Software Application for Stiffness Relaxation New Method of Bouc-Wen Hysteresis Differential Model Used in Simulation of Romanian Friction Dampers

Mihai Negru(✉) and Adriana Ionescu

Faculty of Mechanics, University of Craiova, Calea Bucuresti 107, Craiova, Romania
`mihai.negru@edu.ucv.ro`

Abstract. This paper presents a new Stiffness Relaxation method of the classic Bouc-Wen hysteresis model, used to simulate the hysteresis loop of Romanian friction dampers SERB-C-194 in seismic analysis of buildings equipped with this type of seismic dampers. The classic model does not accurately simulate the hysteresis loop of friction dampers because it keeps constant the stiffness of the damper as its stroke increases. Friction dampers are devices that strengthen the stiffness as the damper stroke increases. The proposed new method aims to simulate a stiffer damper but which is affected by the phenomenon of Stiffness Relaxation. Such methods have been proposed by Sivaselvan and Rheinhorn [1, 2] which have introduced a Stiffness Relaxation factor R_k which only works for the situations of continuous increase of the damper stroke. Our method offers a way to solve this problem by an "envelope" of the damper displacements. In this case the hysteresis loops of the new model are in accordance with the real situation observable in the hysteresis loops obtained experimentally. The new differential hysteresis model was implemented in the HistPlot program developed by the authors and is useful in determining the parameters of the differential model for simulating experimental hysteresis loops. This improved model is further used for earthquake dynamic simulation of buildings equipped with anti-seismic dampers using the GenEcAm program developed by the authors.

Keywords: Friction Damper · Hysteresis model · Stiffness Relaxation

1 Introduction

The SERB C-194 friction damping device [1], as seen in the hysteretic loops obtained experimentally (Fig. 1) are systems that increase their rigidity as the amplitude of the displacement increases due to the elastic behavior of the spring steel discs that are part of the damper.

The classic Bouc-Wen model is a model that models hysteretic loops with constant stiffness [2]. Therefore, for the modeling of damping devices with stiffening reinforcement it is necessary to adapt the classic Bouc-Wen model.

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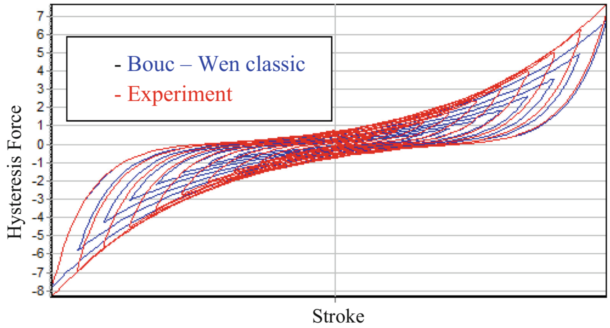


Fig. 1. Friction damper Hysteretic loop shape (adimensional)

In order to model the real behavior of the romanian friction dampers, it is therefore necessary to model a hysteretic loop in which the rigidity at low amplitudes is higher than that offered by the classic Bouc-Wen model and decreases as the amplitude of the displacement increases so that at maximum amplitude, the hysteretic force obtained with the classic Bouc-Wen model coincides with the force obtained with the adapted Bouc-Wen model. Basically, a stronger damper must be modeled and this has to be affected by the phenomenon of stiffness relaxation.

2 The Adaptation of B-W Model by Stiffness Relaxation

The adaptation of the Bouc-Wen model for stiffness relaxation was first proposed by Sivaselvan and Reinhorn [3] in 2001. Thus, they propose the following form for the expression of hysteretic rigidity K_h:

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

where:

K_0 – total initial stiffness;

α – the ratio of stiffness to initial stiffness;

N – exponent that controls the transition of elastic domain to the elasto-plastic domain;

β and γ – parameters that control the shape of the hysteretic loop;

z – axial force in the damper;

$F_y{}^*$ – creep force calculated as proposed by Wang and Foliente in 2001 [4]:

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

According to this rule, the unloading branch of the hysteretic loop is supposed to go to a point called the pivot located on the initial elastic branch at a distance $\alpha \cdot F_y$ located on the opposite side of the decreasing branch where α is the relaxation parameter [3].

According to Sivaselvan's studies, the stiffness relaxation phenomenon of the classic Bouc-Wen model is controlled by a stiffness relaxation factor R_k given by the formula [5]:

$$R_k = \frac{F_c + \alpha_1 \cdot F_y}{K_0 \cdot d_c + \alpha_1 \cdot F_y} \tag{3}$$

where:K_0 – total initial stiffness;

F_c – force;

d_c – displacement;

$F_y = {F_y}^+$ or ${F_y}^-$ depending on the part where the coordinate point is located (d_c, F_c) with respect to the initial elastic branch defined by the slope K_0;

α_1 – stiffness relaxation parameter.

Introducing R_k into the formula for hysteretic stiffness results in [5]:

$$K_h = (R_k - \alpha) \cdot K_0 \cdot (1 - (\gamma \cdot \operatorname{sgn}(z \cdot (\dot{\xi}) + \beta) \cdot \left|\frac{z}{F_y^*}\right|^N) \tag{4}$$

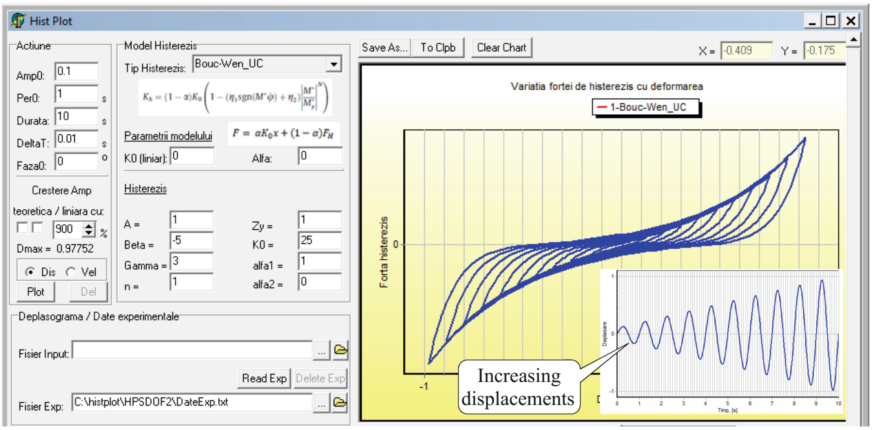
Wang and Foliente in 2001 [4] proposed, for the further improvement of the stiffness relaxation adaptation, the use of the d_{max} value instead of the d_c value, d_{max} corresponding to the maximum value of the displacement in a cycle or the weighted average between d_{max} and d_c. In this case, the minimum value can be used for R_k. Charalampakis in 2013 [6] proposes to optimize the value of R_k by minimize its value. Thus, if ${R_k}^{trial}$ is the value obtained with the equation of R_k, the minimum value of R_k calculated in each step is [6]:

$$R_k^{\min} = \min\left\{R_k^{\min}, R_k^{trial}\right\} \tag{5}$$

Thus, the value of the R_k parameter is an interpolated value between ${R_k}^{min}$ and ${R_k}^{trial}$.

In the study of this improvement of the classic Bouc-Wen model for rigidity reasons, we noticed that the method proposed by Sivaselvan and later improved by Wang, is useful for hysteresis loops with progressive nonlinear characteristic specific to SERB C-194 dampers, only in conditions which the amplitude of the displacements is increasing over time (Fig. 2), in which case ${R_k}^{min}$ has a correct variation throughout the period of damper excitation. Otherwise, the results obtained are identical to those unsuitable, obtained with the classic Bouc-Wen model. These conclusions are exemplified in Fig. 2 and Fig. 3 using HistPlot software made by the authors, where Bouc_Wen_UC is the adapted B-W model by stiffness relaxation.

The methods that we have proposed in this paper, which provides correct results of the application of the proposed improvements in other cases than those mentioned, is the approximation of an "Envelope" for the minimum values of the variation curve of the stiffness relaxation factor ${R_k}^{trial}$. This "Envelope" of the minimum values is easy to determine for a very wide range of variation of the relative level displacements and therefore of the displacements in the dampers. This fact is useful only if the variation of the relative level displacements in time is known in advance, which is perfectly possible in quite a number of situations encountered in the theoretical, experimental or numerical study to perform comparative studies of the results obtained.



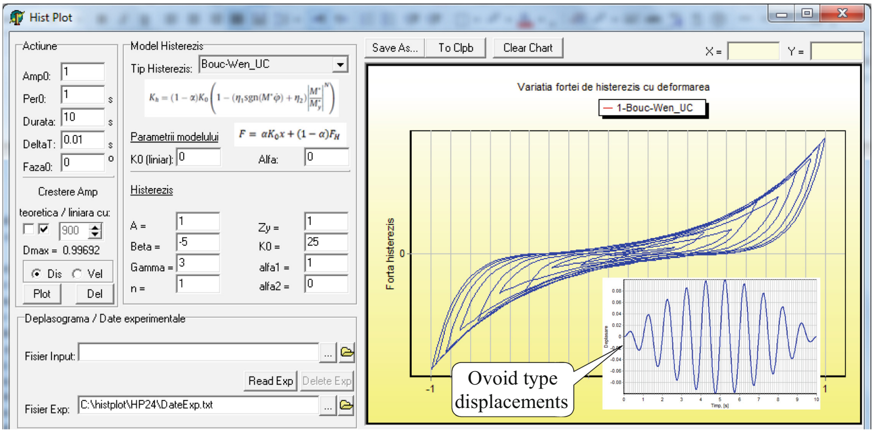
Amp0: 0.1
Per0: 1 s
Durata: 10 s
DeltaT: 0.01 s
Faza0: 0 o
Crestere Amp teoretica / liniara cu: ☐ ☐ 900 %
Dmax = 0.97752
● Dis ○ Vel
Tip Histerezis: Bouc-Wen_UC

$K_h = (1-\alpha)K_0\left(1-(\eta_1 \operatorname{sgn}(M^*\dot{\varphi})+\eta_2)\left|\frac{M^*}{M_y^*}\right|^N\right)$

$F = \alpha K_0 x + (1-\alpha)F_H$

K0 (liniar): 0
Alfa: 0
A = 1
Beta = -5
Gamma = 3
n = 1
Zy = 1
K0 = 25
alfa1 = 1
alfa2 = 0
Fisier Input:
Fisier Exp: C:\histplot\HPSDOF2\DateExp.txt
X = -0.409
Y = -0.175

Fig. 2. Suitable simulation of Friction damper hysteresis loop using Bouc_Wen_UC model



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Durata: 10 s
DeltaT: 0.01 s
Faza0: 0 o
Crestere Amp teoretica / liniara cu: ☐ ☑ 900 %
Dmax = 0.99692
● Dis ○ Vel
Tip Histerezis: Bouc-Wen_UC

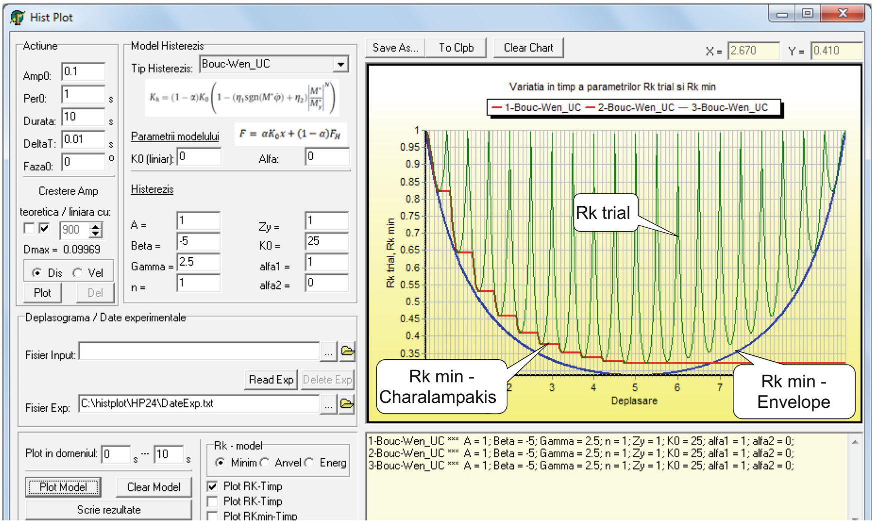
$K_h = (1-\alpha)K_0\left(1-(\eta_1 \operatorname{sgn}(M^*\dot{\varphi})+\eta_2)\left|\frac{M^*}{M_y^*}\right|^N\right)$

$F = \alpha K_0 x + (1-\alpha)F_H$

K0 (liniar): 0
Alfa: 0
A = 1
Beta = -5
Gamma = 3
n = 1
Zy = 1
K0 = 25
alfa1 = 1
alfa2 = 0
Fisier Input:
Fisier Exp: C:\histplot\HP24\DateExp.txt
X =
Y =

Fig. 3. Unsuitable simulation of Friction damper hysteresis loop using Bouc_Wen_UC model

Figure 4 and Fig. 5 show the results we obtained by approximating the minimum values of the R_k^{trial} curve when the variation curve of the relative level displacement is increasing in the first half of the excitation period and decreasing in the second half. The results we obtained with this method, which improves the method proposed by Sivaselvan, Wang and Charalampakis, are presented for an ovoid sinusoidal variation whose amplitude increases from 0 to a maximum value after which it decreases again to 0.



Amp0: 0.1
Per0: 1 s
Durata: 10 s
DeltaT: 0.01 s
Faza0: 0 o
Crestere Amp teoretica / liniara cu: ☐ ☑ 900
Dmax = 0.09969
● Dis ○ Vel
Tip Histerezis: Bouc-Wen_UC

$$K_h = (1-\alpha)K_0\left(1 - (\eta_1 \operatorname{sgn}(M^*\dot{\varphi}) + \eta_2)\left|\frac{M^*}{M_y^*}\right|^N\right)$$

$$F = \alpha K_0 x + (1-\alpha) F_H$$

K0 (liniar): 0
Alfa: 0
A = 1
Beta = -5
Gamma = 2.5
n = 1
Zy = 1
K0 = 25
alfa1 = 1
alfa2 = 0
Fisier Input:
Fisier Exp: C:\histplot\HP24\DateExp.txt
Plot in domeniul: 0 s --- 10 s
Rk - model: ● Minim ○ Anvel ○ Energ
☑ Plot RK-Timp
☐ Plot RK-Timp
☐ Plot RKmin-Timp
X = 2.670
Y = 0.410

```
1-Bouc-Wen_UC ***  A = 1; Beta = -5; Gamma = 2.5; n = 1; Zy = 1; K0 = 25; alfa1 = 1; alfa2 = 0;
2-Bouc-Wen_UC ***  A = 1; Beta = -5; Gamma = 2.5; n = 1; Zy = 1; K0 = 25; alfa1 = 1; alfa2 = 0;
3-Bouc-Wen_UC ***  A = 1; Beta = -5; Gamma = 2.5; n = 1; Zy = 1; K0 = 25; alfa1 = 1; alfa2 = 0;
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Fig. 4. HistPlot – $R_k{}^{trial}$, $R_{k\ min}$ for Bouc_Wen_Uc model (ovoid type displacements)

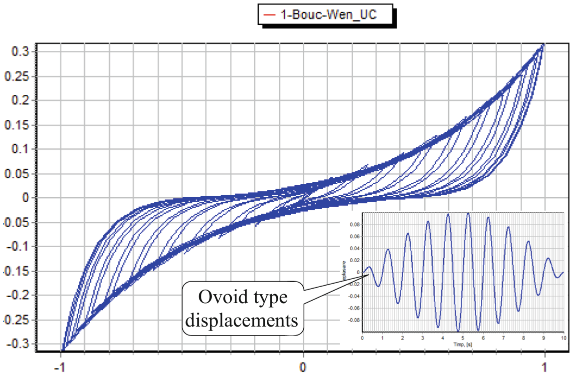

Fig. 5. HistPlot – Hysteretic loop (adimensional) of Bouc_Wen_UC model with “Envelope” option for ovoid type displacements

3 Conclusions

This new adaptation, which we have proposed, solves to a certain extent the limitations of the method proposed by Sivaselvan, extending the scope to other types of variation of the amplitude of the relative level displacement for which the $R_k{}^{min}$ curve can be approximated.

We named this new adaptation of the Bouc-Wen model, the Bouc-Wen_UC model, and it allows an analytical and computational modeling with a higher degree of adequacy of the SERB friction dampers. For fitting the experimental hysteresis loop of friction dampers, the parameters of this new model can be determined using the *HistPlot* application.

This new differential hysteresis model was implemented in GenEcAm software, made by the authors, in order to be used for dynamic seism simulation of the buildings equipped with these types of dampers.

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