1. Abstract

Buckling Restrained Braces (BRB) are hysteretic steel dampers with high energy dissipating capacity. The nonlinear response of the inner component of the brace is covered by the buckling restraining mechanisms, so it is not possible to visually inspect the level of damaged of the element after large earthquakes. A possible procedure to overcome this difficulty is to record and evaluate the nonlinear response of the system under strong shaking. In this paper a preliminary evaluation of typical system identification techniques for linear time invariant system are applied to evaluate its performance when apply to the response of a nonlinear system that exhibits the hysteresis of a buckling restrained braced structure. The degree of nonlinearity is modified to evaluate the applicability of the methods in nonlinear systems. The results of two procedures are presented here, the non-parametric identification based on Power Spectral Density functions and the parametric identification based on Stochastics Substructure Identification with its covariance approach. Despite the obvious contradiction of using a linear identification technique on nonlinear response, this has been applied in several studies as a way to estimate the basic equivalent linear properties of the systems. The initial conclusion of this paper is that the observed results of these methods do not provide the equivalent system response. Both methods give similar results indicating that the predominant system period is close to the initial linear conditions and not to the secant one, measured at the maximum deformation point of the hysteresis. On the contrary the identified damping ratio, increases when the nonlinearity does.

2. Introduction

Buckling Restrained Braces (BRB) are starting to be used as an efficient hysteretic damper in seismic areas. They consist of a steel core brace that resist axial loads and an outer casing filled with concrete that restrains the buckling of the brace. The final response of the elements is a stable hysteresis loop with high energy dissipating capacity. Because the buckling restraining mechanism hides the core brace component, it is not possible to visually inspect the level of damaged that has occurred in the component after a large earthquake. In this article an analysis is performed on a single degree of freedom system to try to do identify the effect of different system identification techniques on the nonlinear response of a representative model of a buckling restrained structure.

This article is part of a research on system identification techniques applicable to detect the nonlinear response of structures with buckling restrain braces.

As an initial test two typical system identification techniques are used to evaluate its results when applied to nonlinear response of a single degree of system that exhibits the hysteresis of a buckling restrained braced system.

3. The Model

The nonlinear response is modeled using the Bouc Wen model (Wen, 1976) adjusted for represent smooth bilinear response (Black, Markis and Aiken, 2004). The hysteresis is modified for different elastic vibration periods (0.5 and 2.0 seconds, defined as $T$), post stiffness values (0, 0.2 and 0.5 of the elastic stiffness, $K_{post}$) and yield level (Reduction values, $R$, of 2, 5 and 10 of the elastic response). Damping values in all cases is 2% critical viscous damping ratio considering the initial stiffness. Figure 1 presents the typical hysteresis obtained.
4. The Identification Procedures

In this article only linear based system identification techniques are used. This is a standard procedure in analysis where the nonlinear response of the system is windowed and inside the window a linear response is assume. The objective of the article is to present the results obtained from this procedure.

The excitation is Gaussian White Noise (wgn) applied at the base of the model. Displacement \( (d) \), acceleration \( (a) \) and restoring force \( (Q) \), are captured from the response of each system. The identification is made over the acceleration data.

For the Gaussian noise excitation the identification is done using the non-parametric peak picking technique (Bendat and Piersol, 1986) and the parametric technics Stochastics Subspace Identification (Van Overschee, 1994).

4.1 Peak Peaking Technique

Peak Picking from Power Spectral Density (PSD) identification is performed on a nonlinear single degree of freedom system. The PSD is estimated using the Welch Method. Window length \( (Vh) \) of 30, 45, 60 and 90 second are used. The selected peak is associated with the predominant frequency and the equivalent stiffness of the system.

4.2 SSI-COV Technique

SSI-COV identification is performed on a nonlinear single degree of freedom system. A stabilization diagram is performed for order 2 to 100, and the automatic technique (Boroschek and Bilbao, 2015), which choose the stable modes of the system, is carried out. The modes are chosen and their respective identified stiffness \( (K_{id}) \) is plotted over hysteresis and compared with the initial stiffness \( (K_{el}) \).

5 Response Cases

The identified variables for both methods for changing yield level, post yielding stiffness, period and stiffness nonlinear transition are evaluated. Figures 2 to 8 presents some of the responses obtained.

5.1 Variation of Yield Level

The first variation is the modification of the yield force. For this the reduction factor, \( R \), is modified with, \( R = 0.5, 5 \) and \( 10 \). The linear and \( R=10 \) is presented in Figures 2 and 3. The identified stiffness with both methods and in all the cases is similar to the initial one. The form of the PSD spectrum shape exhibits changes as the system goes into nonlinear range, showing more local maxima and a wider bandwidth.
From SSI-COV results, the increase in the incursion in the nonlinear range reduces the equivalent stiffness (85% of initial one) and increasing the equivalent damping ratio with the increase on nonlinearity of the system, reaching 20% ratio above the original 2% when $R$ is 10. This result is presented in Figure 4.

Figure 2: Linear system response to wgn. Hysteresis and Identified stiffness. Psd spectrum.

Figure 3. $R=10$ system response to wgn. Hysteresis and Identified stiffness. Psd spectrum.
5.2 Variation of Post Yield Stiffness

The increases in $K_{post}$ and small incursion in nonlinear range ($R=2$) does not modify significantly the linear PSD showing a stable peak around the elastic frequency. However, when this incursion is larger ($R=8$), the obtained stiffness is lower than the initial one, figure 5. When the incursion in the nonlinear range is large, $R=8$, a decrease in the equivalent stiffness is visible reaching approximately 90% of its initial value, however, this is due to $R$, and $K_{post}$ has only a small impact. On the other hand, a light decrease in the identified damping ratio is observed, changing from ~15% when no $K_{post}$ is zero to ~11% when $K_{post}$ is 0.5.

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Figure 4 $R=10$ system response to wgn. Hysteresis and Identified stiffness. SSI-COV.
5.3 Transition between Elastic and Inelastic Response

When the transitions to the yielding phase is smoother, $n$ values decrease in the Bouc-Wen model, the equivalent stiffness tends to decrease, starting from the initial stiffness identified in systems with $n = 20$, to approximately an equivalent stiffness that is 85% of the initial one, when $n = 0.8$, Figures 6 and 7. The influence of post yielding stiffness parameter is not as strong for the level evaluated.

Figure 6. Response to varying transitions, $n=0.8$. PSD Method

Figure 7. Response to varying transitions, $n=0.8$. SSI-COV
For systems with high Reduction Factor, (\( R=8 \)) the equivalent stiffness can go from 88% of the elastic stiffness, in systems with sharpness transition (\( n=20 \)), up to approximately 70% in systems with very smooth transitions (\( n=0.8 \)), and; the equivalent damping varies from approx. 15% to approx. 22%. Figure 8 shows a system with high ductility and smooth transition. Again, post yielding stiffness ratio makes a little decrease in the identified damping ratio under this conditions.

**Figure 8**

5.4 Single Pulse and Gaussian Noise Excitation

In this case a pulse is applied over the acceleration Gaussian noise, in order to produce one large yield displacement in the middle of linear and elastic oscillation. Three pulses were used, applied at the 10%, 50%, and 90% of the total time of data. Figure 12 show them.

**Figure 9. Displacement response record including a pulse**
PSD spectrum of is plotted in Figure 10. All of them show the same behavior resulting in the initial period. This result implies that a single incursion in nonlinear range does not changes the equivalent stiffness of the system, and a limited number of incursion would not change this result significantly either. On the other hand, when the degradation of stiffness starts before the system reach the yield force, as happened when \( n = 1 \), and many cycles of the hysteresis are wider and rounded, the equivalent stiffness decrease, as is visible in Figure 11.

![Figure 10. Nonlinear response two Gaussian noise with an added single pulse. High elastic to inelastic transition value (n=15).](image)

![Figure 11. Nonlinear response two Gaussian noise with an added single pulse. Low elastic to inelastic transition value (n=1).](image)

7. Conclusion

Linear identification technique was applied to a nonlinear system subject to a White Gaussian Noise ground motion. The equivalent stiffness that resulted from these analyses is closest to the initial stiffness than to the equivalent linear model secant values derived from the maximum deformation point of the hysteresis. On the contrary the identified damping ratio, increases when the nonlinearity does.

Large nonlinearities in these systems produce PSD spectrum with a clear maxima amplitude and large bandwidth. SSI-COV identified similar periods and damping ratios that increase with the level of nonlinear response.

The use of this identification methods in nonlinear systems has to be used with care in order to properly evaluate the response of structures with the model used in this part of the research.
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