Green strain tensor and the second-Piola Kirchhoff stress tensor.
3) The material model which was developed by Petersson and Popov [17] and later improved by Mosaddad and Powell [18] is adopted as the combined isotropic-kinematic hardening plasticity model. This model is based on Mroz' multi-surface plasticity model with multi-linear uniaxial stress-strain relationship and Von Mises yield criterion. The actual material properties are determined from the virgin state (monotonically increasing curve) and saturated state (when steady state of the material is fully developed) of the material. The transition between these states of the material is controlled by a weighting function w which is a function of the accumulated plastic strain. The weighting function w can be determined through trial and error process. It is worth noting that this model also has the ability to simulate both the elastic-perfectly plastic model and the kinematic hardening model. The spread of plasticity is checked at four Gaussian points in six layers across the thickness (a total of 24 integration points).
4) An incremental predictor with Newton-Raphson iterations is adopted with the aid of displacement control to trace the complete equilibrium path. In addition, the arc-length method [19, 20] with either displacement or load control is elaborately implemented to be used under cyclic loading. The applicability to trace the "snap-backs" during cyclic loading is the valuable feature of this implementation. An automatic switching to the arc-length method based on the current stiffness parameter is also included. The automatic sizing of load increment is employed based on several criteria such as the number of required and desired iterations, current stiffness parameter and the number of eigen values (negative diagonals appear in the overall stiffness matrix). Further, an automatic restart option has been incorporated in order to perform the analysis under cyclic loads. Convergence of non-linear solution is controlled by the Euclidean norm of the unbalanced forces with allowable tolerance of 0.001 or another prescribed value.

The validity of the finite element program "**CYNAPSS1**" was examined through comparisons with experiments in references [13-14]

NUMERICAL MODELS

All the models are axially loaded braces having circular cross-section with pin end conditions and subjected to eight cycles of constant displacement amplitude ranging from $-2\,\delta_y$ to $+2\,\delta_y$, where δ_y is the yield axial displacement. Due to the symmetry, only one quarter of the brace is analyzed. The finite element mesh division and boundary conditions used for the numerical analysis are shown in Figure 1. The axial load is applied with eccentricity of one thousandth of the length L to initiate the buckling. Normalized parameters D/t and λ are chosen so that the influence of each parameter can be clarified, where D is the outer cross-section diameter, t is the tube thickness and λ is the reduced slenderness ratio as indicated in Table 1. The uniaxial stress-strain relationships representing the three plasticity models used in this study are shown in Figure 2, where the yield stress, σ_y, is equal to 624.4 N/mm^2 and the Young's modulus, E, is equal to 210000 N/mm^2. The geometrical effects are investigated through considering the variation of the diameter-to-thickness ratio and the reduced slenderness ratio as indicated in Table 1.

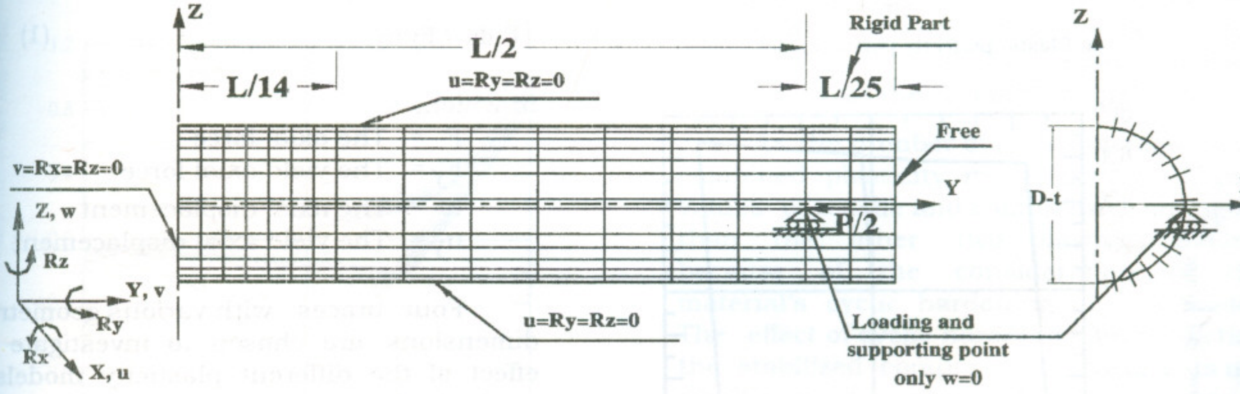


Figure 1 FEM mesh division and boundary conditions used in the analysis

Table 1 Description of the investigated models

Model	D/t	λ	Plasticity Model
M24-05ep	24	0.5	Elastic-perfectly plastic model
M60-05ep	60	0.5	Elastic-perfectly plastic model
M24-10ep	24	1.0	Elastic-perfectly plastic model
M60-10ep	60	1.0	Elastic-perfectly plastic model
M24-05K	24	0.5	Kinematic hardening model
M60-05K	60	0.5	Kinematic hardening model
M24-10K	24	1.0	Kinematic hardening model
M60-10K	60	1.0	Kinematic hardening model
M24-05C	24	0.5	Combined hardening model
M60-05C	60	0.5	Combined hardening model
M24-10C	24	1.0	Combined hardening model
M60-10C	60	1.0	Combined hardening model

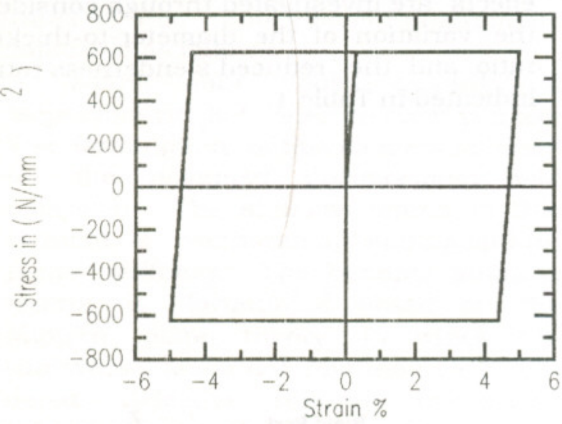
Where,

λ = reduced slenderness ratio

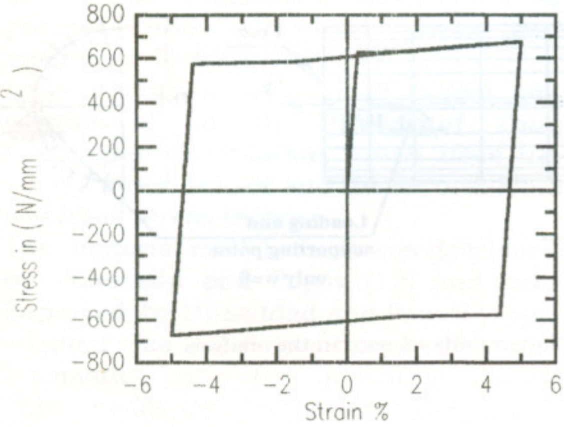
$$= \frac{L/r}{\pi\sqrt{E/\sigma_y}}$$

L = length ,

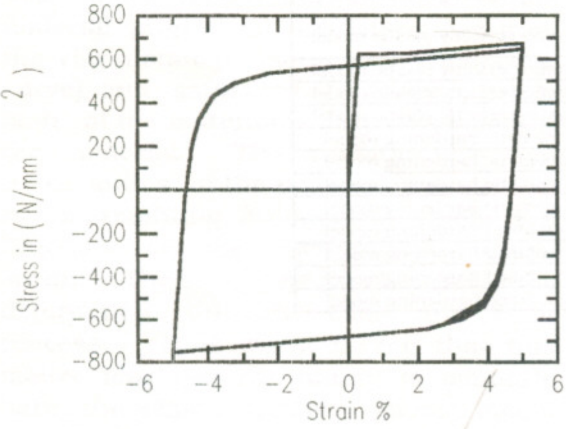
r = radius of gyration



(a) Elastic-perfectly plastic model



(b) Kinematic hardening model



(c) Combined hardening model

Figure 2 Uniaxial stress-strain relationship

RESULTS AND DISCUSSION

Two criteria are applied to evaluate the performance of the brace under cyclic loading, namely the strengths, in both tension and compression, and the energy dissipation capacity. The energy dissipation capacity is defined as the accumulated energy dissipated per cycle. Further, its normalized value with respect to $F_y u_y$ is referred to as normalized absorbed energy that corresponds to the area under the normalized load-displacement curve, i.e.,

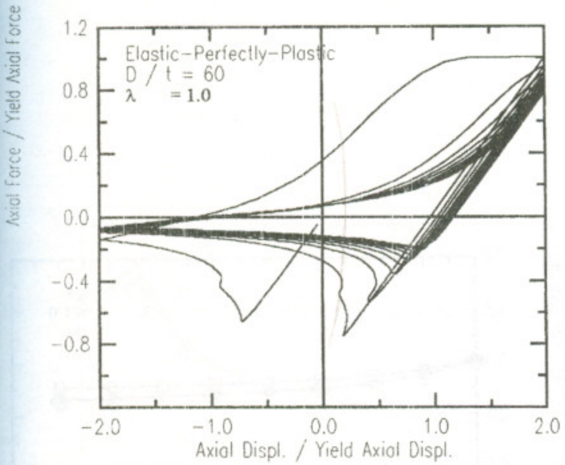
$$\int F \, du \, / \, F_y u_y \qquad (1)$$

in which,

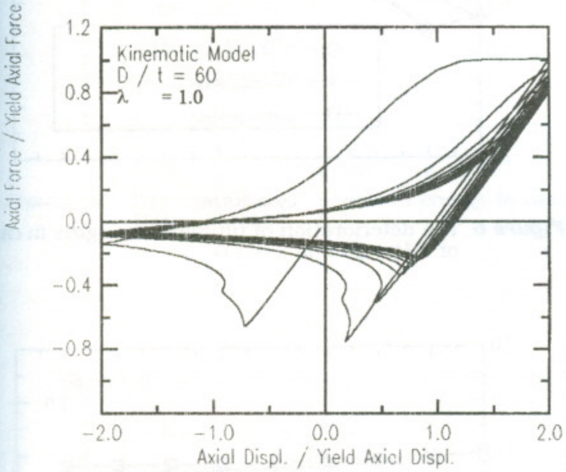
F = The axial force
F_y = The yield axial force
u = The axial displacement
u_y = The yield axial displacement

Four braces with various geometrical dimensions are chosen to investigate the effect of the different plasticity models on predicting the strength and energy dissipation capacity of the brace under cyclic loading. The models are subjected to eight cycles starting from compressive loading with normalized displacement range of 4.0 and normalized mean displacement of 0.0.

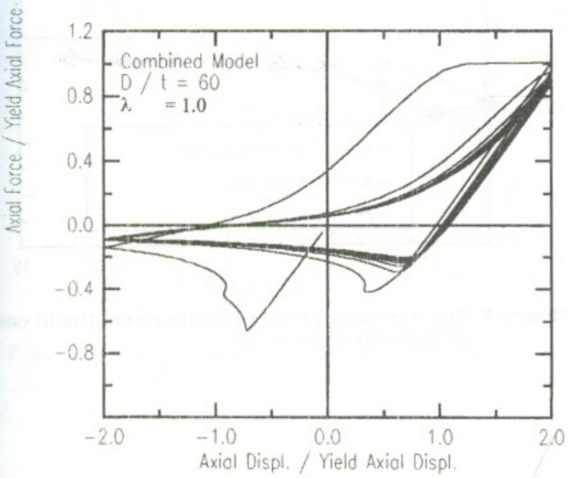
Typical computed hysteresis load-displacement loops for the three plasticity models used in this analysis are shown in Figure 3. It is worth noting that how the snap backs could be traced during the calculations of the subsequent cycles due to the elaborate implementation of the arc-length method in the present finite element program.



(a) Elastic-perfectly plastic model



(b)kinematic hardening model



(c) Combined hardening model

Figure 3 Normalized axial load-axial displacement hysteresis loops

Shown in Figures 4-7 are the deterioration of normalized ultimate strengths versus number of cycles, with the different plasticity models, for the four geometrical cases. Generally, the compressive strength of the brace is deteriorated significantly with the increase of the number of cycles. This may be due to the accumulated local/global buckling (or deformation). The local buck-ling reduces the full plastic moment of the cross section and consequently the compressive strength in the subsequent load cycles. In the four geometrical cases, the combined plasticity model predicts early reduction in the compressive strength because of the well presentation of Bauschinger effect in this model which causes more residual deformation at the end of first load cycle.

As the number of cycles increases, the combined plasticity model predicts higher values of tensile and compressive strengths than the other two plasticity models because of the consideration of the material's cyclic hardening in this model. The effect of cyclic hardening, on predicting the stabilized compressive strength, is not significant in case of high values of diameter-to-thickness ratio and/or the slenderness ratio. This may be attributed to the dependence of the compressive strength on the local buckling phenomenon in case of high value of diameter-to-thickness ratio and on the accumulated global deformations in case of high slenderness ratio.

Figures 8-11 show the cumulative normalized absorbed energy versus the number of cycles, with the different plasticity models, for the four geometrical cases. It can be noticed that, in all geometrical cases, the combined plasticity model predicts early reduction in the energy dissipation capacity. This is due to the Bauschinger effect which is considered by combined plasticity model.

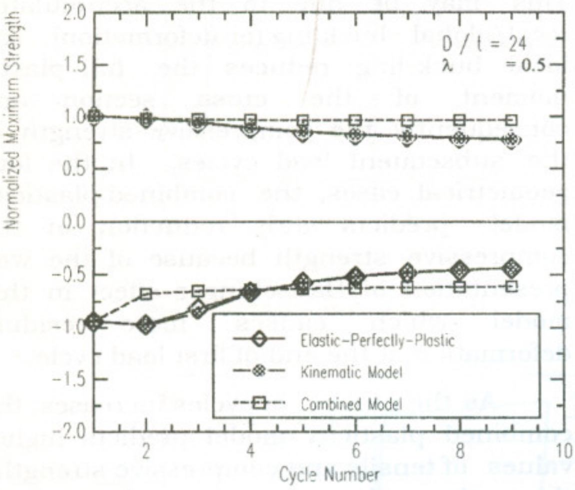


Figure 4 The deterioration of ultimate strengths in case of D/t = 24 and λ = 0.5

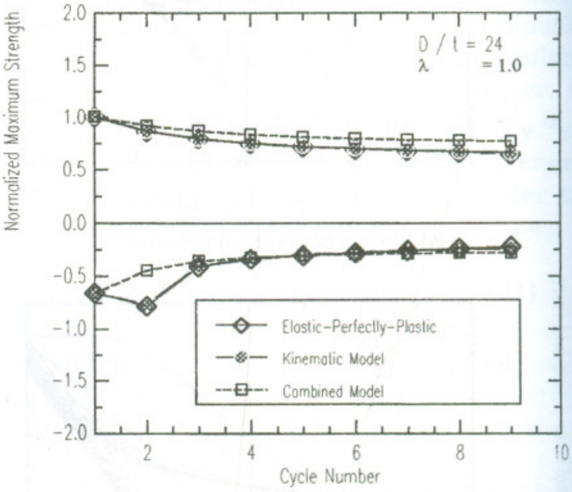


Figure 6 The deterioration of ultimate strengths in case of D/t = 24 and λ = 1.0

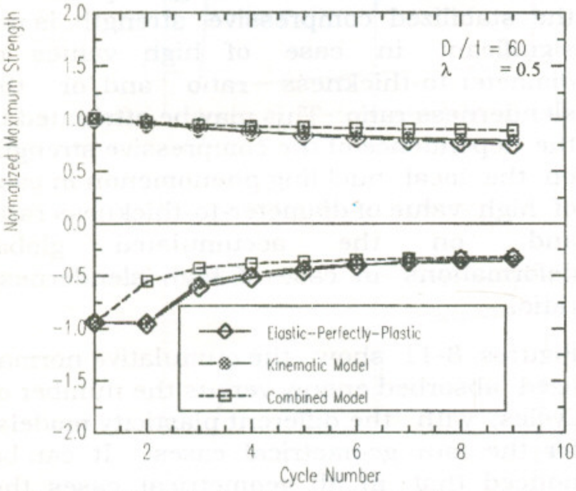


Figure 5 The deterioration of ultimate strengths in case of D/t = 60 and λ = 0.5

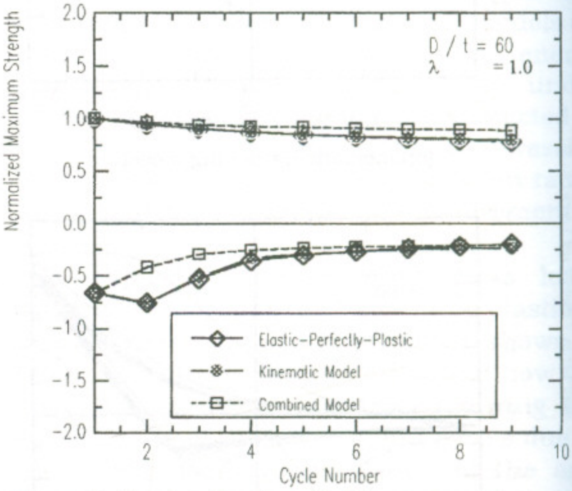


Figure 7 The deterioration of ultimate strengths in case of D/t =60 and λ = 1.0

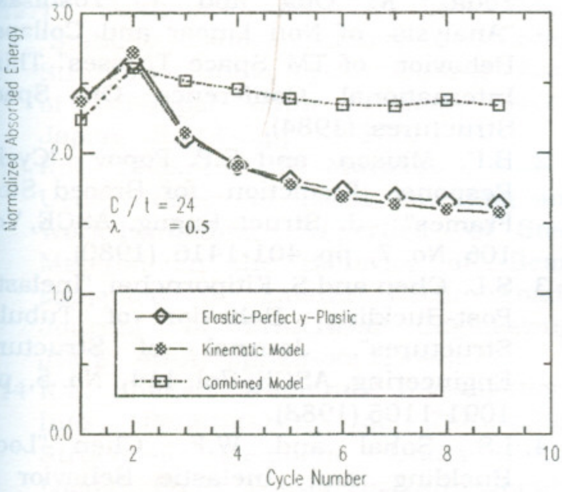


Figure 8 The cumulative absorbed energy in case of D/t = 24 and λ = 0.5

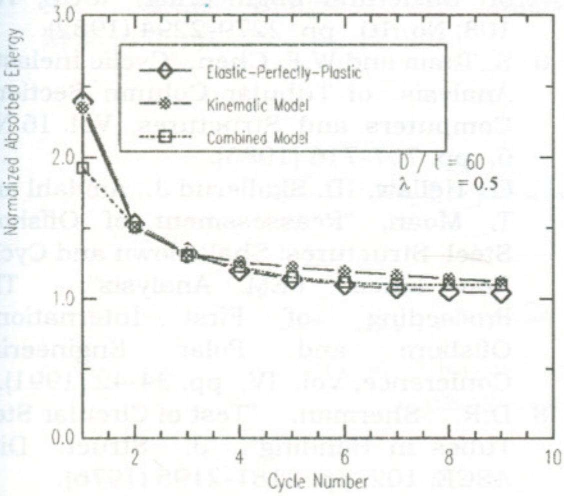


Figure 9 The cumulative absorbed energy in case of D/t = 60 and λ = 0.5

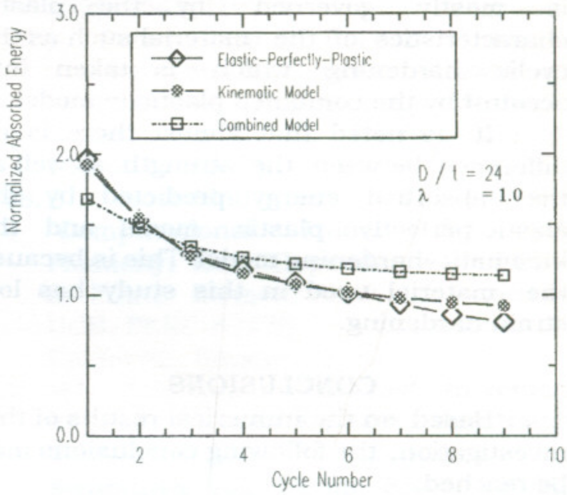


Figure 10 The cumulative absorbed energy in case of D/t =24 and λ = 1.0

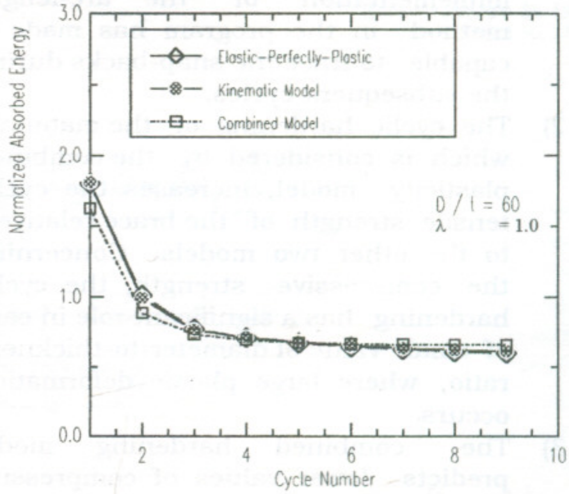


Figure 11 The cumulative absorbed energy in case of D/t =60 and λ = 1.0

As the number of cycles increases, in case of small diameter-to-thickness ratio, the energy dissipation capacity of the member predicted by the combined plasticity model is larger than the other plasticity models. This is because the deformation in this case is mostly governed by the plastic characteristics of the material such as the cyclic hardening which is taken into account by the combined plasticity model.

It is noted that almost there is no difference between the strength as well as the absorbed energy predicted by the elastic-perfectly plastic model and the kinematic hardening model. This is because the material used in this study has low strain hardening.

CONCLUSIONS

Based on the numerical results of this investigation, the following conclusions may be reached;

1) The finite element program, CYNAPSS1, has proved to be a powerful tool for elasto-plastic large deformation analysis of steel shell structures under cyclic loading. Moreover, the elaborate implementation of the arc-length method in the program has made it capable to trace the snap-backs during the subsequent cycles.
2) The cyclic hardening of the material , which is considered by the combined plasticity model, increases the cyclic tensile strength of the brace relatively to the other two models. Concerning the compressive strength, the cyclic hardening has a significant role in case of small value of diameter-to-thickness ratio, where large plastic deformation occurs.
3) The combined hardening model predicts lower values of compressive strength and absorbed energy during the first few cycles due to the Bauschinger effect which is well presented by this model.
4) The absorbed energy predicted by the combined hardening model, in case of small diameter-to-thickness ratio, is higher than the prediction of the two other plasticity models due to the effect of the cyclic hardening under large plastic deformation.

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تأثير نماذج اللدونة على تنبؤ السلوك الدورى للدعامات

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ملخص البحث

فى هذا البحث يتم دراسة أثر إستخدام نماذج لدونة مختلفة على التنبؤ النظرى للمقاومة والسلوك الدورى للدعامات. تم إعتبار معاملات هندسية مختلفة للدعامات على المستوى الشامل والمحلى. تم إستخدام طريقة العناصر المحددة معتبرا كل من االاخطية المادية والهندسية. تم التغلب على الصعوبة فى الحسابات العددية الناتجة من حدوث الإنهيار الخلفى أثناء التشكل الدورى بإستخدام طريقة طول القوس فى برنامج العناصر المحددة. تم إختبار النتائج عن قرب بالنسبة للمقاومة القصوى و سعة تبديد الطاقة.