

Practical Three Dimensional Nonlinear Static Pushover Analysis

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The recent advent of performance based design has brought the nonlinear static pushover analysis procedure to the forefront. Pushover analysis is a static, nonlinear procedure in which the magnitude of the structural loading is incrementally increased in accordance with a certain predefined pattern. With the increase in the magnitude of the loading, weak links and failure modes of the structure are found. The loading is monotonic with the effects of the cyclic behavior and load reversals being estimated by using a modified monotonic force-deformation criteria and with damping approximations. Static pushover analysis is an attempt by the structural engineering profession to evaluate the real strength of the structure and it promises to be a useful and effective tool for performance based design.

The ATC-40 and FEMA-273 documents have developed modeling procedures, acceptance criteria and analysis procedures for pushover analysis. These documents define

force-deformation criteria for hinges used in pushover analysis. As shown in Figure 1, five points labeled A, B, C, D, and E are used to define the force deflection behavior of the hinge and three points labeled IO, LS and CP are used to define the acceptance criteria for the hinge. (IO, LS and CP stand for Immediate Occupancy, Life Safety and Collapse Prevention respectively.) The values assigned to each of these points vary depending on the type of member as well as many other parameters defined in the ATC-40 and FEMA-273 documents.

This article presents the steps used in performing a pushover analysis of a simple three-dimensional building. SAP2000, a state-of-the-art, general-purpose, three-dimensional structural analysis program, is used as a tool for performing the pushover. The SAP2000 static pushover analysis capabilities, which are fully integrated into the program, allow quick and easy implementation of the pushover procedures prescribed in the ATC-40 and FEMA-273 documents

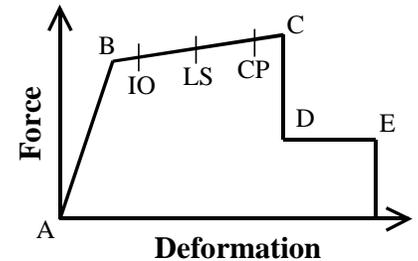


Figure 1: Force-Deformation For Pushover Hinge

for both two and three-dimensional buildings.

The following steps are included in the pushover analysis. Steps 1 through 4 discuss creating the computer model, step 5 runs the analysis, and steps 6 through 10 review the pushover analysis results.

1. Create the basic computer model (without the pushover data) in the usual manner as shown in Figure 2. The graphical interface of SAP2000 makes this a quick and easy task.

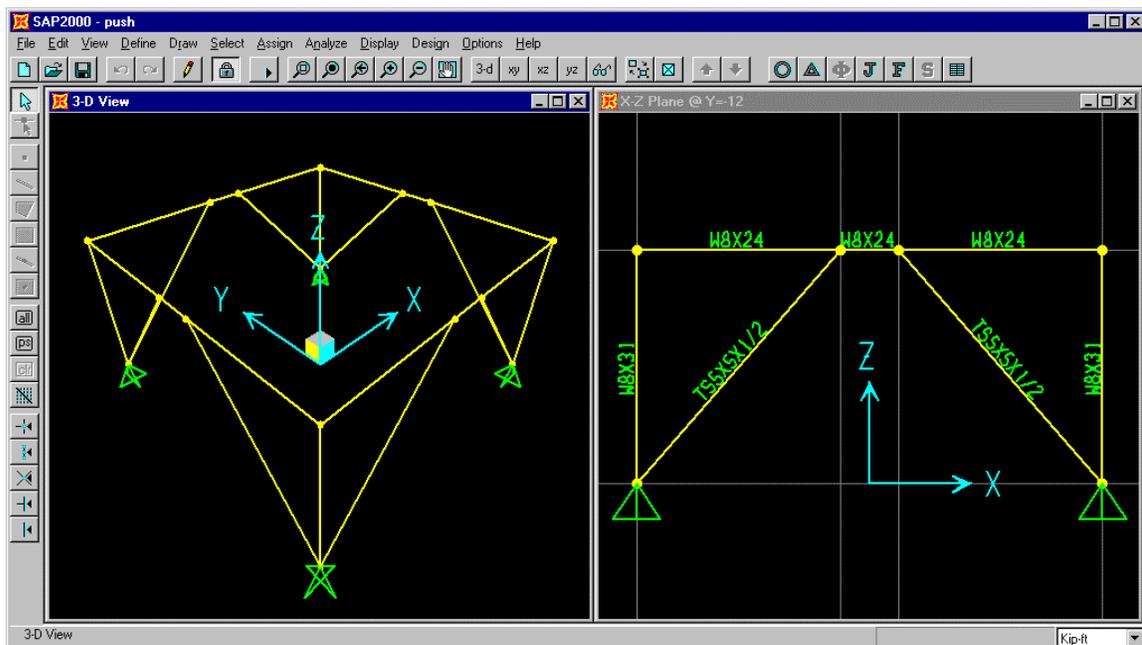


Figure 2: Basic SAP2000 Model (Without Pushover Data)

2. Define properties and acceptance criteria for the pushover hinges as shown in Figure 3. The program includes several built-in default hinge properties that are based on average values from ATC-40 for concrete members and average values from FEMA-273 for steel members. These built in properties can be useful for preliminary analyses, but user-defined properties are recommended for final analyses. This example uses default properties.

3. Locate the pushover hinges on the model by selecting one or more frame members and assigning them one or more hinge properties and hinge locations as shown in Figure 4.

4. Define the pushover load cases. In SAP2000 more than one pushover load case can be run in the same analysis. Also a pushover load case can start from the final conditions of another pushover load case that was previously run in the same analysis. Typically the first pushover load case is used to apply gravity load and then subsequent lateral pushover load cases are specified to start from the final conditions of the gravity pushover. Pushover load cases can be force controlled, that is, pushed to a certain defined force level, or they can be displacement controlled, that is, pushed to a specified displacement. Typically a gravity load pushover is force controlled and lateral pushovers are displacement controlled. SAP2000 allows the distribution of lateral force used in the pushover to be based on a uniform acceleration in a specified direction, a specified mode shape, or a user-defined static load case. The dialog box shown in Figure 5 shows how the displacement controlled lateral pushover case that is based on a user-defined static lateral load pattern (named Push) is defined for this example.

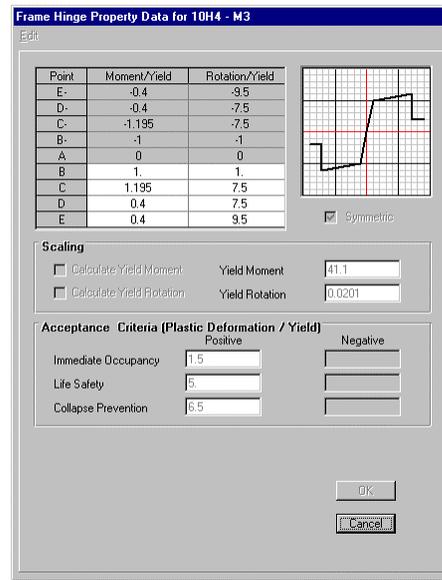


Figure 3: Frame Hinge Property



Figure 4: Assign Pushover Hinges

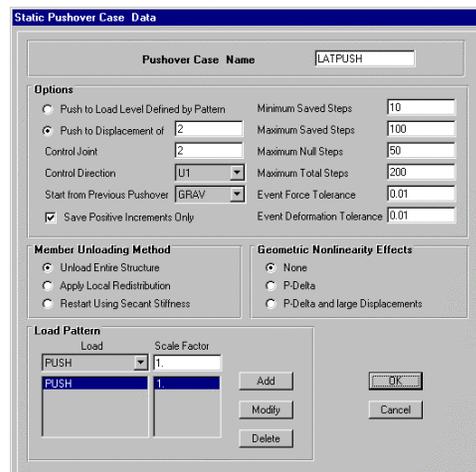


Figure 5: Pushover Load Case Data

- Run the basic static analysis and, if desired, dynamic analysis. Then run the static nonlinear pushover analysis.
- Display the pushover curve as shown in Figure 6. The File menu shown in this display window allows you to view and if desired, print to either a printer or an ASCII file, a table which gives the coordinates of each step of the pushover curve and summarizes the number of hinges in each state as defined in Figure 1 (for example, between IO and LS, or between D and E). This table is shown in Figure 7.

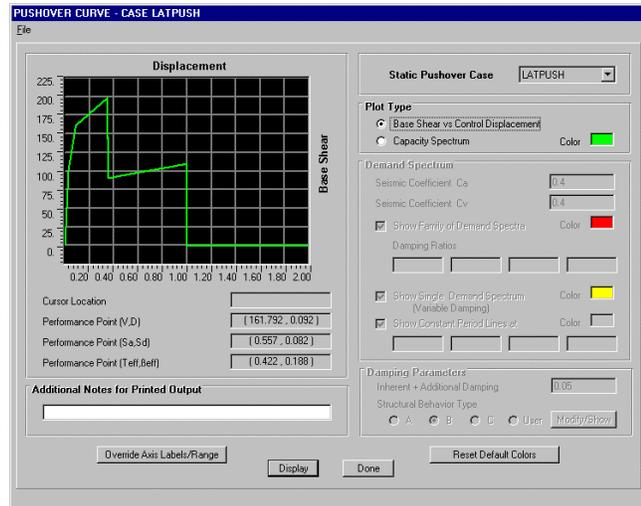


Figure 6: Pushover Curve

- Display the capacity spectrum curve as shown in Figure 8. Note that you can interactively modify the magnitude of the earthquake and the damping information on this form and immediately see the new capacity spectrum plot. The performance point for a given set of values is defined by the intersection of the capacity curve (green) and the single demand spectrum curve (yellow). Also, the file menu in this display allows you to print the coordinates of the capacity curve and the demand curve as well as other information used to convert the pushover curve to Acceleration-Displacement Response Spectrum format (also known as ADRS format, see page 8-12 in ATC-40).

Step	Displacement	Base Shear	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	>E	TOTAL
0	0.0000	0.0000	60	0	0	0	0	0	0	0	60
1	0.0274	100.4879	57	3	0	0	0	0	0	0	60
2	0.0821	157.4939	51	8	1	0	0	0	0	0	60
3	0.0878	161.1401	48	11	1	0	0	0	0	0	60
4	0.3481	198.9614	46	6	3	2	1	2	0	0	60
5	0.3481	160.7877	46	6	3	2	1	0	2	0	60
6	0.3513	161.2326	46	6	3	2	1	0	0	2	60
7	0.3513	142.7613	46	6	3	2	1	0	0	2	60
8	0.3530	144.4506	46	6	3	2	1	0	0	2	60
9	0.3564	144.9255	46	6	3	0	1	2	0	2	60
10	0.3565	108.0511	46	6	3	0	1	0	2	2	60
11	0.3596	108.2019	46	6	3	0	1	0	0	4	60
12	0.3596	89.6470	46	6	3	0	1	0	0	4	60
13	0.4538	93.9015	40	12	3	0	1	0	0	4	60
14	0.6538	99.5164	40	0	15	0	1	0	0	4	60
15	0.8538	105.1312	40	0	10	5	1	0	0	4	60
16	1.0031	109.3216	40	0	0	13	1	2	0	4	60
17	1.0031	-0.4843	40	0	0	11	1	0	0	8	60
18	1.2031	-0.4404	40	0	0	11	1	0	0	8	60
19	1.4031	-0.3965	40	0	0	11	1	0	0	8	60
20	1.6031	-0.3526	40	0	0	11	1	0	0	8	60
21	1.8031	-0.3086	40	0	0	11	1	0	0	8	60
22	2.0000	-0.2654	40	0	0	11	1	0	0	8	60

Figure 7: Tabular Data For Pushover Curve

- Review the pushover displaced shape and sequence of hinge formation on a step-by-step basis as shown in the left-hand side of Figure 9. The arrows in the bottom right-hand corner of the screen allow you to move through the pushover step-by-step. Hinges appear when they yield and are color coded based on their state (see legend at bottom of screen).

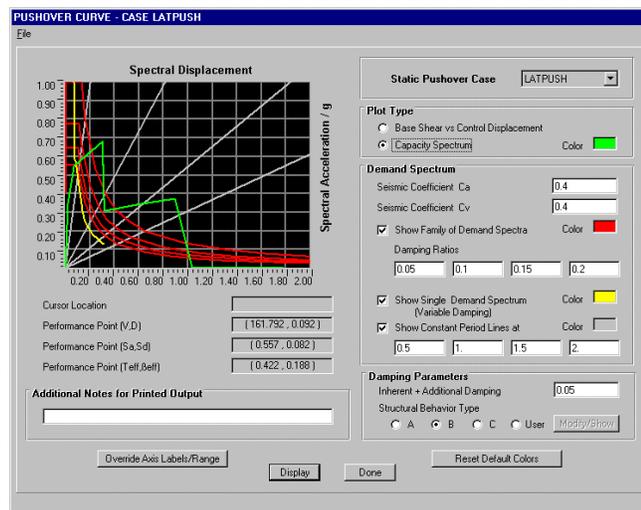


Figure 8: Capacity Spectrum Curve

9. Review member forces on a step-by-step basis as shown in the right-hand side of Figure 9. Often it is useful to view the model in two side-by-side windows with the step-by-step displaced shape in one window and the step-by-step member forces in the other, as shown in Figure 9. These windows can be synchronized to the same step, and can thus greatly enhance the understanding of the pushover results.
10. Output for the pushover analysis can be printed in a tabular form for the entire model or for selected elements of the model. The types of output available in this form include joint

displacements at each step of the pushover, frame member forces at each step of the pushover, and hinge force, displacement and state at each step of the pushover.

For buildings that are being rehabilitated it is easy to investigate the effect of different strengthening schemes. The effect of added damping can be immediately seen on the capacity spectrum form (step 7, Figure 8). You can easily stiffen or strengthen the building by changing member properties and rerunning the analysis. Finally you can easily change the assumed detailing of the building by modifying the hinge acceptance criteria (step 2, Figures 1 and 3) and rerunning the analysis.

References

- ATC, 1996
Seismic Evaluation and Retrofit of Concrete Buildings, Volume 1, ATC-40 Report, Applied Technology Council, Redwood City, California.
- FEMA, 1997
NEHRP Guidelines for the Seismic Rehabilitation of Buildings, Developed by the Building Seismic Safety Council for the Federal Emergency Management Agency (Report No. FEMA 273), Washington, D.C.

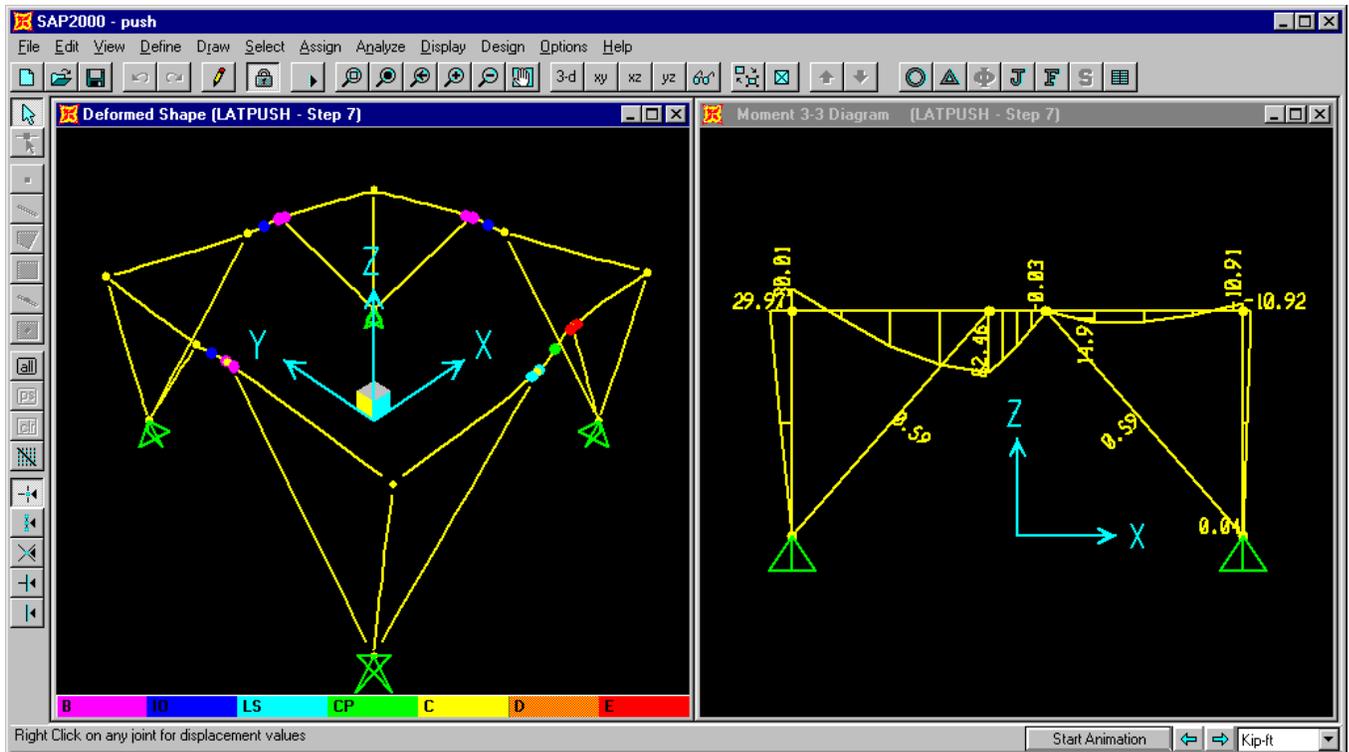


Figure 9: Step-By-Step Deformations and Member Forces For Pushover

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