New Strength Degradation of Bouc-Wen Hysteresis Differential Model for Romanian Anti-Seismic Devices Used in Buildings Seism Protection Systems

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Abstract. In this paper is presented a new mathematical differential model used for simulating the hysteresis phenomenon of romanian seismic energy dissipating devices which are usefull in seismic protection of buildings suprastructure. Existing mathematical models do not provide adequate modeling of the behavior of these devices during seism. The new mathematical model proposed in this paper represents a modification of the Bouc-Wen differential mathematical model through a new Strength Degradation method that reduces the capacity of the Backbone curve of the hysteresis characteristic. This is done through a yield force whose expressions have been proposed by several authors, but the new expression of the yield force proposed in this paper ensures an adequate simulation of the seism behavior of the Romanian anti-seismic devices SERB C-194. The new expression of yield force depends on four variable parameters that amplify the versatility of this new mathematical model which can simulate a wide variety of hysteretic loops difficult to model with other mathematical models of hysteresis.

Keywords: Seismic energy dissipating device · Bouc-Wen model · Strength Degradation

1 Introduction

SERB C-194 romanian seismic dissipation devices [1] have an elastic component made by deforming a set of steel discs and a hysteretic component that occurs due to the phenomenon of dry friction that accompanies the relative movement between the discs. By combining the two mechanical phenomena this type of damper presents a loop of progressive nonlinear elastic hysteresis (Fig. 1).

Figure 1 presents a comparison between the hysteresis loop of romanian dampers obtained by experiment [2] and by using the classical hysteresis model Bouc-Wen. We can notice that this mathematical model does not accurately simulate the behavior of the device, especially at small displacements.

Due to the specific shape of the displacement-force hysteretic curve, these devices cannot be simulated in civil engineering-specific seism analysis programs.

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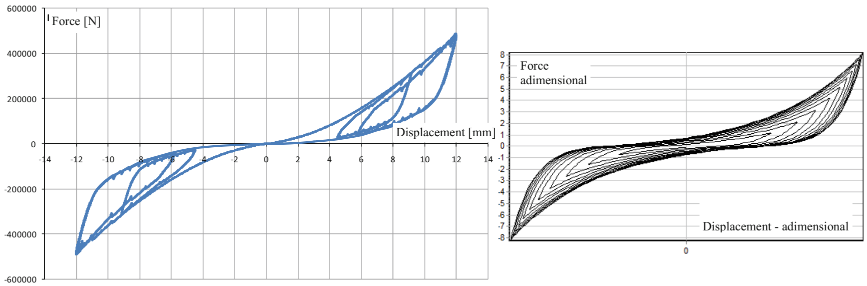


Fig. 1. Shape Comparison between Hysteresis loop experimental (left) and B-W model (right)

2 Strength Degradation of B-W Model of Hysteresis

Bouc-Wen model consider the hysteretic rigidity K_h as [3]:

$$K_h = (1-\alpha) \cdot K_0 \cdot \left(1 - (\gamma \cdot \operatorname{sgn}(z \cdot \dot{\xi}) + \beta) \cdot \left|\frac{z}{F_y^*}\right|^N\right) \tag{1}$$

where:

K_0 – total initial stiffness; α – ratio of stiffness to initial stiffness;
N – exponent for the transition between elastic and elasto-plastic domain;
β and γ – shape parameter of the hysteretic loop; z – inside damper force;
${F_y}^*$ – yield force proposed by Wang [4] is:

$$F_y^* = (1-\alpha) \cdot \left[\left(\frac{1+\operatorname{sgn}(z)}{2}\right) \cdot F_y^+ + \left(\frac{1-\operatorname{sgn}(z)}{2}\right) \cdot F_y^-\right] \tag{2}$$

Rules for correcting the classical Bouc-Wen model in terms of strength degradation were made by Sivaselvan [3] and Mostaghel [5]. According to these studies, in these improvements of the theoretical Bouc-Wen model the strebgth degradation is modeled by reducing the capacity of the backbone curve specific to that hysteresis. This is equivalent to specifying a law of variation for the yield force F_y. Sivaselvan proposed the following formula for changing the yield force F_y [3]:

$$F_y^{+/-} = F_{y0}^{+/-} \cdot \left(1 - \left(\frac{\xi_{\max}^{+/-}}{\xi_{cap}^{+/-}}\right)^{1/\beta_1}\right) \cdot \left(1 - \frac{\beta_2}{1-\beta_2} \cdot \frac{H}{H_{cap}}\right) \tag{3}$$

where: ${F_{y0}}^{+/-}$ - initial yield force on the positive or negative branch of the loop;
$\xi_{\max}$– the displacement corresponding to the current cycle maximum amplitude;
ξ_{cap} - the maximum displacement of the damper;
H – dissipated hysteretic energy;
H_{cap} – hysteretic energy dissipated in the cycle with maximum displacement;
β_1 – parameter of strength degradation due to ductility;
β_2 - parameter of strength degradation due to energy dissipation.

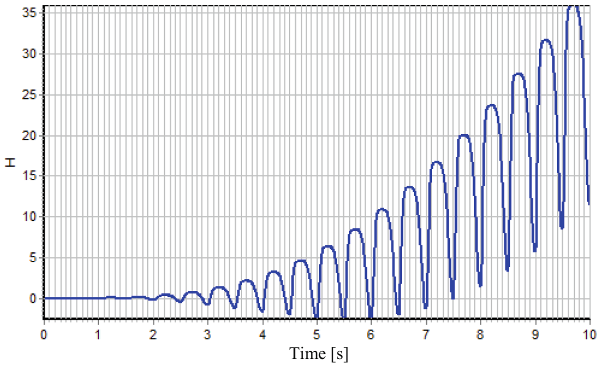


Fig. 2. Variation of energy *H* over time

The relation for H determined by Sivaselvan is [3]:

$$\dot{H} = z \cdot \dot{\xi} \cdot \left(1 - \frac{K_{el} + R_k \cdot K_h}{R_k \cdot K_0}\right) \tag{4}$$

where: z - hysteretic force;

$\dot{\xi}$ – speed;

K_{el} - elastic stiffness of the elastic component of the damper;

R_k – Stiffness relaxation factor;

K_h – hysteretic rigidity.

Implementing this modification to the classic Bouc-Wen model in the *HistPlot* software application made by the authors, we noticed the limitations of this method proposed by Sivaselvan in the case of hysteretic loops with progressive nonlinear characteristic specific to C-194 SERB dampers.

In the case of hysteretic loops with progressive nonlinear elastic characteristic specific to SERB C-194 dampers, the variation of hysteretic energy H, calculated by equation (Fig. 2) proposed by Sivaselvan is in some cases negative, which indicates the impossibility of applying this method of adapting the Bouc- Wen classic, in simulating the behavior of SERB seismic energy dissipating device.

In order to apply the method of improving the classic Bouc-Wen model in terms of Strength degradation, for the most accurate modeling of the hysteresis loop of SERB devices, we proposed another equation that takes into account the phenomenon of loss of resistance only due to the increase in the amplitude of the displacement.

Although Sivaselvan [3] proposes as an equation that models the strength degradation, the relationship:

$$F_y^{+/-} = F_{y0}^{+/-} \cdot \left(1 - \left(\frac{\xi_{\max}^{+/-}}{\xi_{cap}^{+/-}}\right)^{1/\beta_1}\right) \tag{5}$$

This does not allow a sufficient modification of the hysteretic force to ensure the correct modeling of the real hysteretic loop of the romanian dampers, which resulted from the checks we performed. Therefore, in this paper we proposed a new mathematical relation for Fy's calculation, which was deduced by comparing the geometry of the real hysteresis loop with that obtained with the classical differential mathematical B-W model.

We observed the following specific characteristics of modeling the SERB C-194 damper loops using the classic B-W model:

- at low amplitudes (up to 10% of maximum displacement) the classic model offers hysteresis force values up to four times lower than the real values;
- at medium amplitudes (between 40% and 60% of maximum displacement) with the classic model we obtain hysteretic force values of 1.4 to 1.8 times lower than the real values;
- at high amplitudes (between 90% and 100% of maximum displacement) with the classic model we obtain values of hysteretic force very close to the real values;
- the strength degradation factor in the case of romanian dampers should decrease from 4 to 1 as the amplitude of the displacement increases.

Analyzing these conclusions resulting from the comparison between the two types of hysteresis loops, we considered it necessary to find an adaptation factor of the classic Bouc-Wen model, whose mathematical relationship depends on the amplitude of the displacement and decreases from the value 4 to the value 1, nonlinear, as the amplitude of the displacement increases.

The new relationship we have proposed for the adaptation of the classic Bouc-Wen model for reasons of strength degradation, for the successful modeling of the SERB devices, is:

$$F_y^{+/-} = F_{y0}^{+/-} \cdot \left(\frac{\beta_1}{1 + \left(\frac{|\xi_{\max}|}{\xi_{cap}} \right)^{\beta_2}} - \left(\frac{|\xi_{\max}|}{\xi_{cap}} \right)^{\beta_3} \right)^{\beta_4} \tag{6}$$

where:

$\xi_{\max}$ – the most recent amplitude of the displacement at which the speed changes its sign;

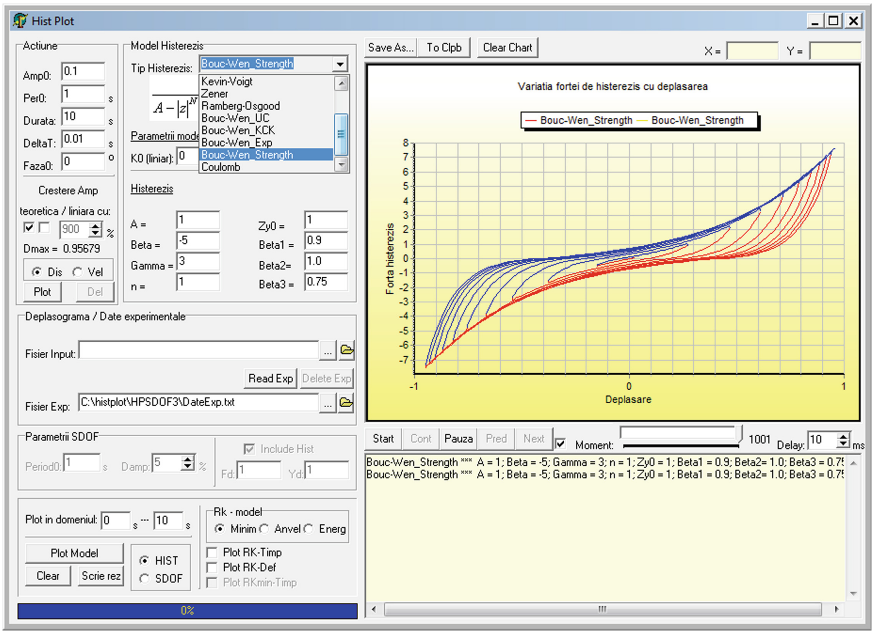
ξ_{cap} – the maximum displacement of the damper;

$\beta_1, \beta_2, \beta_3, \beta_4$ – variable parameters depending on the shape and size of the hysteresis loop.

This results, in a modified Bouc-Wen model that we implemented in the *HistPlot* application, made by the authors, named Bouc-Wen_Strength.

We implemented this adaptation factor in the *HistPlot* software application and the correct results were obtained for the hysteresis loops modeled with the Bouc-Wen model adapted to the proposed mathematical relation, for any variation of the displacement that presents symmetrical amplitudes of the hysteretic force.

In Fig. 3 is presented, using HistPlot software, the hysteresis loop we obtained with the adapted Bouc-Wen_Strength model that adequately models the real behavior of the romanian dampers.



Amp0: 0.1
Per0: 1 s
Durata: 10 s
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K0 (liniar): 0
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Dmax = 0.95679
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A = 1
Beta = -5
Gamma = 3
n = 1
Zy0 = 1
Beta1 = 0.9
Beta2= 1.0
Beta3 = 0.75
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Fisier Exp: C:\histplot\HPSDOF3\DateExp.txt
Period0: 1 s
Damp: 5 %
☑ Include Hist
Fd: 1
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Plot in domeniul: 0 s ··· 10 s
● Minim ○ Anvel ○ Energ
● HIST ○ SDOF
☐ Plot RK-Timp
☐ Plot RK-Def
☐ Plot RKmin-Timp
☑ Moment: 1001
Delay: 10 ms

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Bouc-Wen_Strength ***  A = 1; Beta = -5; Gamma = 3; n = 1; Zy0 = 1; Beta1 = 0.9; Beta2= 1.0; Beta3 = 0.7
Bouc-Wen_Strength ***  A = 1; Beta = -5; Gamma = 3; n = 1; Zy0 = 1; Beta1 = 0.9; Beta2= 1.0; Beta3 = 0.7
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Fig. 3. HistPlot application, the hysteretic loop obtained with the Bouc-Wen_Strength model when modeling SERB seismic energy dissipating device.

The adaptation factor, proposed in this paper, for obtaining the Bouc-Wen_Strength model, depends on four parameters whose values influence the correction of the hysteretic forces offered by the classic Bouc-Wen model, resulting in increased ways of adapting the mathematical model for simulation of different hysteretic loops shapes.

3 Conclusions

This new Bouc-Wen model, which is specifically designed for simulation of the behavior of ȘERB supra-structure dampersrs, has the following advantages:

- adequately models the hysteretic loop of the C-194 SERB devices;
- has the same versatility as the classic Bouc-Wen model but also has the ability to correct the strength (Strength degradation);
- it is easy to implement computationally because it consists only in multiplying $F_y{}^{+/-}$ with a new term;
- applies to variations of relative level displacement with relatively equal successive amplitudes, an element very common in theoretical and computational studies. Amplitudes may increase or decrease, but the difference between two successive amplitudes must be small enough because they directly influence the correctness of the modeling of the real hysteretic loop;
- has four shape parameters that allow an easy adaptation of the resulting hysteretic loop to the particular data of the modeled damper.

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