MODELLING ISSUE OF STEEL BRACES USING A PHYSICAL MODELLING METHOD

Dong-Hyeon SHIN[1], and Hyung-Joon KIM[2]

SUMMARY

The cyclic response of bracing members should be reasonably reflected into their analytical models in order to simulate quite complex mechanisms including the global buckling phenomena and the yielding of material. Of various analytical approaches, a physical modelling method has been widely implemented using the feature of its easy applicability. A bracing member is modeled as two elastic beam-column segments which are connected to each other using a plastic hinge located at the center of member. This method combines analytical formulations based on the nonlinear behavior of the brace with several empirical normalized formulas developed on the basis of available experimental data. The objecteve of this study is to investigate a modelling issue of steel braces using the physical modelling method. It is observed that analytically obtained hystereis loops of braces over-estimate the compressive loading ranges compared with the experimental ones. This phenomenon might be resulted from the assumption of constant plastic hinge rotation of brace at the elastic shortening zone. From the observations of several experimental data, the plastic hinge rotation variates during the repeated loading cycles. Such variation in the plastic hinge rotation results in an increase in the hinge moment and buckling strength.

Keywords: *steel braces; plastic hinge rotation; physical modelling method; cyclic response.*

INTRODUCTION

Steel braced frames have become a popular structural system to resist lateral load due to their high strength and stiffness to resist such external loads. This lateral force resisting system has been widely adopted on the construction field in the basis of advantages such as relatively simple design, fabrication, and erection (Tremblay et al., 2008). In order to provide adequate lateral force resistance, steel braced frames shoud be designed to have sufficient strength and ductility capacity. To achive these, diagonal braces should sustain plastic deformations and dissipate hysteretic energy in a stable manner through successive cycles of buckling in compression and yielding in tension (Bruneau et al., 2011). The main design strategy for steel braced frames is to ensure that plastic deformation is only concentrated on the bracing members, maintining the columns and beams undamged, hence allowing the frames to survive strong lateral loadings without losing their resistance for gravity-loads (AISC, 2010a; AISC. 2010b; AIJ, 1995). In this reason, the steel bracing member has a important role to obtain proper lateral force resisting capacity of frames.

The cyclic behavior of bracing members is dependent on quite complex mechanisms including the global buckling phenomena, the yielding of material, the local buckling effects, and the post-buckling deterioration of compressive load capacities due to the Bauschinger effects and the tangent modulus deterioration (Remennikov and Walpole, 1997). Regarding this, an understanding of inelastic behavior of a steel brace member subjected to reversed cycles of axial loading is necessary to evaluate and design braced frames. Furthemore, it is required to properly reflect the cyclic behavior of such bracing member into the analytical process in order to reasonably estimate the seismic

[1] *Assistant Professor, Pusan National University, Korea, e-mail: shindh@pusan.ac.kr*
[2] *Professor, University of Seoul, Korea, e-mail: hyungjoonkim@uos.ac.kr*

performance of braced frames.

A first approach taken to model cyclic behaviors of steel braces has been to implement in analytical process using a finite element method (Haddad, 2017). To compensate complicated finite element models consuming large amount of computational time, phenomenological models have been suggested by various researchers (Zayas et al., 1981) to properly reflect the complicate mechanism of bracing members subjected to cyclic loadings. Use of these modelling approaches is less computationally intensive than finite element methods based on computational mechanics, however they have limited application field in that phenomenological models were constructed with various empirical equations and coefficients required to be calibrated on experiment-specific data. Later developments on models are dependent on physical theory to characterize the various branches of the hysteresis loops as well as the transitions from any branch to possible others during the loading history (Bruneau et al., 2011). Using this concept, physical theory models have been developed in many researches (Ikeda and Mahin, 1986; Jin and El-Tawil, 2003; Dicleli and Calik, 2008).

Physical theory models are intended to predict the behavior of steel braces in the basis of knowledge of member geometry and material properties. It consist of two elastic members and a plastic hinge which can easily and reasonably capture hysteretic behavior including out-of-plane deformation of steel braces. Despite of these improvements on analytical models, it is still questionable on the physical theory model since cyclic behaviors of steel braces are strongly dependent on axial force-moment interaction, axial-rotational deformation, and axial force-deformation relation of single plastic hinge concentrated on the center of bracing member. This study employs the physical theory model to predict the hysteretic behavior of the selected braces and investigates the modelling issues related to existing physical theory models focusing on the plastic hinge rotations which can mainly influence on the prediction results of such modelling method.

A PHYSICAL MODELLING METHOD

Existing analytical models for bracing members

The cyclic responses of steel braces can be simulated by using various analytical modelling approaches. A finite element (FE) model has been frequently utilized for predicting the structural behavior of steel braces in that stresses and strains of local elements in the brace can be easily captured with reasonable precision (Fell, 2008; Haddad, 2017). Also, the FE model can predict local buckling at the mid-span or both ends of the steel brace. On the other hand, it is time-consuming process to perform the nonlinear dynamic analysis of steel braced frames although overwhelming analysis results including its member response, structural cyclic response, and stress and strain distributions in the plastic hinge regions are provided.

A phenomenological model consists of a single spring element or an assembly of spring elements representing steel braces. The cyclic behavior of the phenomenological model is established using hysteretic rules obtained from experimental works (Jain and Goel, 1978). The axial load-displacement curve calibrated by empirical parameters can be easily applied to brace elements in steel braced frames that might be analyized using a nonlinear dynamic analysis. Although simplified application to the nonlinear dynamic analysis of the frame of interest is possible, empirical parameters should be experimentally verified for every braces with different material, geometrc and boundary conditions, and sectional properties.

A modelling method using a physical theory model combines the modelling schemes of the FE model and phenomenological model in order that disadvantages of both modelling methodologies are addressed. The physical theory model utilizes spring elements for easy application to nonlinear dynamic analyses of steel braced frames. Instead of empirical parameters used for the calibration of experimental results, physical theories are implemented into the model to represent the influence of geometric and boundary conditions, slenderness ratios, and width-to-thickness ratios required to define the hysteretic behavior of steel braces.

Description of the physical theory model

The physical theory model is developed based on analytical expressions for axial force-axial deformation behavior of a pin-ended bracing member with a plastic hinge located at mid-span as shown in Figure 1. The plastic state of the lumped hinge, as shown in Figure 2, is defined by a axial force-moment interaction (*P-M* interaction) curve. Axial and rotational deformation at the plastic hinge are defined according to a flow rule which consists of three characteristics: 1) the gradual plastification process of the plastic hinge, 2) the variation of the tangent modulus of elasticity during cycles, and 3) the residual displacements due to material nonlinearities in the nominal elastic range.

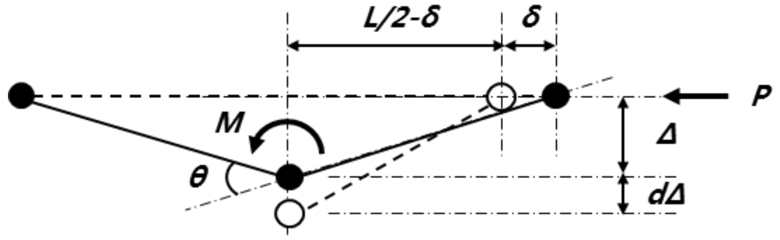
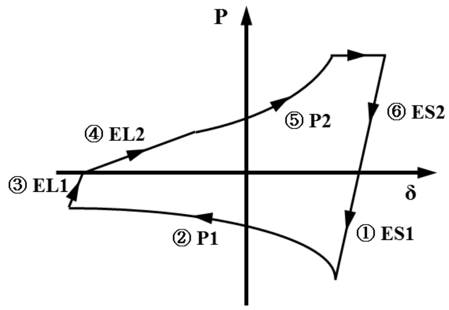
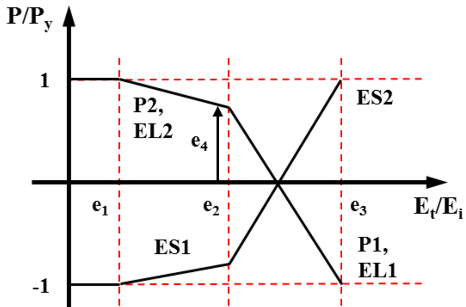


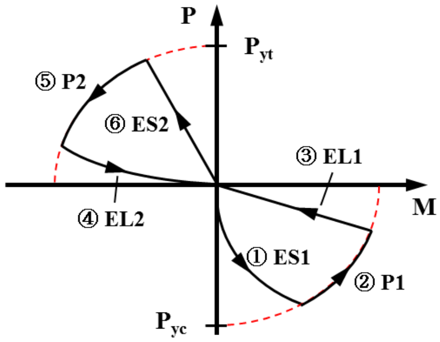
Figure 1. Description of the physical theory model



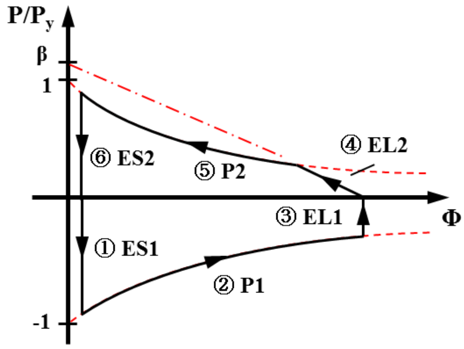
(a) Axial load-displacement curve



(b) Normalized tangent modulus



(c) Axial load-moment curve



(d) Axial load-plastic rotation curve

Figure 2. Parameters to define a physical theory model

A gradual plastification process at the plastic hinge is presented in Figure 2(a). It can be divided into six zones: 1) an elastic shortening zone in compression (ES1 zone), 2) a plastic zone in compression (P1 zone), 3) an elastic elongation zone in compression (EL1 zone), 4) an elastic elongation zone in tension (EL2 zone), 5) a plastic zone in tension (P2 zone), and 6) an elastic shortening zone in tension (ES 2 zone). If axial loads and corresponding moments of the steel brace of interest are reached to the yielding surface in the P-M interaction curve, plasticity of the plastic hinge is developed.

The variation of tangent moduli of elasticity is defined as a function of a normalized tangent modulus and axial load. Four parameters from e_1 to e_4 are required to define the normalized tangent modulus as shown in Figure 2(b) where E_i is the initial elastic modulus and E_t is the tangent modulus. The sub-parameters are calculated from a stress-strain curve of non-buckled steel materials. The physical theory model assumes that there is no deterioration in the tangent modulus during later cycles. The value of e1 is an E_t/E_i value when an axial load P becomes the yield strength P_y in the ES1 and P2 or EL2 zones whereas a value of e_3 is an E_t/E_i value at the initiation of unloading. Values of e_2 and e_3 are E_t/E_i and P/P_y values at the transition from the ES2 to ES1 zones or from the EL1 to EL2 zones. A value of E_t/E_i is suddenly reduced at the transition from the EL1 to EL2 zones where a normalized load P/P_y becomes a value of e_4. The values e_2 and e_4 are the important paramters determining the buckling and yielding of a steel brace.

According to an assumption that the plastic hinge occurred at the mid-span of a steel brace follows elasto-plastic behavior, secondary moments at the plastic hinge are increased after the combined action of axial load and moments in the steel brace is on the yield surface in the *P-M* interaction curve. This phenomenon is depicted on Figure 2(c) where P_{yt} and P_{yc} are the expected yield strength and initial buckling strength of the steel brace, respectively. The characterization of the EL2 zone needs an experimental parameter β which is adopted to consider the deterioration of plastic hinge rotations and it is presented on an axial load-hinge rotation curve as shown in Figure 2(d).

MODELLING ISSUES USING A PHYSICAL MODELLING METHOD

Brace specimens tested by previous research (Black et al., 1980) were prepared in order to simulate their cyclic responses using the physical modelling method. Table 1 summarizes general information of specimens of which dimensions and material properties are typically utilized in the construction field. In constructing the analytical models of steel braces of interest, the expected tensile yield strength, P_{yc}, and the expected buckling strength, P_{yt} are first calculated using the materials and section properties, as summarized in Table 2. In addition, there are three parameters that should be pre-defined to determine the tangent moduli, E_t varing according to repeated cyclic loadings. Parameter, α_c and α_t reflecting strain hardening of steel are magnification factors for the positive and negative moment capacities in the P-M interaction curves, respectively. A parameter β is a reduction factor for the plastic hinge rotation in the EL2 zone.

Table 1. Summary of general information related to brace specimens (obtained from Black et al., 1980)

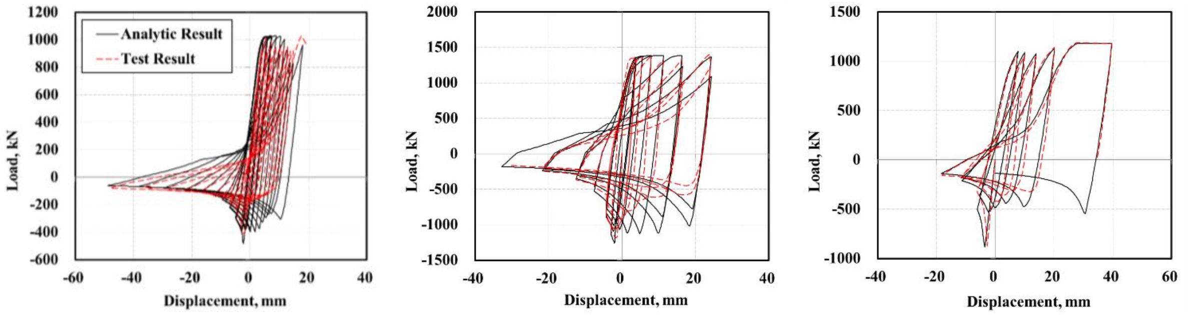
Specimen	H x B x t_w x t_f	L, mm	A, mm^2	KL/r	I, mm^4	Z, mm^3	F_y, MPa
Strut 1	210 x 134 x 5.4 x 10.2	3,810	3,970	120	4,066,581	93,242	279
Strut 2	162 x 154 x 8.1 x 11.6	1,550	4,740	40	7,117,557	140,601	291
Strut 3	157 x 153 x 6.6 x 9.3	3,070	3,790	80	5,535,878	110,121	277

Table 2. Modelling parameters of the physical modelling method

Specimen	α_c	α_t	β	E1	E2	E3	E4	PYC, kN	PYT, kN
Strut 1	0.8	1.05	1.2	0.1	0.9	1.0	0.65	483	1120
Strut 2	0.9	1.10	1.4	0.1	0.9	1.0	0.26	1257	1384
Strut 3	1.1	1.00	1.2	0.1	0.9	1.0	0.20	876	1180

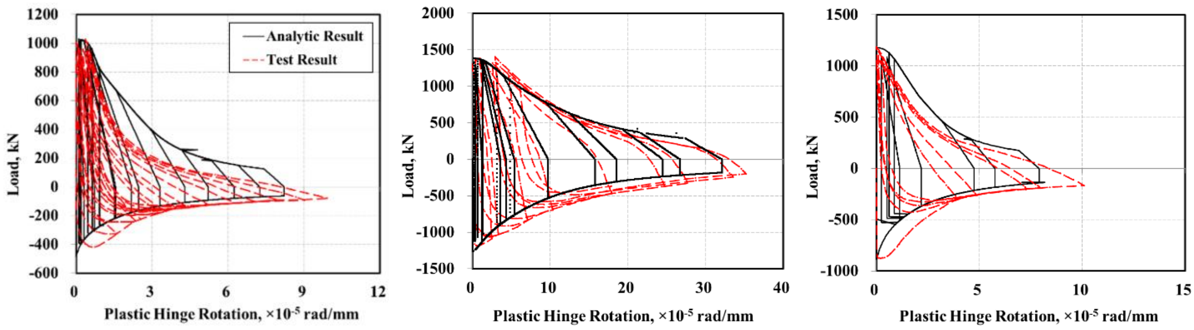
Figures 3 and 4 present the load-displacement and load-plastic hinge rotation relations obtained from the analyses with test results. The physical theory model can reasonably predict the cyclic response of the test specimens in terms of their tensile strengths and initial buckling strengths. The analytical results well estimate axial deformation, geometric shortening axial deformation, plastic axial deformation, and tensile yield axial deformation of six zones presented in Figure 2. However, the buckling strengths after the initial buckling measured from the analyses are over-estimated in comparison to those of the test results. Especially the stiffness is almost constant without any reduction, which is much different from the test results. The stiffness in the plastic zone is determined by four axial deformation components while the stiffness in the elastic shortening zone depends on the elastic axial deformation due to a constant plastic hinge rotation. For the physical theory model, the axial stiffness of steel braces is influenced by several parameters such as materials and section properties. Of them, the the plastic hinge rotation is most important parameter which is demonstrated from the comparison between test and analysis results in terms of the load-plastic hinge rotation relations. It is clearly found on the elastic shortening zone of Figure 4.

Buckling strength is defined as the transition from the elastic zone to the plastic zone in compression. The plastic zone in compression is a state that an axial load and plastic hinge moment approach a yielding surface computed based on the P-M interaction curve. In the analytical model using the pre-defined P-M interaction curve, the buckling strengths are influenced by the corresponding moments depending on the plastic hinge rotations at the hinge region. The moment at the plastic hinge can be calculated from a function of the tangent modulus of elasticity, moement of inertia, plastic hinge rotaion, and the applied axial loads. Since the previous two parameters are deterministic values which are not changed during the loading protocol, they have no effects on the buckling strength of steel braces. In the physical theory model, the plastic hinge rotation is also assumed as constant in the elastic shortening zone. In this reaon, the plastic hinge moment is only related to the variation of the applied axial load of braces. On the other hand, test results show that the plastic hinge rotation at the elastic shortening zone is no more constant. As presented in Figure 4, the plastic hinge rotation changes during the later cycles of loading protocols. Such increase in the plastic hinge rotation results in the increase of moment measured at the plastic hinge and changes on the buckling strengths. As loading cycles are accumulated, the ratios of the buckling strength measured from the analyses to those obtained from the test results are increased and they almost reach to more than 2.0 although the ratios at the first loading cycle are close to 1.0 meaning that the analytical model well predict the intial buckling strength of brace specimens.



(a) Strut 1 (b) Strut 2 (c) Strut 3

Figure 3. Comparison of load-displacement relations obtained from analyses with test results



(a) Strut 1 (b) Strut 2 (c) Strut 3

Figure 4. Comparison of load-plastic hinge rotation relation obtained from analyses with test results

CONCLUSION

The physical theory model is an efficient method to estimate the cyclic response of a steel brace under repeated loadings since it requires a small amount of computation time with rigorous experimental validation. This paper decribes an approach estimating cyclic response of braces using the physical theory model and investigate a main reason on the discrepancy between analysis and test results. The analytical results using the physical theory model can significantly overestimate the buckling strengths of steel braces, which is an evidence that the existing physical theory model is required to be improved. Especially, it is required to further study on the effects of plastic hinge rotation in the elastic shortening zone and to suggest methodology to reflect such effects on the analytical procedure of the physical theory model.

REFERENCES

Tremblay, R., Haddad, M., Martinez, G., Richard, J., Moffatt, K. (2008) "Inelastic cyclic testing of large size steel bracing members", The 14th World Conference on Earthquake Engineering, October 12-17th, Beigin, China.

Bruneau, M., Uang, C. M., Sabelli, R. (2011) "Ductile Design of Steel Structures, 2nd Edition", McGraw-Hill Education, USA.

AISC (2010a) "Seismic Provisions for Structural Steel Buildings, ANSI/AISC 341-10", American Institute of Steel Construction, Chicago, USA.

AISC (2010b) "Specification for Structural Steel Buildings, ANSI/AISC 360-10", Ametican Institute of Steel Construction, Chicago, USA.

AIJ (1995) "Reconnaissance report on damage to steel building structures observed from the 1995 Hyogoken-

Nanbu Earthquake, Nakashima, M., and Bruneau, M., editors for English Edition", Architectural Institute of Japan, Osaka, Japan.

Remennikov, A. M., Walpole, W. R. (1997) "Analytical prediction of seismic behavior for concentrically-braced steel systems, Earthquake Engineering and Structural Dynamics, Vol. 26, No. 8.

Ikeda, K., Mahin, S. A. (1986) "Cyclic response of steel braces", Journal of Structural Engineering, Vol. 112.

Jin, J., El-Tawil, S. (2003) "Inelastic cyclic model for steel braces", Journal of Engineering Mechanics, Vol. 129, No. 5, pp. 548-557.

Dicleli, M., Calik, E. E. (2008) "Physical Theory Hysteretic Model for Steel Braces", Journal of Structural Engineering, Vol. 134, No. 7, pp. 1215-1228.

Zayas, A. Z., Shing, P. B., Mahin, S. A., Popov, E. P. (1981) Inelastic Structural Modeling of Braced Offshore Platforms for Seismic Loading, Report No. UCB/EERC-81/04, Berkeley Earthquake Engineering Research Center, University of California.

Fell, B. V. (2008) "Large-scale testing and simulation of earthquake-induced ultra low cycle fatigue in bracing members subjected to cyclic inelastic buckling", Ph. D. Dissertation, University of California, Davis, USA.

Jain, A. K., Goel, S. C. (1978) "Hysteretic models for steel members subjected to cyclic buckling or cyclic end moments and buckling", UMEE Report, No. 78R6, University of Michigan, Ann Arbor, Mich., USA.