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Avoiding common pitfalls in push-over analysis

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ABSTRACT

Static Nonlinear Analysis technique, also known as sequential yield analysis, or simply "push-over" analysis has gained significant popularity during the past few years. It is one of the three analysis techniques recommended by the NEHRP Guidelines for Seismic Rehabilitation of Existing Buildings (FEMA 273/274) and a main component of the Spectrum Capacity Analysis method (ATC-40). While the proper application of push-over analysis can provide valuable insights into the expected performance of structural systems and components, its misuse can lead to an erroneous understanding of the performance characteristics. Unfortunately, many engineers are unaware of the subtle details that have to be observed in order to obtain useful results from such analysis. This paper is an attempt to identify the most important considerations necessary for a push-over analysis to provide meaningful results.

INTRODUCTION

Push-over analysis is a technique by which a computer model of the building is subjected to a lateral load of a certain shape (i.e., inverted triangular or uniform). The intensity of the lateral load is slowly increased and the sequence of cracks, yielding, plastic hinge formations, and failure of various structural components as a function of increasing lateral load is recorded. Push-over analysis can provide a significant insight into the weak links in seismic performance of a structure. A series of iterations are usually required during which, the structural deficiencies observed in one iteration, are rectified and followed by another. This iterative analysis and design process continues until the design satisfies a pre-established performance criteria.

The performance criteria for push-over analysis is generally established as the desired state of the building given a roof-top or spectral displacement amplitude (commonly referred to as the *target displacement*).

A variety of technical tools may be used for push-over analysis. The preferred approach is to use nonlinear program software with built-in push-over analysis capabilities. Several publicly available computer programs such as DRAIN-2DX, DRIAN-3DX, ANSR, and IDARC feature push-over analysis options. Push-over analysis may be also performed by sequential application of linear analysis software. Details of steps necessary for push-over analysis using linear structural analysis programs are given in the FEMA-274 and ATC-40 documents.

In performing push-over analysis by successive linear analyses, one should note that the starting point of each analysis reflects the state of building at the end of previous analysis. Therefore, all component actions (i.e., displacements and forces) obtained at each step of the analysis are actually action increments which have to be added up to reflect the analysis results. This, generally, requires a substantial amount of manual bookkeeping of displacements and forces. It should also be realized that push-over results obtained by successive linear analyses is inherently approximate, incapable of accurate modeling of the P-Δ effects and weak in assessment of true member forces. Despite these facts, if used properly, it can provide a good approximation to the global force-displacement curve for the building (see Figure 1).

The focus of this paper is on common mistakes committed during a direct push-over analysis performed by application of nonlinear analysis programs. Many of the observations made here, however, are equally well (if not more profoundly) applicable to push-over analysis by successive application of linear analysis techniques. Ten of the most important considerations for a meaningful push-over analysis are discussed below.

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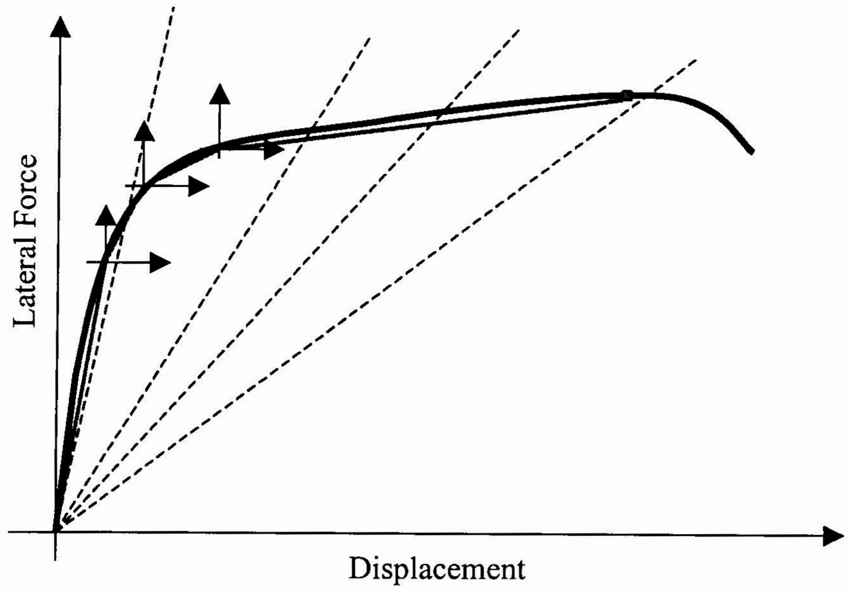

Figure 1. Direct push-over analysis versus push-over by successive application of linear analysis

COMMON PITFALLS TO AVOID

Do not underestimate the importance of the loading shape function.

The shape of the distributed lateral load applied in the push-over analysis is customarily selected to represent the predominant dynamic mode shape of the building. Quite often, an inverted triangular shape is used consistent with the codified static lateral force distribution. It is most common to keep the load shape constant during the push. Increasingly, however, adaptive load shapes are used which are self-modified by the program at various stages of the loading to represent the altered mode shapes of the building due to the induced cracks, yields, and plastic hinge formations. Adaptive load functions can provide a more accurate reflection of the force-displacement characteristics of the building. At this time, however, no consistent guidelines for definition and application of adaptive load functions exist.

Loading shape importance increases for tall buildings whose earthquake response is not dominated by a single mode shape. For these buildings, a loading shape function based on the first mode shape may seriously underestimate the seismic demand on the intermediate floor levels. Loading shape functions constructed by weighted linear combination of mode shapes where modal participation factors are used as the weighting factors have been utilized successfully by the authors in the past. FEMA-273, on the other hand, suggests an inverted triangular distribution modified by an exponent, as a simple alternative. Although it is true that the influence of the loading shape function is much stronger for tall, multi-mode, buildings, their influence is considerable even on analysis of smaller, more simple structures.

Know your performance objectives before you push the building.

Obviously, no building can be displaced to infinity without damage. Since the objective of push-over analysis is to assess the status of building and its components in a damaged state, it is of paramount importance to understand the specific performance objectives desired for the building. Performance objectives which are generally established as global seismic behavior states (i.e., collapse prevention, life safety, or immediate occupancy) have to be translated into technical terms such as: (a) a given set of design spectra, and (b) specific limit states acceptable for various structural components when subjected to the seismic demand embodied in these design spectra. A push-over analysis without a clearly defined performance objectives is of little use.

If it is not designed, it cannot be pushed.

In contrast with the conventional design analysis, the gross member sizes do not suffice for a meaningful push-over analysis. The push-over analysis result is a strong function of force-displacement characteristics of individual members and their connections. If the details of these characteristics are not known, the push-over analysis will be an exercise in futility. For example, the force-deformation properties of concrete are vastly different from that of steel and care should be taken to determine the initial stiffness, the cracking and the yielding moments and also the post yield behavior. For steel structures, the moment curvature is primarily a bilinear envelope. The possible failure mechanisms in the joint panel zones, however, should be considered in the analysis. Possible premature weld fractures at the joints will prevent adjoining members from achieving their full plastic capacities. If such fractures are anticipated, they should be given their due consideration.

<u>Do not ignore gravity loads.</u>

Inclusion or exclusion of the gravity loads has a pronounced effect on the shape of the push-over curve and the member yielding and failure sequence. Due to the unsymmetric distribution of positive and negative reinforcements in most reinforced concrete beams, the gravity load delays the onset of yielding and cracking in the beams, resulting in a stiffer structure at lower magnitudes of base shear. The ultimate capacity of the structure, however, is usually reduced with increasing gravity load. If P-Δ effects are included, this variation in ultimate capacity is pronounced at large displacement levels.

<u>Do not push beyond failure unless otherwise you can model failure.</u>

Once the deformation (i.e., displacement or curvature) of structural components such as beams, columns, and walls exceeds the ultimate deformation, their resistance to corresponding actions (i.e., shear, axial force, or moment) is either drastically curtailed or outright diminished. Unfortunately, most computer codes used for push-over analysis are incapable of modeling the post-failure behavior of structural components and the ultimate force (moment) is assumed retained by the member as if no failure has occurred. This would portray an inaccurate picture of the force distribution among structural components and an erroneous force-displacement curve for the building (Figure 2). If the computer program you use can not model structural failure (most cannot), then either the push has to be stopped at the onset of the first failure, or extreme care must be exerted on the interpretation of the post-failure behavior as reported by the program.

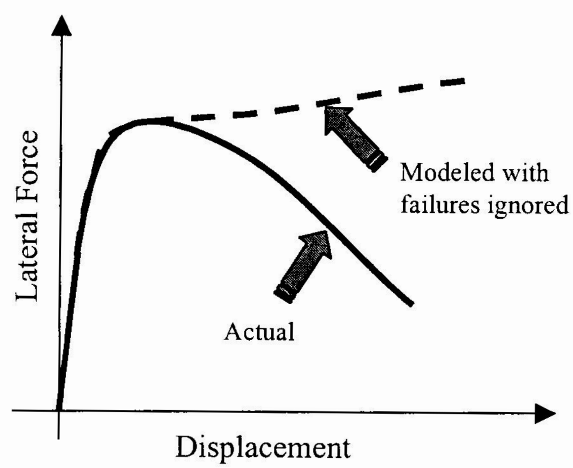

Figure 2. Push-over curves may be drastically different depending on how the post-failure behavior of structural components are modeled.

<u>Pay attention to rebar development and lap lengths.</u>

For reinforced concrete members of existing structures, it is very important to note the development lengths as provided when calculating member capacities. If inadequate development lengths are present, as they are in most of the older buildings, the contributing steel area should be reduced to account for this inadequacy. Failure to do so will result in overestimating the actual capacity of the members and results in an inaccurate push-over curve.

<u>Do not ignore shear failure mechanisms</u>

If the shear capacity of structural members is not sufficient enough to permit the formation of flexural plastic hinges, shear failure will precede the formation of plastic hinges at the end of the member. In reinforced concrete members, even if the shear capacity is sufficient, but lateral reinforcement is not spaced close enough at the plastic hinge zones, the concrete may crush in the absence of sufficient confinement. If this happens, the plastic capacity is suddenly dropped to what can be provided by the longitudinal steel alone. Very few of the computer programs used routinely for push-over analysis consider either of the above two scenarios. As a consequence, designers should be aware of these problems and deal with them manually, if the computer program they are using cannot address these issues automatically.

P-Δ effects may be more important than you think.

The P-Δ effects become increasingly significant with larger lateral displacements and larger axial column forces. One should note that the strong column – weak girder design strategy commonly deals with the moment capacity of columns in the undeformed state. In a substantially deformed state, the moment capacity of columns may be sufficiently reduced to counteract the strong column – weak girder behavior envisioned by the design. Cases of plastic hinge formations during a push-over analysis in columns "designed" to be stronger than the girders are not rare.

Do not confuse the push-over with the real earthquake loading.

Although push-over analysis can provide very useful information regarding the expected seismic performance of a building, it does not represent a realistic sense of the actual loads imparted on a building by earthquake ground motion. The push-over load is monotonically increased while the earthquake generated forces continually change in amplitude and direction during the duration of earthquake ground motion. It is not wise to expect the push-over analysis to identify all the weak links of a structure when subjected to unknown earthquake ground motions, nor is it wise to expect the earthquakes to concentrate damage only on the weak points identified by a push-over analysis. This is particularly true for near-fault ground motions which tend to concentrate the damage on the lower floors, an effect which is difficult to model by the push-over loads. The best that can be hoped for is for the push-over curve to effectively envelope the earthquake generated forces and displacements.

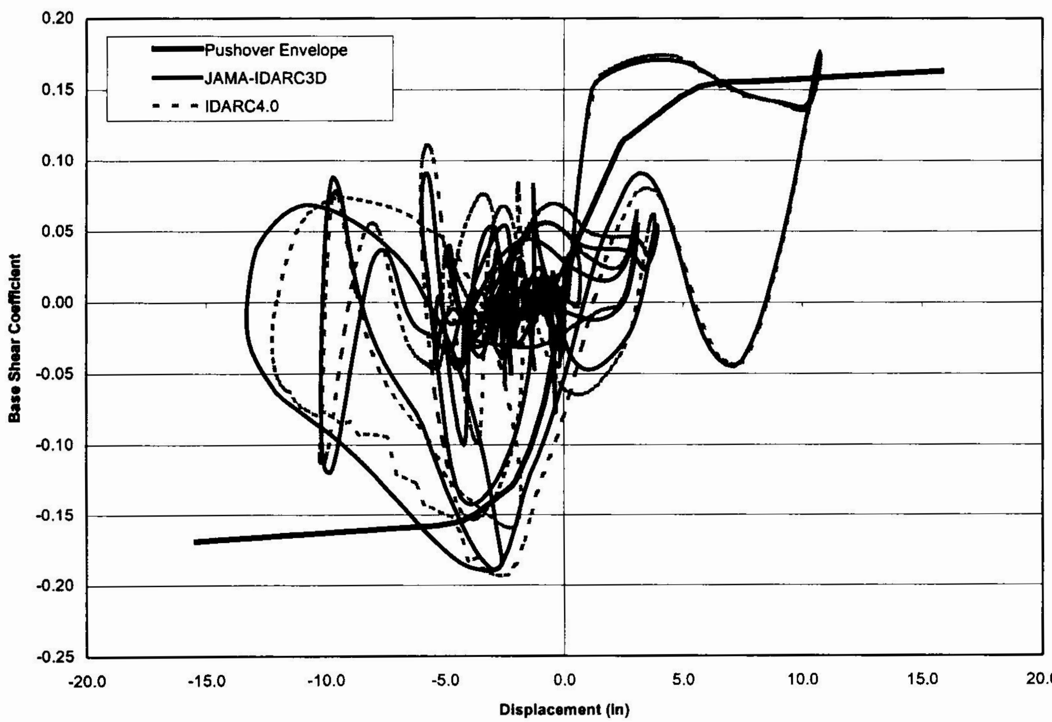

Figure 3. A comparison of base shears obtained by pushover and dynamic earthquake ground motion.

To illustrate this point, a simple two story structure was subjected to the larger (360^0) component of the Newhall LA County fire station record from the 1994 Northridge earthquake. The base shears using two different computer programs, JAMA-IDARC3D and IDARC4.0 and the pushover envelope using an inverted triangular loading are compared in Figure 3. In this case, the maximum base shears from the earthquake are greater than those predicted from a push-over with an inverted triangular load. A different lateral load pattern may provide a push-over curve which would more effectively envelope the ground motion response for this building.

Three-dimensional buildings may require more than a planar push.

For buildings with strong asymmetry in plan, or with numerous non-orthogonal elements, a planar (two dimensional) push-over analysis may provide inaccurate results. For such cases a three dimensional model of the building must be constructed and subjected to push-over analysis. Three dimensional buildings may be pushed in the principal directions independently, or pushed simultaneously in orthogonal directions. One may also want to push such buildings according to a shape which represent a higher mode or a combination of several modes.

Once a push-over analysis is performed properly, a good insight into the inherent weak points of the structure is obtained (see Figure 4).

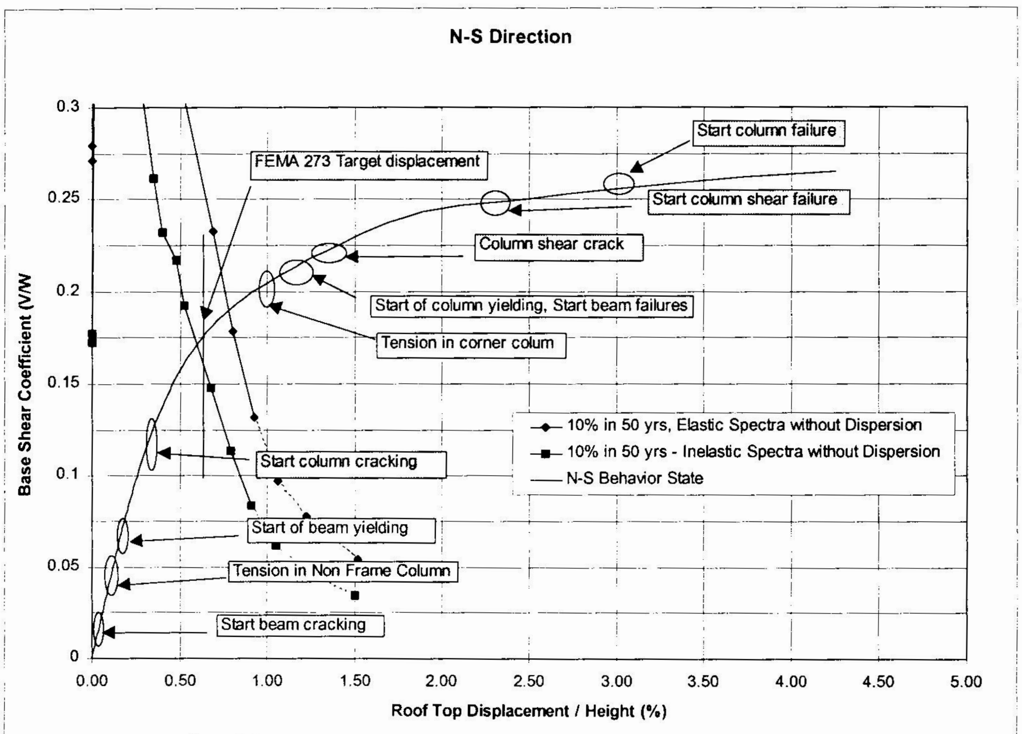

Figure 4. A typical push-over curve with component behavior stages identified.

CONCLUSION

Important considerations for a meaningful push-over analysis were presented. The ten most important issues were identified discussed in more detail. Advantages and limitations of push-over analysis for evaluating seismic performance of buildings were discussed. The research presented in this paper was supported by John A. Martin and Associates, Inc., of Los Angeles, California. The opinions expressed are those of authors and do not necessarily reflect the official positions of the sponsoring organization.

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