Evaluating Existing Concrete Structures with Masonry Infill Walls by Nonlinear Static Analysis

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Understanding the Structural Role of Unreinforced Masonry (URM) Infill Walls with Concrete structures

Reinforced concrete (RC) frames with unreinforced masonry (URM) infill walls are commonly used as the structural system for buildings in many seismically active regions around the world. Structural engineers recognize that many buildings of this type have performed poorly during earthquakes. URM infill walls used in many countries worldwide of either burnt clay bricks or cement concrete block masonry. These URM infill walls are generally treated as non-structural elements, because they are used mainly for architectural purposes, and structural engineers often ignore them during structural design.

1. Global Behavior of URM

During earthquakes, infill walls affect the response of the structure, and may either ***beneficial or detrimental effects***. Infill walls contribute to the lateral force resisting capacity and damping of the structure up to a certain level of ground motion. Infill walls increase the initial stiffness and decrease the fundamental period of the structure, which might be beneficial or detrimental, depending on the frequency content of the ground motion.

URM infill walls are prone to early brittle failure, and infill wall failures may lead to the formation of a weak story, which can cause the building to collapse. Infill walls interact with the surrounding frame in such a way that column shear failure is made more likely. In addition, an unequal spatial distribution of infill walls for functional reasons – for example, windows and open commercial spaces on the street frontage and full walls adjacent to neighboring buildings can create torsion that places additional demands on columns and may cause them to fail

Because of the potentially dire consequences of ignoring the structural role of URM infill walls, proper consideration of infill walls is essential in any structural analysis of RC frame buildings with infill walls. This document provides engineers with guidance on how to model infill walls and include them in structural analyses.

The URM walls function as structural elements, and they may have beneficial or detrimental effects. Infill walls contribute to the lateral force resisting capacity and damping of the structure up to a certain level of structural response. They increase the initial stiffness and decrease the initial period of the structure, which might be beneficial or detrimental depending on the frequency content of the experienced ground motion. URM infill walls are prone to early brittle

failure. Infill walls interacting with frames tend to alter the building's overall strength and stiffness distribution. This may be despite the design intent of the engineer, because infill walls are typically considered as "non-structural" and therefore neglected in the frame design. Many buildings have a soft story created by commercial space (shops) or parking at the ground floor (Figure 1-a & 1-b)

Even in buildings without open spaces at the ground floor, brittle infill wall failure may lead to the formation of a weak and soft story during ground shaking in buildings that would have otherwise not had one (Figure 1-c & 1-d).

In addition, infill walls interact with the surrounding frame in such a way that column shear failure is made more likely (Figure 1-e). Infill walls can also induce torsion when some sides of the building have solid infill walls and the other sides have either infill walls with openings or no infill walls for architectural or usage purposes (Figure 1-f).
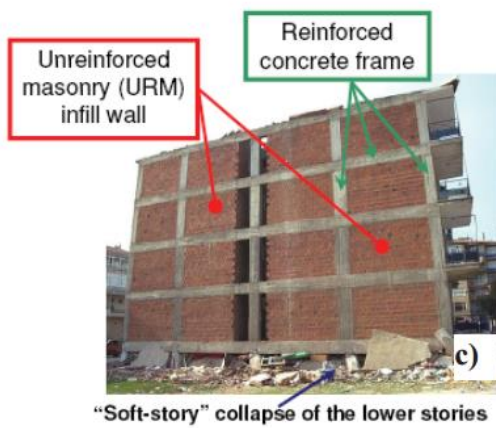
Figure 1. Masonry infill-related damage in recent earthquakes.

An Example of the Effects of Unreinforced Masonry Infill

Before moving ahead, it is instructive to see how infill alters the behavior of a bare RC frame. Using pushover analysis, we compare here the differences in behavior between a bare frame and the same frame with infill walls in all the stories except the first, shown in Figure 2 below. The effect of the infill is emulated by a *single diagonal compression strut* in each bay.
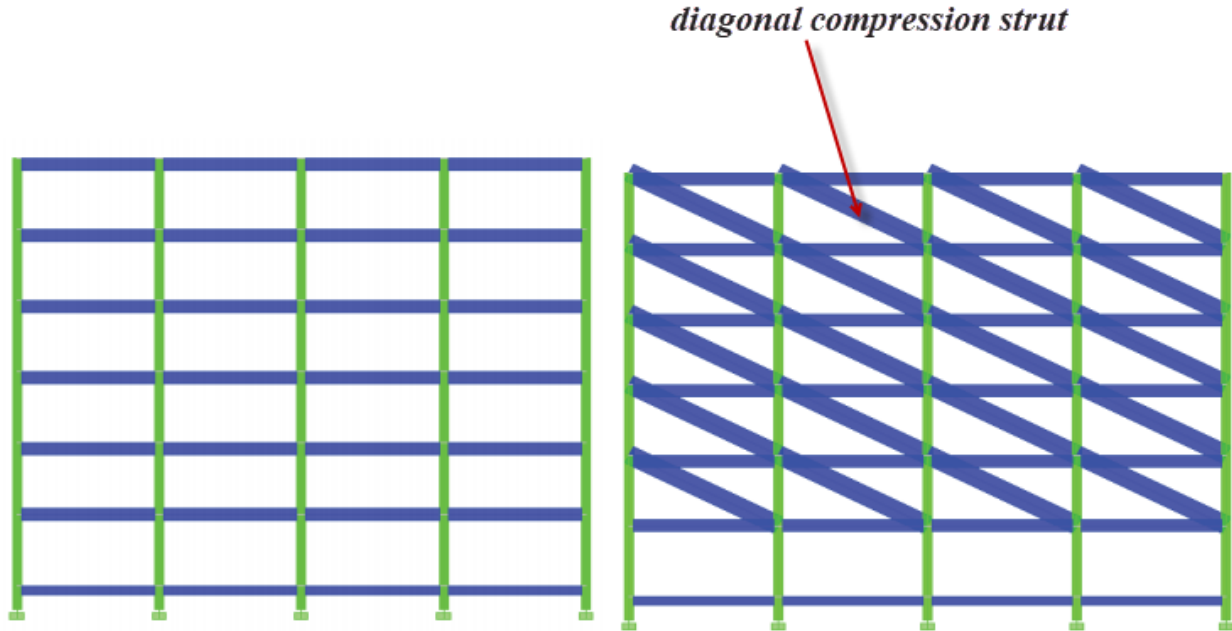
Figure 2. Bare frame (left) and the same frame with infill in all stories except ground (right).

The pushover curves are compared in Figure 3. ***The strength and stiffness of the infilled frame is significantly increased due to the presence of infill, but the displacement capacity decreases and a soft story develops***, ***which is evident from the displacement profiles in Figure 4.*** The deformation accumulates in the bottom story – the true behaviour during an earthquake when infill is considered in the analysis, rather than being distributed evenlyover all stories when the designer ignores the infill and incorrectly models the building as a bare frame.

So, based on these results, infill walls can be beneficial as long as they are properly taken into consideration in the design process and **the failure mechanism is controlled (i.e., no weak**

story is allowed to occur). However, this example also shows that failing to consider infill walls during structural design can lead to deadly weak-story collapses.
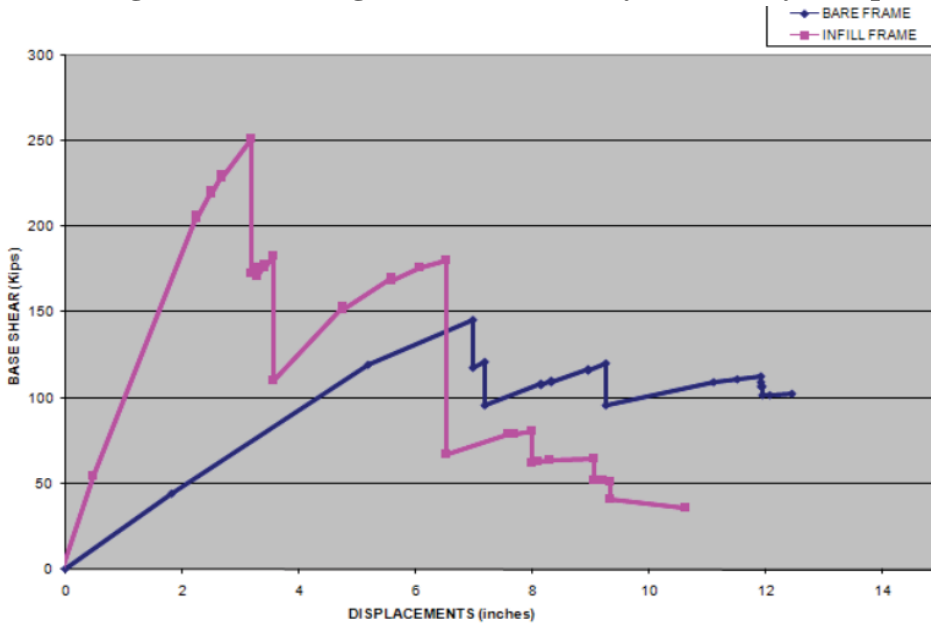

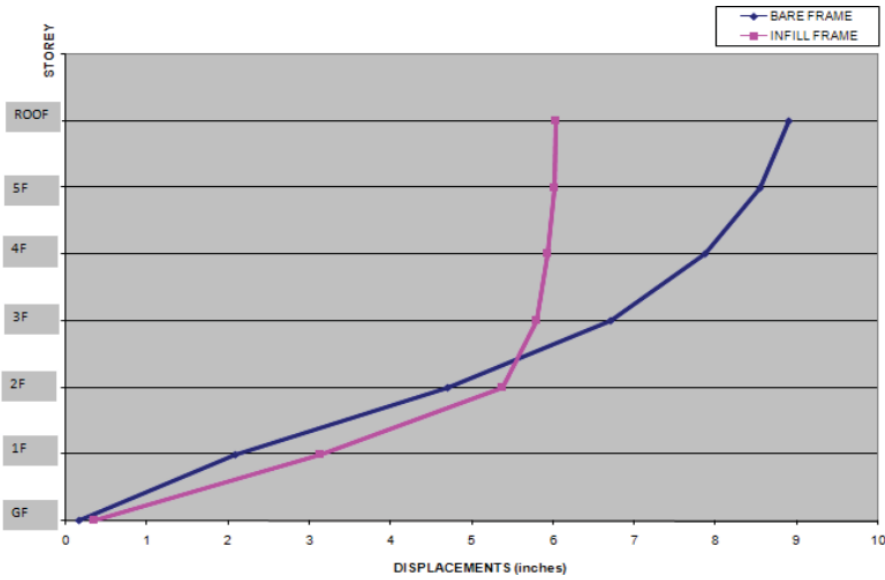Figure 3. Pushover curve comparison for the bare and infilled frames.

Figure 4. Displacement profile comparison for the bare and infilled frames.

Performance Based Analysis

1. Guidelines & Standards

The guidelines and standards mentioned in the introduction include modelling procedures, acceptance criteria and analysis procedures for pushover analysis. These documents define force-deformation criteria for potential locations of lumped inelastic behavior, designated as *plastic hinges* used in pushover analysis. As shown in Figure 5 below, five points labelled A, B, C, D, and E are used to define the force deformation behavior of the plastic hinge, and three points labelled IO (Immediate Occupancy), LS (Life Safety) and CP (Collapse Prevention) are used to define the acceptance criteria for the hinge. In these documents, if all the members meet the acceptance criteria for a particular performance level, such as Life Safety, then the entire structure is expected to achieve the Life Safety level of performance. The values assigned to each of these points vary depending on the type of member as well as many other parameters, such as the expected type of failure, the level of stresses with respect to the strength, or code compliance.
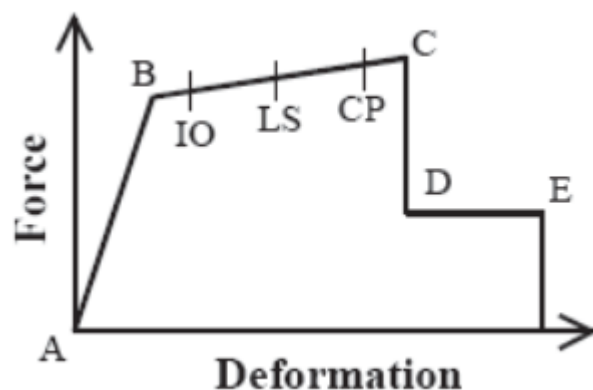
Figure 5. Force-Deformation Relation for Plastic Hinge in Pushover Analysis.

Both the ATC-40 and FEMA 356 documents present similar performance-based engineering methods that rely on nonlinear static analysis procedures for prediction of structural demands. While procedures in both documents involve generation of a "pushover" curve to predict the inelastic force-deformation behavior of the structure, they differ in the technique used to calculate the global inelastic displacement demand for a given ground motion. The FEMA 356 document uses the Coefficient Method, whereby displacement demand is calculated by modifying elastic predictions of displacement demand. The ATC-40 Report details the Capacity-Spectrum Method, whereby modal displacement demand is determined from the intersection of a capacity curve, derived from the pushover curve, with a demand curve that

consists of the smoothed response spectrum representing the design ground motion, modified to account for hysteretic damping effects.

2. Modeling Infill Walls as Struts

The most common method of modeling infill walls is to use equivalent diagonal compression struts (Figure 6).

Figure 6. Equivalent diagonal compression strut modeling of infill walls (reproduced from FEMA 356, a public Domain document).

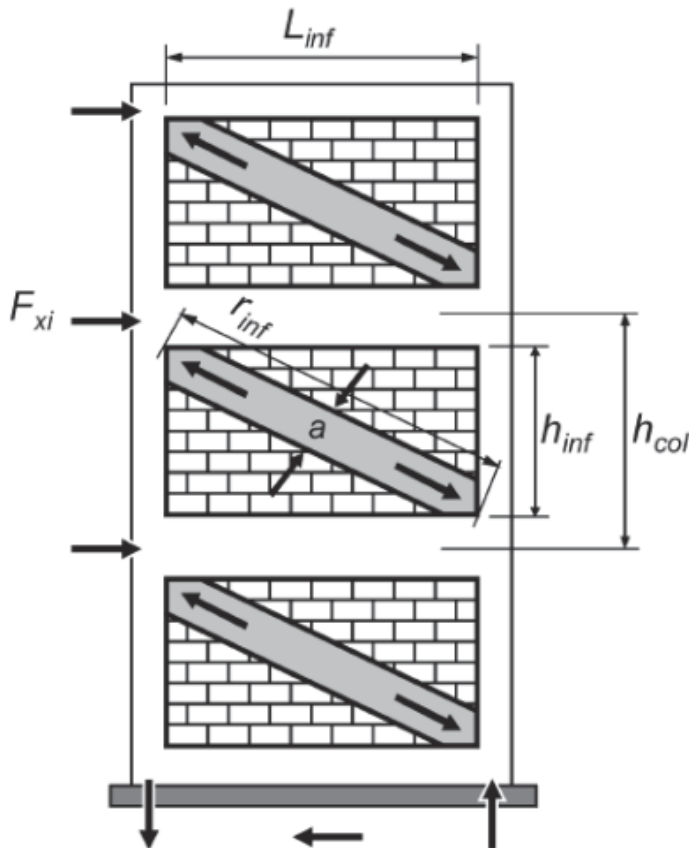The axial stiffness of an equivalent strut can be calculated with Equation 2 according to Section 7.5.2 of FEMA-356.

$$\lambda_1 = \left(\frac{E_m \, t_{inf} \sin(2\theta)}{4E_{fe} \, I_{col} \, h_{inf}} \right)^{0.25}$$

$$a = 0.175 \cdot \left(\lambda_1 h_{col} \right)^{-0.4} L_{diag}$$

$$k_{inf} = \frac{a \cdot E_m \cdot t_{inf}}{L_{diag}}$$

In these equations, E_m and E_{fe} are the elastic moduli of the infill and the frame material, respectively, t_{inf} is the thickness of the infill wall, h_{col} and I_{col} are the height and moment of inertia of the section of the column of the surrounding frame, h_{inf} is the height of the infill wall panel and L_{diag} is the length of the diagonal strut. The strength of the compression strut is calculated with the following Equation:

$$N_{comp} = \frac{A_{inf} \cdot fs_{inf}}{\cos\theta}$$

A_{inf} is the cross-sectional area of the infill wall, fs_{inf} is the shear strength of masonry and θ is the angle of the diagonal strut with the horizontal.

o **Special Case of Retrofitted Masonry Wall**

As a special case, it is also possible to model an infill wall retrofitted with mesh reinforcement and concrete by using **TWO** diagonal struts, one of which is a compression member and the other is a tension member. In this case, stiffness is calculated with the following Equation and distributed equally to the struts.

$$\lambda_1 = \left[\frac{(E_m \cdot t_{inf} + E_c \cdot t_c) \cdot \sin(2\theta)}{4 \cdot E_{fe} \cdot I_{col} \cdot h_{inf}} \right]^{0.25}$$

$$a = 0.175 \cdot (\lambda_1 \cdot h_{col})^{-0.4} \cdot L_{diag}$$

$$k_{inf} = \frac{a \cdot (E_m \cdot t_{inf} + E_c \cdot t_c)}{L_{diag}}$$

E_m, E_c and E_{fe} are the elasticity moduli of the infill, concrete used for retrofit and the frame material, respectively. The other terms in the equation are defined as follows: t_{inf} is the thickness of the infill wall, t_c is the thickness of the concrete, θ is the angle of the diagonal strut with the horizontal, h_{col} and I_{col} are the height and moment of inertia of the section of the column of the surrounding frame, h_{inf} is the height of the infill wall panel and L_{diag} is the length of the diagonal strut. The strengths of compression and tension members are calculated with the following Equations.

$$Ncomp = \frac{A_{inf} \cdot fs_{inf} + A_c \cdot 3.3 \cdot \sqrt{f_c}}{\cos \theta}$$

$$Ntens = \frac{A_s \cdot f_{ys} \cdot L_{inf}/s}{\cos \theta}$$

A_{inf} and A_c (in2) are the cross-sectional area of the infill wall and concrete, respectively, fs_{inf} is the shear strength of masonry, f_c is concrete strength (psi), and θ is the angle of the diagonal strut with the horizontal. A_s is the total cross-sectional area of horizontal mesh reinforcement with spacing s, f_{ys} is the strength of steel, and L_{inf} is the wall length.

NOTE: For masonry struts, use the actual masonry properties, if known, to calculate the equivalent strut capacity. If the actual properties are not known, use the low values in ASCE-41. Parametric studies, where the analyst conducts a series of analyses that vary one property of interest, such as a material strength, while leaving the others fixed, are very useful in bounding the potential response when the masonry properties are not known.

Using lower masonry strengths is not necessarily conservative, because stronger infill panels can cause shear failures in the adjacent columns.

Pushover Analysis using Csi ETABS Software

Pushover analysis is a very powerful feature offered only in the non-linear version of ETABS. In addition to performing pushover analyses for performance-based seismic design, this feature can be used to perform general static nonlinear analysis and the analysis of staged (incremental) construction. ETABS menus and documentation refer to pushover analysis as static nonlinear analysis.

Performing any nonlinear analysis takes time and requires patience. Please read the following information carefully before performing pushover analysis. Make sure to pay special attention to the Important Considerations section later in this guide. The key points for conducting pushover analysis can be summarized as follows:

1. **Defining how nonlinearity is considered**
2. **Determining analysis cases**
3. **Defining loading**
4. **Selecting the type of load control**
5. **Analysis Results**
6. **Procedure for conducting pushover analysis**

1.   Defining how nonlinearity is considered

Several types of nonlinear behavior can be considered in a pushover analysis:

Material Nonlinearity at Discrete, User-Defined Hinges in Frame/Line Elements.

Plastic hinges can be assigned at any number of locations along the length of any frame element**,** wherever yielding or other inelastic behavior is expected. Uncoupled moment, torsion, axial force and shear hinges are available. There is also a coupled P-M2-M3 hinge that considers the interaction of axial force and bending moments at the hinge location. More than one type of hinge can exist at the same location. For example, you might assign both an M3 (moment) and a V2 (shear) hinge to the same end of a frame element. Default hinge properties are provided based on ATC-40 and FEMA-356 criteria.

For reinforced concrete frame buildings, use coupled P-M hinges when modelling columns and uncoupled moment hinges for beams. *Separate shear hinges are recommended*. To reduce the

size and complexity of the model, a number of analysts check shear forces in each member against that member's shear capacity rather than using shear hinges.

NOTE: Define the hinges using the criteria in ASCE 41. *The hinge properties should properly consider the likely as-built conditions, rather that only the design drawings or code provisions*. Many buildings in various countries worldwide will have columns with poor confinement and inadequate ties. Model the hinges conservatively, assuming that the strength and deformation capacity are on the low end of the possible range.

Material Nonlinearity in the Link Elements.

The available nonlinear behavior includes gap (compression only), hook (tension only), uniaxial plasticity along any degree of freedom, and two types of base isolators (biaxial plasticity and biaxial friction/pendulum). The link damper property has no effect in a static nonlinear analysis.

Geometric Nonlinearity in All Elements.

You can choose between considering only P-delta effects or considering P-delta effects plus large displacements. Large displacement effects consider equilibrium in the deformed configuration and allow for large translations and rotations. However, the strains within each element are assumed to remain small. *The P-Delta effects option (without large deformations) is recommended.*

Adding or Removing Elements.

Members can be added or removed in a sequence of stages during each analysis case.

2.   Determining Analysis Cases

Static nonlinear analysis can consist of *any number of cases*. Each static nonlinear case can have a different distribution of load on the structure. For example, a typical static nonlinear analysis might consist of three cases. The first would apply *Gravity* load to the structure, the second would apply one distribution of lateral load over the height of the structure, and the third would apply another distribution of lateral load over the height of the structure.

A static nonlinear case may start from zero initial conditions, or it may start from the results at the end of a previous case. In the previous example, the gravity case would start from zero initial conditions, and *each of the two lateral cases could start from the end of the gravity case.*

Static nonlinear analysis cases are completely independent of all other analysis types in ETABS. In particular, any initial P-delta analysis performed for linear and dynamic analysis has no effect upon static nonlinear analysis cases. ***The only interaction is that linear mode shapes can be used for loading in static nonlinear cases.***

3. Defining loading

The distribution of load applied on the structure for a given static nonlinear case is defined as a scaled combination of <u>ONE</u> or <u>MORE</u> of the following:

- o *Any static load case.*
- o *A uniform acceleration acting in any of the three global directions. The force at each joint is proportional to the mass assigned to that joint (i.e., that calculated from the tributary area) and acts in the specified direction.*
- o *A modal load for any Eigen or Ritz mode. The force at each joint is proportional to the product of the modal displacement (eigenvector), and the mass tributary to that joint, and it acts in the direction of the modal displacement.*

The load combination for each static nonlinear case is incremental, meaning it acts in addition to the load already on the structure if starting from a previous static nonlinear case.

- ➤ Floor slabs in reinforced concrete frame buildings are generally modelled as ***rigid diaphragms***. The rigid diaphragm causes the joints connected to the same floor slab to displace the same amount horizontally.

- ➤ *You will need to consider diaphragm deformations, and model the diaphragms as flexible, in the following cases:*

  - ➤ *Concrete slab is thinner than 100 mm (4 inches);*
  - ➤ *Diaphragm has span to depth ratio of 4:1 or greater, where span is defined as the span between lines of lateral resistance; and*
  - ➤ *Diaphragm has large opening (30% or more of floor area is a good rule of thumb).*

4. Selecting the Type of Load Control

ETABS has two distinctly different types of control available for applying the load. Each analysis case can use a different type of load control. The choice generally depends on the physical nature of the load and the behaviour expected from the structure:

Force Control. The full load combination is applied as specified. Force control should be used when the load is known (such as gravity load), and the structure is expected to be able to support the load in the elastic range. The analysis applies the full load value defined by the sum of all loads specified in the Load Pattern box (unless it fails to converge at a lower force value). This option is useful for applying gravity load to the structure.

Displacement Control. A single Monitored Displacement component (or the Conjugate Displacement) in the structure is controlled. The magnitude of the load combination is increased or decreased as necessary until the control; displacement reaches a value that you specify. Displacement control should be used when specified drifts are sought (such as in seismic loading), where the magnitude of the applied load is not known in advance, or when the structure can be expected to lose strength or become unstable.

➢ **Use Conjugate Displ. for Control**

The conjugate displacement is a generalized displacement measure that is defined as the work conjugate of the applied Load Pattern. It is a weighted sum of all displacement degrees of freedom in the structure: each displacement component is multiplied by the load applied at that degree of freedom, and the results are summed.

The conjugate displacement is usually the most sensitive measure of displacement in the structure under a given specified load. It is usually recommended that you use the conjugate displacement unless you can identify a displacement in the structure that monotonically increases during the analysis.

When you use the conjugate displacement to control the analysis, the load increments are adjusted in an attempt to reach the specified monitored displacement. However, the analysis will usually only approximately satisfy the targeted displacement, particularly if the monitored displacement is in a different direction than the conjugate displacement.

➢ **Monitor**

The Monitored Displacement is a single displacement component at a single point that is monitored during a static nonlinear analysis. When plotting the pushover curve, the program always uses the monitored displacement for the horizontal axis. The monitored displacement is also used to determine when to terminate a displacement-controlled analysis. The analysis is terminated when the Monitored Displacement reaches the specified Displacement Magnitude (unless it fails to converge at a lower displacement value).

NOTE: For the most meaningful pushover curve, it is important that you choose a monitored displacement that is sensitive to the applied load pattern. ***For example, you should not typically monitor degree of freedom UX when the load is applied in direction UY***. *Likewise, you should not monitor joints that are close to the restraints.*

NOTE: ***The target Displacement Magnitude for the Monitored Displacement is given a default value by ETABS of 0.04 times the Z coordinate at the top of the structure***. Note that if the base of the structure has a Z coordinate greater than zero, the default displacement may be quite large. You may change this value as necessary. Only the absolute value of the Displacement Magnitude is used: the direction of loading is determined by the specified load pattern.

5.   Analysis Results

ETABS provides several types of OUTPUT that can be obtained from the static nonlinear analysis:

1. Base Reaction versus Monitored Displacement can be plotted.

2. Tabulated values of Base Reaction versus Monitored Displacement at each point along the pushover curve, along with tabulations of the number of hinges beyond certain control points on their hinge property force-displacement curve can be viewed on the screen, printed, or saved to a file.

3. Base Reaction versus Monitored Displacement can be plotted in the ADRS format where the vertical axis is spectral acceleration and the horizontal axis is spectral displacement. The demand spectra can be superimposed on this plot.

4. Tabulated values of the capacity spectrum (ADRS capacity and demand curves), the effective period and the effective damping can be viewed on the screen, printed, or saved to a file.

5.The sequence of hinge formation and the color-coded state of each hinge can be viewed graphically, on a step-by-step basis, for each step of the static nonlinear case.

6. The member forces and stresses can be viewed graphically, on a step-by-step basis, for each step of the static nonlinear case.

7. Member forces and hinge results for selected members can be written to a file in spreadsheet format for subsequent processing in a spreadsheet program.

8. Member forces and hinge results for selected members can be written to a file in Access database format.

➢ **Check the status of the internal hinges**

Check the status of hinges to see if the structure can meet the demand or not. Based on the hinge states and the failure mechanisms, the need for retrofit and the type of retrofit can be determined.

The color of hinges (Figure7) defines the status of hinges. **This building needs a retrofit to prevent the soft story from forming. Once you have created a model, it is straightforward to modify it by adding new elements in different places to test out potential retrofit solutions.**
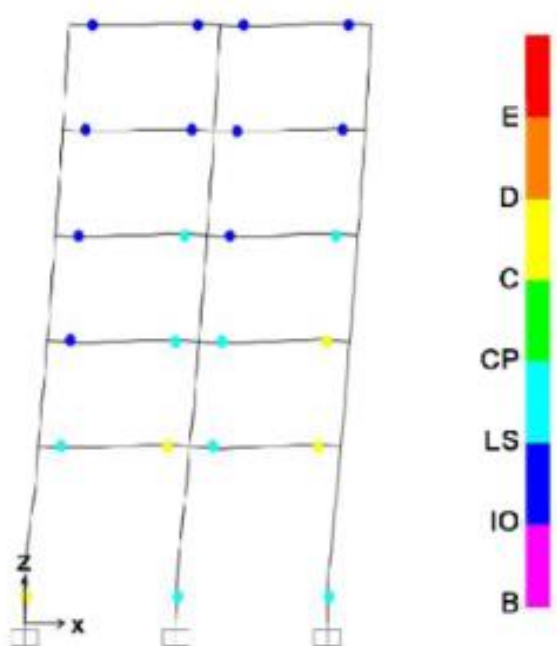

Figure 7. Hinge Status Color.

6.   Procedure for Conducting Pushover Analysis

The following general sequence of steps is involved in performing a static nonlinear analysis:

1. Create a model just like you would for any other analysis. Note that material nonlinearity is restricted to frame and link elements, although other element types may be present in the model.

2. Define the static load cases, if any, that are needed for use in the static nonlinear analysis (Define > Static Load Cases command). Define any other static and dynamic analysis cases that may be needed for steel or concrete design of frame elements.

3. Define hinge properties, if any (Define > Frame Nonlinear Hinge Properties command).

4. Assign hinge properties, if any, to frame/line elements (Assign > Frame/Line > Frame Nonlinear Hinges command).

5. Define nonlinear link properties, if any (Define > Link Properties command).

6. Assign link properties, if any, to frame/line elements (Assign > Frame/Line > Link Properties command).

7. Run the basic linear and dynamic analyses (Analyze > Run command).

8. Define the static nonlinear load cases (Define > Static Nonlinear/Pushover Cases command).

9. Run the static nonlinear analysis (Analyze > Run Static Nonlinear Analysis command).

10. Review the static nonlinear results (Display > Show Static Pushover Curve command), (Display > Show Deformed Shape command), (Display > Show Member Forces/Stress Diagram command), and (File > Print Tables > Analysis Output command).

11. Perform any design checks that utilize static nonlinear cases.

12. Revise the model as necessary and repeat

Conclusions

1. Infill walls can be beneficial as long as they are properly taken into consideration in the design process and **the failure mechanism is controlled (i.e., no weak story is allowed to occur)**

2. Nonlinear analysis takes time and patience. Each nonlinear problem is different. Expect to spend a certain amount of time to learn the best way to approach each new problem. Start simple and build up gradually. Make sure the model performs as expected under linear static loads and modal analysis. Rather than starting with hinges everywhere, add them gradually beginning with the areas where you expect the most nonlinearity. Start with hinge models that do not lose strength for primary members; modify the hinge models later or redesign the structure.

3. Perform your initial analyses without geometric nonlinearity. Add P-delta effects, and possibly large deformations later. Start with modest target displacements and a limited number of steps. In the beginning, the goal should be to perform the analyses quickly so that you can gain experience with your model. As your confidence grows with a particular model, you can push it further and consider more extreme nonlinear behavior.

4. Mathematically, pushover analysis does not always guarantee a unique solution. Inertial effects in dynamic analysis and in the real world limit the path a structure can follow. But this is not true for static analysis, particularly in unstable cases where strength is lost due to material or geometric nonlinearity.

5. Small changes in properties or loading can cause large changes in nonlinear response. For this reason, it is extremely important that you consider different loading patterns, and that you perform sensitivity studies on the effect of varying the properties of the structure. At minimum, the recommended lateral load patterns include a uniform load distribution and a triangular load distribution representing the fundamental vibration mode.

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