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USE OF A NEW PHENOMENOLOGICAL MODEL TO CAPTURE THE NONLINEAR BEHAVIOR OF BRACING MEMBERS

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This paper is a summary of an attempt to provide a phenomenological model in order to capture the nonlinear behavior of bracing members. The result obtained from modeling of a bracing system with the aid of the phenomenological model is compared with the result of a test to investigate the accuracy of the investigated model. Furthermore, static non-linear analyses are performed on an inverted V-braced subassembly using the phenomenological model as well as a convenient physical theory model. According to this study, the proposed phenomenological model is capable to favorably capture the behavior of a brace member under a cyclic loading. Hence, it can be used in analytical models of structural lateral bracing systems to assess accurately the nonlinear behavior of these systems.

Keywords: Phenomenological models, Physical theory models, Non-linear static analyses.

1 INTRODUCTION

The reliability of the performance assessment of braced frames crucially depends on the accuracy of the numerical modeling method utilized for bracing members. An appropriate modeling method for braces should be able to capture the full range of their nonlinear behavior including the yielding, buckling and post buckling behavior. Several experiments conducted to investigate the hysteretic response of small to moderate-scale steel braces (Liu and Goel 1988, Tremblay *et al.* 1995, Yang *and* Mahin 2005). Different numerical models also provided to represent the hysteretic behavior of these structural members captured during the tests. These models may be categorized into three main categories: (I) phenomenological models; (II) physical theory models; and (III) continuum finite element models. Capabilities of each approach besides its limitations distinguish it from the others.

Phenomenological models provide the simplest approach in order to capture the nonlinear behavior of braces. A set of empirical rules simply describe the shape of the hysteretic loops which govern the nonlinear behavior of the members in this modeling type. The computational expense of analyses is decreased by implementing phenomenological models which generally consist of a one-dimensional material with a specific hysteretic behavior.

A plasticity-based representation of the inelastic axial force-moment relationship is utilized to capture the nonlinear behavior of bracing members in physical theory models (Higginbotham 1973, Hassan and Goel 1991).

Using detailed finite element modeling is another way to represent the behavior of bracing members. The capability of providing a thorough model including compartments and connections of bracing members beside the appropriate accuracy distinguish this type of modeling from the other types (Field 2003). However, implementing exact finite element models is contingent with high computational expense in addition to complexity of providing input files.

A quasi-static test was conducted on an inverted-V braced subassembly under a cyclic displacement history and progressively increasing amplitude by Yang *et al.* (2009). In the following study, the investigated phenomenological model for bracing members is utilized in order to model the subassembly. The capability of the phenomenological model is proved with respect to the test result. A comparison is also carried out among the result obtained from non-linear analyses with the aid of the phenomenological model and a common physical theory model. The following sections reveal more details about both of these modeling methods and their results.

2 THE PHENOMENOLOGICAL MODEL

In the phenomenological modeling method which is discussed in this study, braces are modeled using truss elements with the hysteretic behavior presented by Leon and Yang (2003) which involves a three linear backbone. The primary source code of this material was developed by Yang (2006) which has been revised in this research in order to be implemented in OpenSEES. The 'BraceMaterial' uniaxial Material option is used to set up the relationship between the member's axial forces and deformation. Also, pinching factors (pinch X equal to 0.5 and pinch Y equal to 0.3) are assumed to model pinching of the deformation and the force, respectively, during reloading. A damage factor of 0.02 for damage due to the ductility is also selected. Figure 1 shows the typical hysteretic behavior of a brace which is modeled by this method.

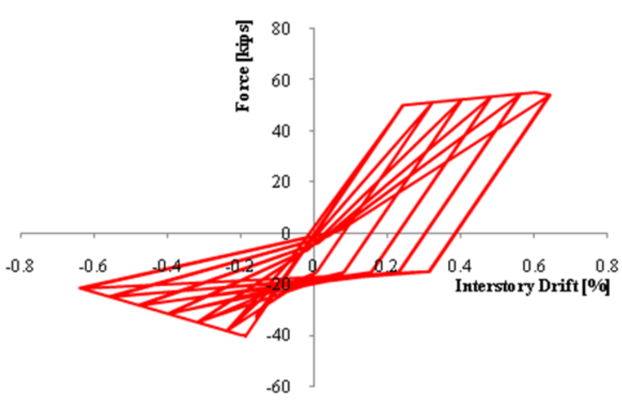

Figure 1. Hysteretic behavior of a typical bracing member modelled by using the Brace-Material.

3 THE PHYSICAL-THEORY MODEL

Recently, a physical theory model has been developed by Uriz and Mahin (2004) in which a brace consists of two parts with the same length and includes a small initial imperfection (L/1000) to simulate its post buckling behavior. Each part of the brace is modeled with the aid of a fiber-based nonlinear beam-column element. In order to obtain a more accurate simulation of the behavior of bracing members, the mentioned model was modified in two ways in next studies. First, different initial imperfection ratios were utilized to reach to a better estimation of compression strength of bracing members. Second, two rotational springs were added at the end nodes of the models of the bracing members under investigations to consider the effects of the stiffness of gusset plates. Among different researches, the amount of the imperfection and the stiffness of the rotational springs at the ends are considered equal to proposed values by Yang *et al*. (2009). These values are 0.01L for the imperfection and 5EI/L for the stiffness of the end springs. L, I and E represent the length of the bracing member and section moment of inertia of the brace and the Yang's modulus of elasticity, respectively.

4 VALIDATION OF THE PHENOMENOLOGICAL MODEL

An inverted-V braced subassembly was tested quasi-statically under a cyclic displacement history and progressively increasing amplitude by Yang *et al*. (2009). The main purpose of the test was to calibrate a physical-theory model for HSS steel braces considering out of plane buckling. The geometry of the tested specimen is shown in Figure 2. Figure 3 shows the displacement history used to perform the experiment by Yang *et al*. (2009).

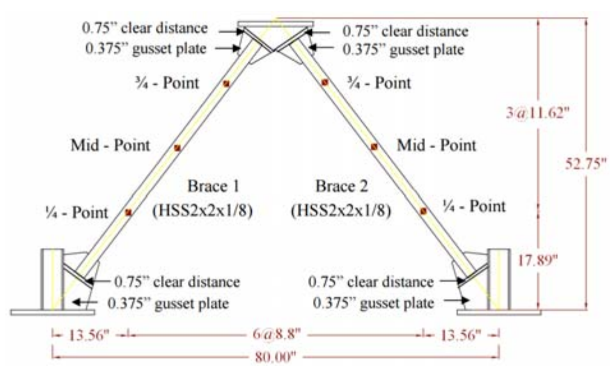

Figure 2. Dimensions and measurement points of the inverted V-braced subassembly (Yang *et al.* 2009).

The reported result of the test is used to prove the ability of the phenomenological model in comparison with the common physical theory model mentioned in the previous section. Two separated nonlinear model is provided to do so. The physical theory model used to model the braces in “Model (a)” and the inelastic behavior of the braces is captured with the aid of the phenomenological model in “Model (b)”.

The analytically simulated response of model (b) is presented in Figure 4. The comparison between different responses of the inverted-V braced subassembly obtained from using two aforementioned modeling methods as well the comparison between the responses of both models and the experimental result (Yang *et al*. 2009) is presented in Figure 5. In this figure, the axial deformation is normalized with respect to the original brace length (L = 66.2 in.) and the axial force is normalized with respect to the expected yield strength (Ag × Fye= 50.23 kips) of the brace.

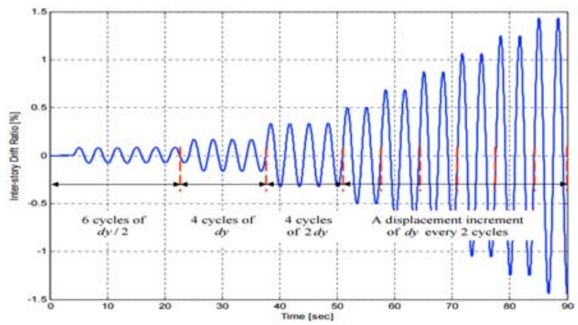

Figure 3. Displacement history used by Yang *et al.* in the quasi-static test (Yang *et al*. 2009).

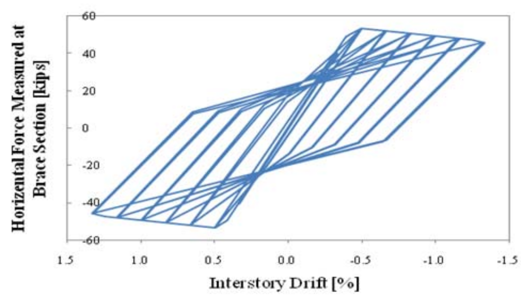

Figure 4. Force-deformation response of the inverted-V braced subassembly (model (b)).

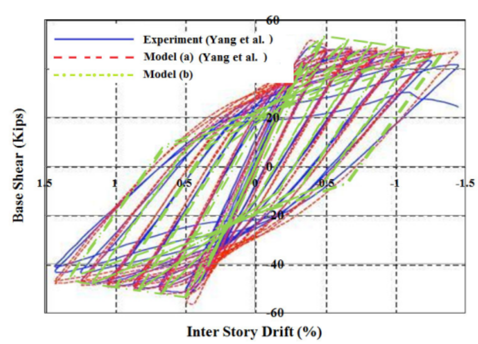

Figure 5. Comparison of force-deformation response of the inverted-V braced subassembly.

As it is obvious in Figure 4 and 5, modeling braces with the aid of “Brace-Material” could capture the buckling and post buckling behavior of them very well.
Nonlinear static analyses performed on both model (a) and model (b) reveals more about the ability of the phenomenological model in comparison with the physical theory model. Figure 6 illustrates the push-over curves of both models.

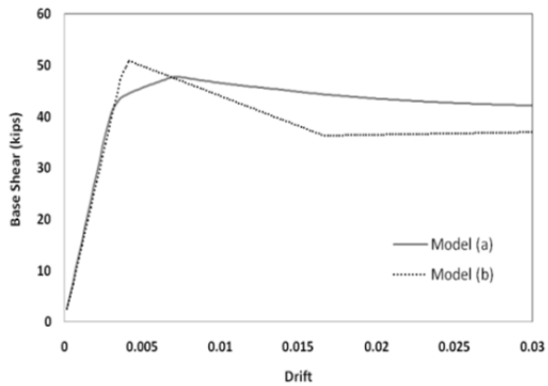

Figure 6. Push-over curve of model (a) and model (b) of inverted V-braced subassembly.

Figure 7 illustrates the force in the compression brace in both model (a) and Model (b) versus the drift of the subassembly. The buckling and the post buckling behavior of the compression brace captured by the phenomenological model in comparison with the physical theory model prove the ability of this modeling method. The drift in which the compression brace buckles is also assessed in model (b) very close to the one detected by model (a).

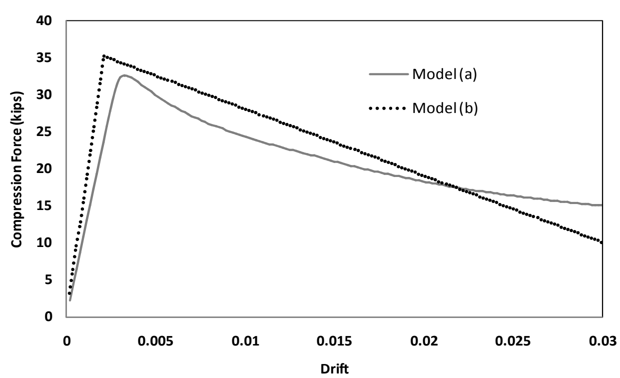

Figure 7. The force in the compression brace of model (a) and model (b) of inverted V-braced subassembly.

As it can be expected, the model (a) represents a more ductile non-linear behavior because of the large value of imperfection proposed by Yang *et al.* (2009).

Furthermore, the drop in the push-over curve of mode (b) is due to the strength drop implemented in the backbone curve of BraceMatrial.

5 RESULTS

The research reported herein focuses on investigating the capability of the phenomenological model to capture nonlinear behavior in bracing members in comparison with a convenient physical theory model and a performed quasi-static test. As stated in previous part, a good consistency between the results of the test and the results of the described models under a cyclic loading was observed. Moreover, Push-Over curves using both modeling methods were obtained similar. Hence, it can be inferred that the phenomenological model is capable to capture the behavior of braces very well. It is worthy to note, the simplicity in the modeling procedure and the decrease in the computational expense of the analyses caused by employing the investigated phenomenological model cannot be neglected besides the acceptable precise of the results of the analyses.

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