INFLUENCE OF HYSTERESIS MODELS ON CALCULATED SEISMIC RESPONSE OF R/C FRAMES

by

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SUMMARY

The nonlinear response of a small-scale ten-story test structure is calculated using four different hysteresis models, two of which are introduced in this paper. The calculated responses are compared with the experimental results, and the performance of each hysteresis model is evaluated. It is shown that the overall nonlinear response was calculated satisfactorily using a simple hysteresis model.

INTRODUCTION

Development of solution techniques for nonlinear dynamic response of structures has been an important step towards establishing a more realistic modeling method. Initially, the satisfaction in upgrading the conventional elastic methods to complicated inelastic solutions was to the extent that many related problems did not get the necessary attention. One of these problems has been the hysteretic behavior of structural elements during an earthquake. In earlier works, an elasto-plastic (simple bilinear) model was used for both steel and reinforced concrete structures.

The results of several experiments on reinforced concrete connections has revealed that the behavior of a reinforced concrete member subjected to cyclic loading is too complicated to be represented by an elasto-plastic model. Several more sophisticated hysteresis models have been developed with closer agreement with experimental results [1,7].

The purpose of the work presented in this paper was to study the effects of using different hysteresis models in seismic analysis of reinforced concrete structures, and, by comparing the calculated results with the observed response of a test structure, to determine the sensitivity of the response to the assumptions made in developing hysteresis models. The experimental results obtained from dynamic testing of a ten-story small-scale structure tested at the University of Illinois provided the basis for comparison.

HYSTERESIS MODELS

Four hysteresis models were included in the study. Two of the models were developed and used by other investigators (the Takeda model and simple bilinear). These models represent two extremes: the Takeda model is relatively realistic (in relation to experimental results) but complicated, whereas the simple bilinear system is simple but does not compare well with measured results from static tests.

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Two new hysteresis models were developed. The first one, called the Sina Model, uses the rules of Takeda model for the first quarter of loading. In subsequent quarters, pinching effects (extremely small incremental stiffness near the deformation axis) are taken into account. The second model was developed aiming at a simple model, comparable to the simple bilinear model, while it compared more closely with experimental results.

Takeda Model. This model was developed based on results from several experiments on reinforced concrete connections [7]. Figure 1-a shows the primary force-deformation curve for a reinforced concrete section with equal tensile and compressive reinforcement, and some of the rules of Takeda model. This model assumes that the member is initially uncracked.

Among the more important characteristics of Takeda model is that it recognizes the fact that stiffness at each stage is a function of the maximum deformation experienced. In relation to observed behavior, Takeda model does not include pinching effects often seen in static testing of interior beam-to-column reinforced concrete connections. Nevertheless, the model has been successful in matching large-amplitude dynamic responses obtained from testing of model structures [7].

The Takeda model is described by sixteen rules, each defining the regime of the changes in stiffness upon a loading, unloading, or load-reversal stage. Many of the rules are concerned with small-amplitude cycles, resulting in complication of the model. References 4 and 7 provide the complete information on the Takeda Model.

Simple Bilinear. This model ignores the cracking of concrete and operates on a bilinear primary curve (Fig. 1-b). Upon unloading from a point beyond the "yield" point on the primary curve, the stiffness is assumed to be equal to the initial stiffness. When the force changes sign (at the intersection of the unloading curve with the deformation axis), no change in stiffness is considered. This is a notable disagreement with experimental results for reinforced concrete connections which usually exhibit a reduction in stiffness when the load is reversed.

The general characteristics of the simple bilinear hysteresis model are that relatively large energy dissipation is considered for large-amplitude responses while no hysteretic energy dissipation is taken into account for small amplitudes.

Despite its substantial differences with experimental results, the simple bilinear model has been used extensively for both steel and reinforced concrete structures because of its simplicity. This model comprises only three rules.

Sina Model. The inclusion of pinching effects was the primary objective of developing the Sina model. Attempts were made to keep the model simple while simulating the static experimental results. In this line, no special rules other than those related to pinching were considered for small-amplitude loops. The resulting hysteresis model (Fig. 1-c) is defined by nine rules as compared to the sixteen rules used in the Takeda model. The first four rules of the two models are the same.

The rules of Sina model are presented in Reference 5. The moment at the point where the crack is closed (point B in Fig. 1-c), is predefined and is assumed to remain unchanged through subsequent cycles. However, the deformation attained increases. The model is versatile in that respect that the extent to which the pinching effects are considered can be changed by assigning different values to M_B. Nevertheless, making decision about the location of B is an extra task which may complicate the problem.

Q-Hyst Model. This model is similar to the simple bilinear model, modified by softening the unloading and load reversal branches (Fig. 1-d). The model ignores cracking of concrete and is described by only four rules which are presented in Reference 5.

The stiffness of an unloading branch from the post-yielding part of the primary curve is the same with that considered by Takeda [7]. This stiffness is a function of initial cracked stiffness and the maximum deformation experienced. The slope of load reversal branch is determined by the coordinates of points X_o and U_m', where U_m' is a point on the primary curve symmetric to U_m with respect to the origin. Branch X_oU_m provides some softening effects comparable to the small incremental stiffness (pinching effect) observed in experimental results. Unlike the simple bilinear model, Q-Hyst system provides some hysteretic energy dissipation in small amlitude responses after the section has yielded.

ANALYTICAL MODEL

An analytical model was developed for seismic analysis of plane reinforced concrete frame structures. The model can be coupled to any of the four hysteresis models described above.

The primary moment-rotation curves were determined based on the calculated moment-curvature relationship for half-length of the elastic portion of each element. Measured material properties were used to obtain moment-curvature relationships. For the Q-Hyst and simple bilinear hysteresis systems, members were assumed to be initially cracked [5].

TEST STRUCTURE

A ten-story three-bay small-scale reinforced concrete structure, tested using the University of Illinois Earthquake Simulator, was used to carry out the analytical study [2]. The structure comprised two identical frames placed parallel to each other on the test platform. The mass at each level was about 465 Kg equally distributed among the columns. The structure was designed using the substitute structure method with the design maximum acceleration of 0.4g. The longitudinal reinforcement distribution and basic material properties are shown in Fig. 2.

The structure was subjected to three simulated earthquake motions in horizontal direction, the first motion corresponding to the design earthquake. The base motion for the simulated earthquakes was modeled after the measured El Centro, NS, 1940. The time axis of the base acceleration was compressed by a factor of 2.5 to result in reasonable ratios between the earthquake frequency content and the natural frequencies of the test structure. The complete information on the design, casting, and testing of the structure is given in Reference 2.

MEASURED AND CALCULATED RESULTS

The structure, described in the previous section, was analyzed for the first five seconds of the measured base acceleration during the design earthquake. The duration was equivalent to 12.5 seconds of the original earthquake, and was long enough to include both small- and large-amplitude responses. Because the two frames in the structure were identical, only one of the frames was analyzed. The calculation was repeated four times, using one of the hysteresis models described above in each case. Response histories for displacement and acceleration at different floor levels, as well as base moment and base shear were calculated. It was noticed that the waveforms for displacement response at different levels were similar. The same was true for acceleration responses at different levels. This observation held for both measured and calculated results. Therefore, comparisons will be made for only the top-level response histories.

Figure 3-b shows the results for the Takeda model. It can be seen that up to 3.2 seconds there was a very close agreement between the calculated and measured results. The waveforms and frequency contents were almost the same, peak points occurred at the same time, and peak values were quite close. It can be concluded that the overall hysteretic behavior of the structure during large-amplitude responses was presented well by the Takeda model. The calculated curve deviated from the measured response beyond T=3.2 seconds when small-amplitude response started. Differences were seen in waveforms, apparent frequencies, and response amplitudes.

The results for the simple bilinear model are shown in Fig. 3-c. Except for its apparent frequency before T=1.7 seconds, and the peak value at $T \approx 2.4$ seconds, the calculated curve was considerably different from the experimental result in all aspects. The analytical model underestimated most of the peak values, indicating that the amount of energy dissipation was overestimated by the simple bilinear model. The apparent frequency of the calculated response was larger than the measured frequency which can be interpreted as a calculated average stiffness larger than the average stiffness of the physical model.

The Sina model resulted in a response reasonably close to the measured response except for the peak values between $T \approx 2$ and 3 seconds (Fig. 3-d). In the period between $T \approx 2$ and 3 seconds, the peak values were overestimated showing an underestimation of energy dissipation during large-amplitude responses. The apparent frequency of the analytical and experimental results were close for the entire response, although there was a period elongation in the calculated curve between $T \approx 3$ and 5 seconds. Relatively close agreement was observed between the calculated and measured low-amplitude responses indicating that the inclusion of pinching effects in Sina model has resulted in a structural stiffness close to the stiffness of the physical model during small amplitudes.

The analytical results for the Q-Hyst model are presented in Fig. 3-e.

The frequency content of the calculated and measured results were reasonably close for the entire response, which signifies that the average stiffness of the structure was presented well by the Q-Hyst model. The calculated and measured waveforms were similar, although the analytical model slightly overestimated the peak values in most instances. This can be interpreted that the overall energy dissipation of the structure was slightly underestimated by the Q-Hyst system. The correlation between the calculated and measured responses had a uniform trend for both large- and small-amplitudes. The relatively close agreement during small-amplitude response (at $T \approx 3$ seconds) indicates that the softened branch used for load-reversal stage in the Q-Hyst model has reproduced a behavior similar to the pinching considered in the Sina model.

CONCLUSIONS

In the foregoing section, different aspects of the performance of the four hysteresis models were discussed. An additional factor would be the computer time needed for each analysis. However, it was found the execution time for all hysteresis models was approximately the same. The reason being that, at each time step, only one rule of the hysteresis model is used and it is immaterial how many other rules are included in the model. The less complicated models needed less compilation time which was trivial compared to the execution time for the analysis of the ten-story structure.

The calculated response history using the simple bilinear model was considerably different from the measured response. The fact that the calculated maximum displacement for this model was relatively close to the measured maximum cannot restore confidence in the simple bilinear model, because the calculated and measured values occurred at different times.

Sina and Q-Hyst models resulted in similar responses. Between the two, the Q-Hyst model is preferred because it is simpler (the Q-Hyst model is expressed by only four rules as compared to the nine rules in the Sina model). Furthermore, to use the Sina model, decision has to be made about the position of the point at which the crack is closed, which complicates the problem without any significant gain.

The choice between the Takeda and Q-Hyst models needs careful consideration. Each model has its own advantages and disadvantages. The Takeda model resulted in a curve quite close to the measured curve during large- but not small-amplitude responses. Moreover, comprising sixteen rules, the Takeda model is very complicated and difficult to comprehend. The Q-Hyst model was successful in calculating a response history with frequency content and waveform similar to those of the measured responses. The maximum displacement was overestimated by 17 percent. Considering the large variations which exist in earthquake motions and their effects on structures, perhaps this error is not significant. The Q-Hyst model is a simple system defined by only four rules; it is easy to understand and use.

The problem considered in this paper represents only one class of structures. Further research is needed before a conclusive result can be obtained. Nevertheless, the outcome from this study revealed that for the particular structure analyzed here, the Q-Hyst model is preferable to the other systems considered because of its satisfactory simulation of displacement history response and because it is simple.

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The CDC 175 computing system at the Computer Department of the University of Illinois was used for the analytical work.

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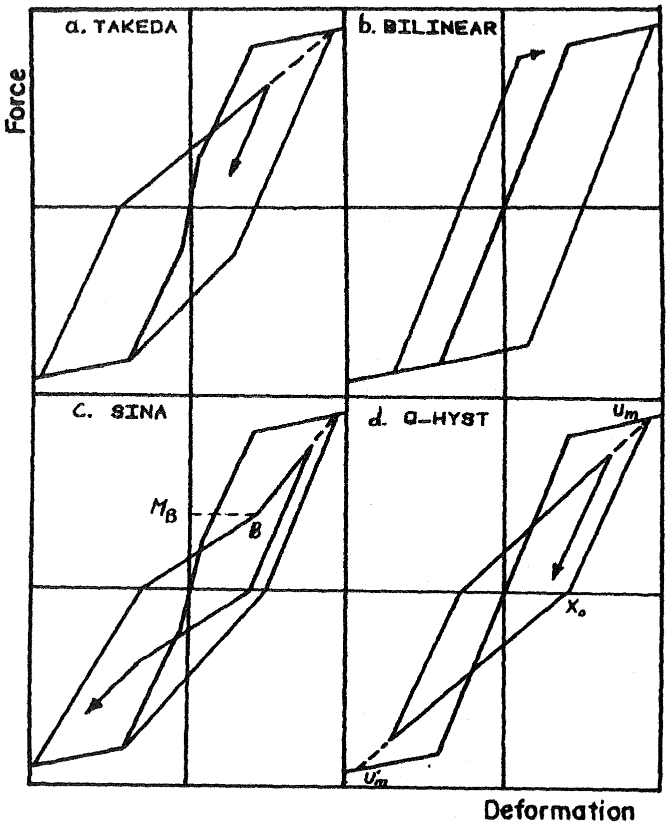
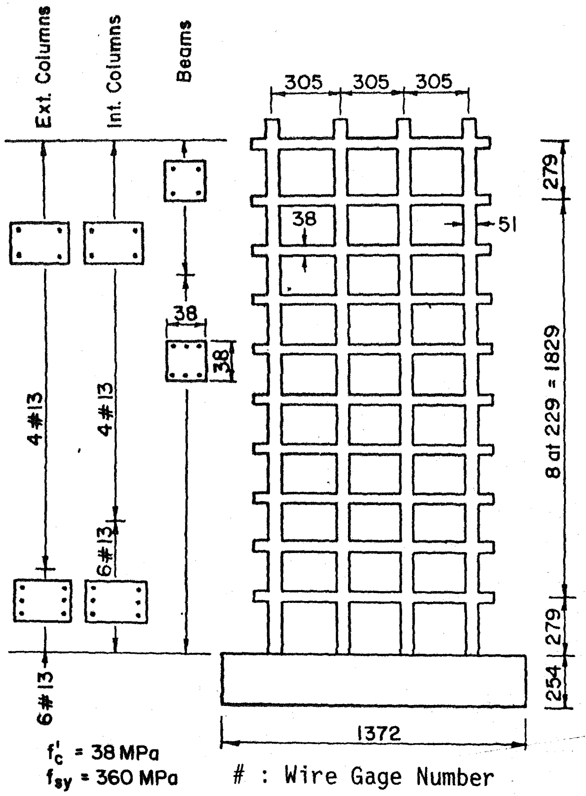


Fig. 1 Hysteresis Models



f'_c = 38 MPa
f_{sy} = 360 MPa

: Wire Gage Number
All Dimensions in mm

Fig. 2 Test Structure

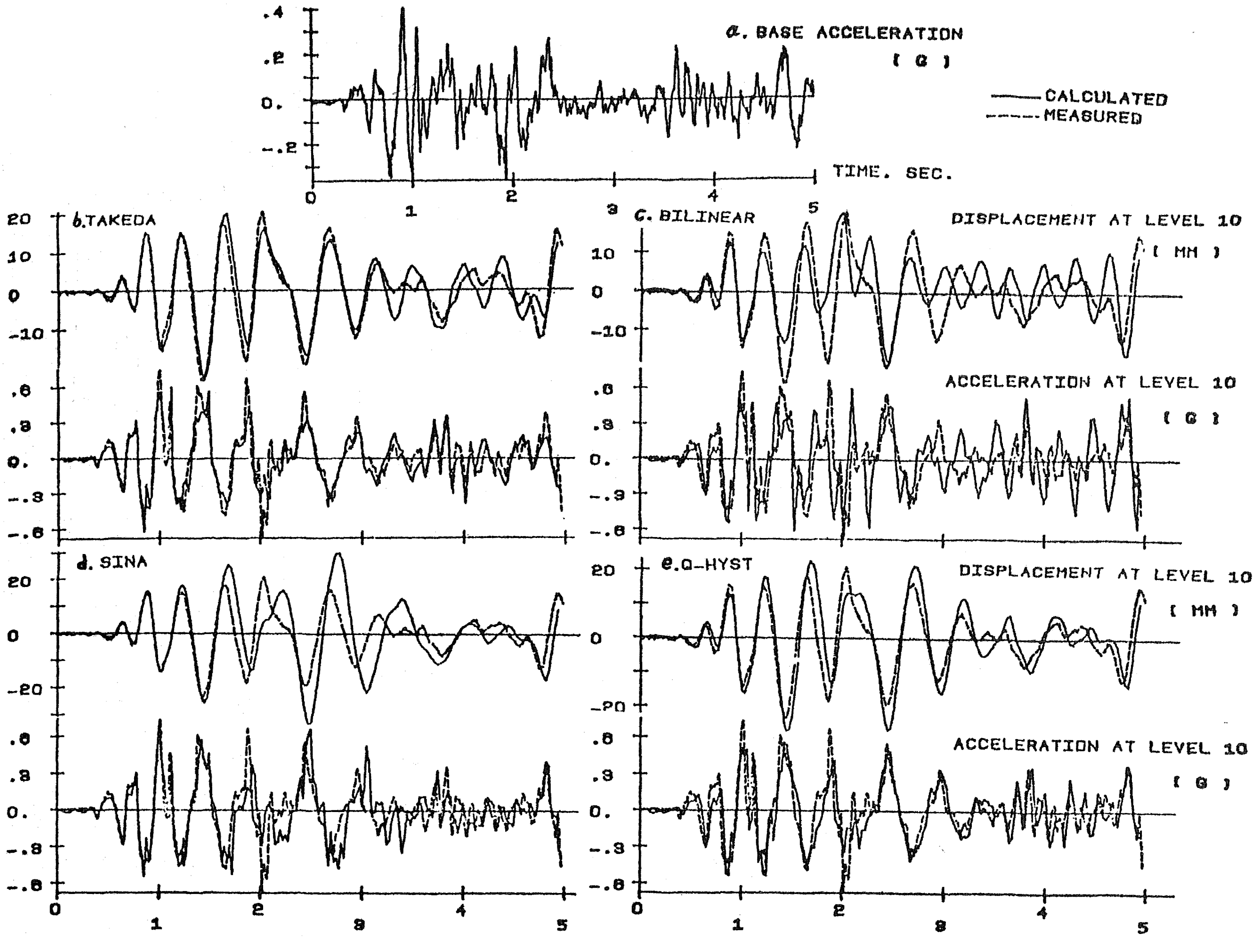


Fig. 3 Measured and Calculated Responses