

4. Nonlinear Structural Response

Lesson Objectives:

- 1) Qualitatively **describe** a **hysteretic curve** and its key terminology including **elastic strain energy**, **dissipated hysteretic energy**, and **plastic deformation**.
- 2) **Define** and **compute** **ductility factors** based on maximum displacement, plastic deformation, and hysteretic energy.
- 3) **Describe** **nonlinear models** and **formulate** **equivalent elastic-perfectly plastic structural systems**.

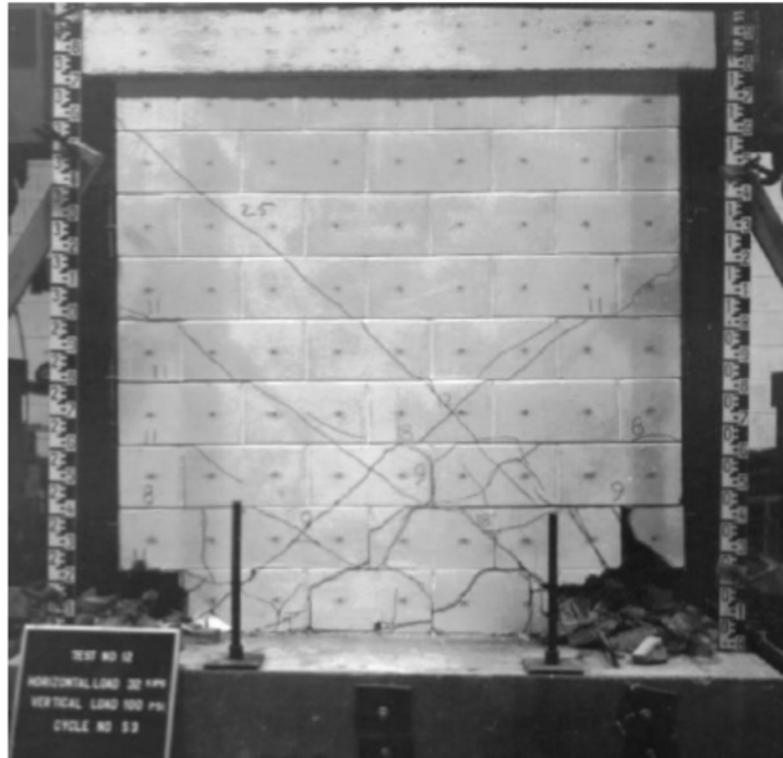
Background Reading:

- 1) **Read** _____.

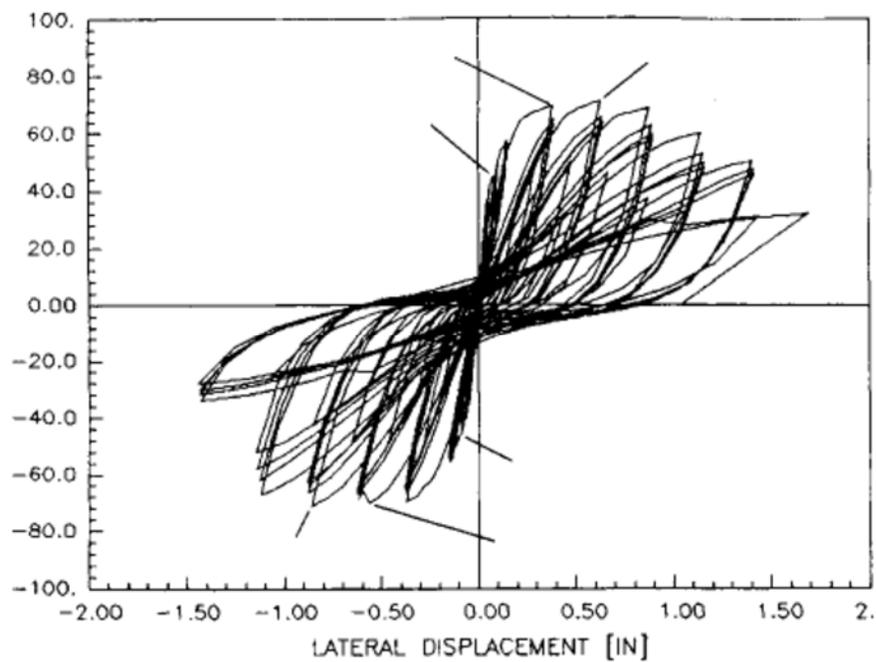
Structural Response:

- 1) In general, structures only remain _____ under moderate loads.
 - a. **Exceptions** may include _____ and _____.
- 2) Therefore once a structural exceeds its elastic limit, _____ is critical.
- 3) What is _____ ?
 - a. Defined as the **ability of a structure** to undergo _____.
 - b. A _____ structure can sustain a significant amount of _____ **prior to collapse** (or near-collapse states).
- 4) Often it is not practical to design structures to **remain** _____.
 - a. _____ and _____ are too high.
 - b. Exceptions exist for _____ and _____.
- 5) **Sources** of _____ include:
 - a. **Material:** _____
 - b. **Deformation:** _____

- c. Loads: _____
- 6) Sketch of **structural** _____ :
- 7) Examples of **brittle materials** include: _____ and _____.
- 8) _____ is considered to be _____.
- 9) The **use of reinforcing steel** within concrete and masonry structures is to enhance the _____.
- a. However, _____ and _____ reinforced walls can lead to _____ or **undesired behavior**.
- 10) Examples of two different masonry walls under cyclic displacement are shown below.
- 11) Note that the _____ produced the desired behavior:
- a. The **maximum attained forces** were _____
- b. The **lateral displacement** was _____
- c. The _____ was ductile, indicated a _____ failure mode.

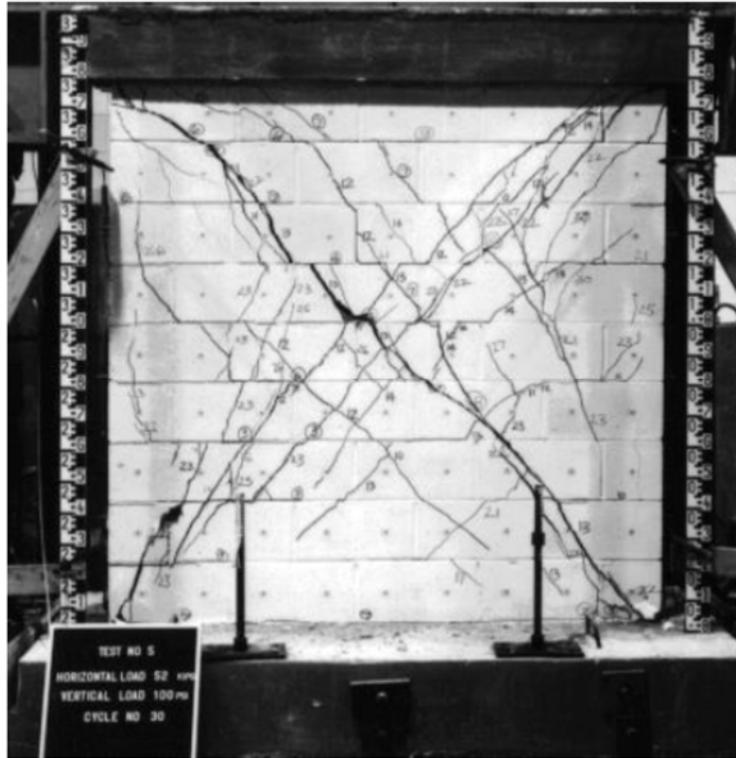


(a) Photo of specimen.

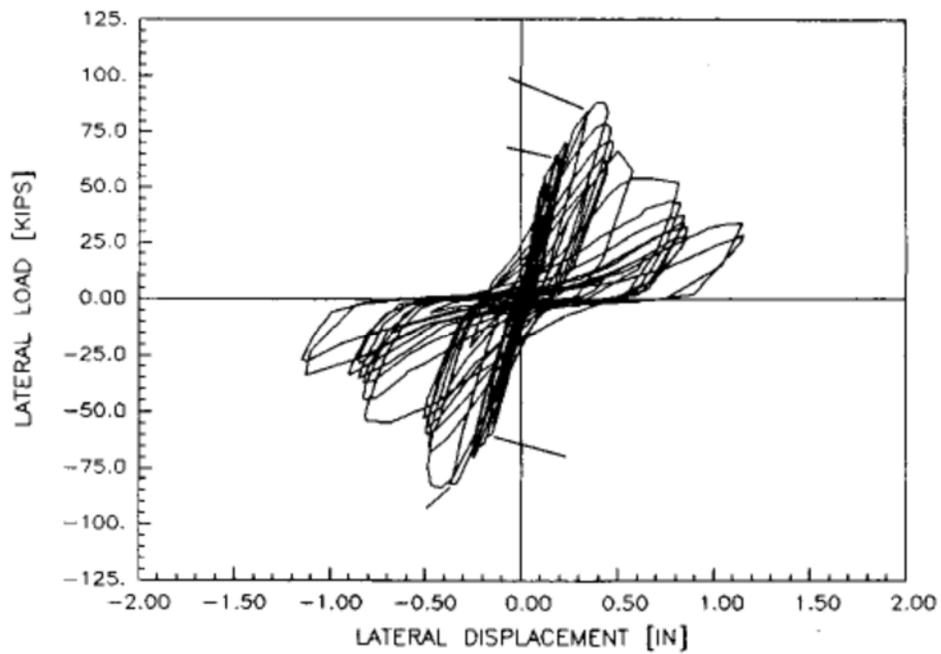


(b) Hysteretic response.

Figure 1. Masonry wall that is _____.



(a) Photo of specimen.



(b) Hysteretic response.

Figure 2. Masonry wall that is _____.

Energy Dissipation:

- 1) The ability of a structure to _____ and _____ energy has a profound influence on its dynamic performance.
- 2) A general sketch can be illustrated as:

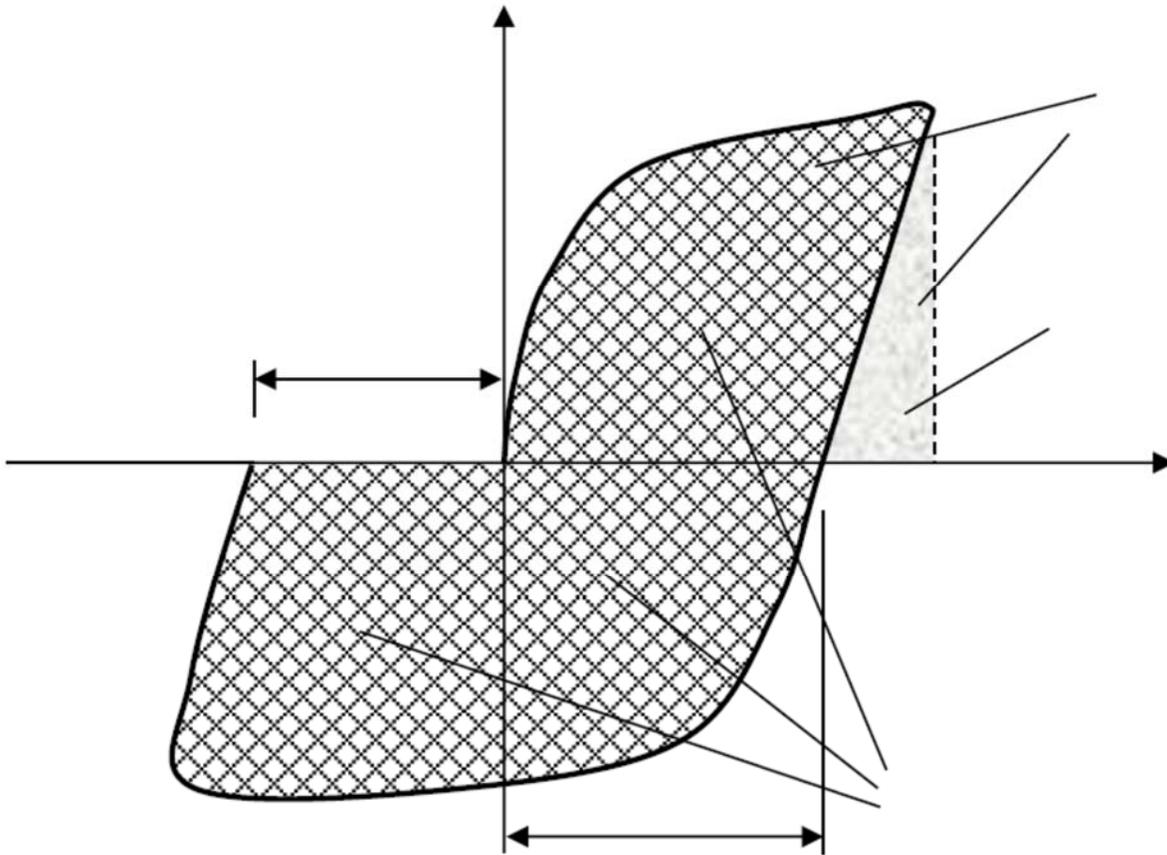


Figure 3. Force displacement hysteretic curve.

- 3) The **total energy absorbed** by the structure is the _____ under the load-deformation curve between zero and maximum deformations.
- 4) However, part of this **energy can be recovered** upon unloading. This is known as the _____.
- 5) The **irrecoverable energy** that the structure dissipated is known as _____. This is the area under the load-deformation curve after the load applied to the structure has been _____ >

- 6) A _____ structure is able to absorb more energy in comparison to a _____ structure.
- 7) However, a _____ structures does not necessarily _____ more energy.
- 8) Therefore in efficient structural dynamics design philosophy, it is desirable to have sufficient _____ to suppress the structural response under loads. This is measured as the size of the _____.

Ductility Factors:

- 1) Ductility quantify the ability of a structure (or material) to withstand an _____ deformation as well as the demand under a design or extreme load.
- 2) A structure is safe if the _____ is less than the _____ or capacity.
- 3) Ductility is a function of the structure _____ and _____.
- 4) Various ductility definitions exist. In these notes, four definitions are outlined.
 - a. _____
 - b. _____
 - c. _____
 - d. _____

Ductility Factor – Cyclic Response:

- 1) Under **cyclic displacement reversals**, the _____ may not reflect the actual maximum deformation experienced by the structure due to _____ that may develop.
- 2) Sketch is illustrated below:

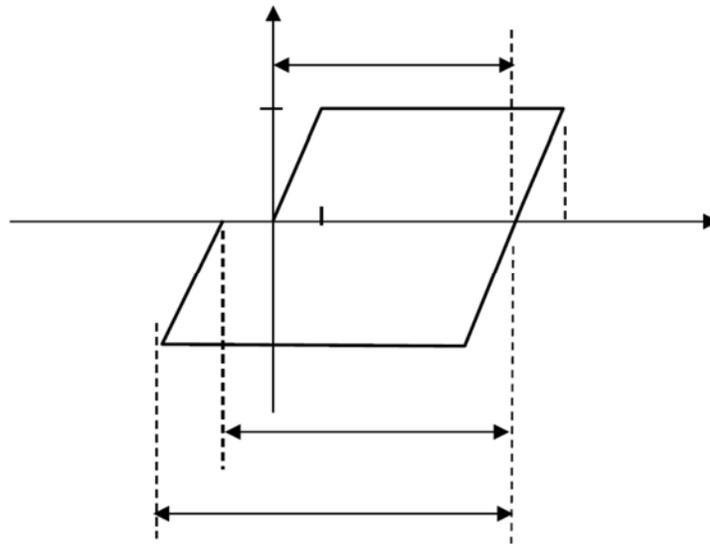


Figure 4. Ductility based upon actual maximum deformation experienced.

- 3) For this case, ductility can be defined as:
- 4) In this equation above, _____ represents the **actual maximum displacement excursion** that can be sustained by the structure before failure with consideration of the **residual** _____.

Structural Response and Progressive Yielding:

- 1) Many structures do not exhibit **idealized** _____ **behavior**, even though they may be constructed of _____ materials.
- 2) This is often due to the _____ across a section of a beam or column during bending. This results in the sequential development of _____ at the structural level.
- 3) In addition, **some materials** such as _____ do not have distinct yield points.
- 4) Sketch of ductility based on first yield:

- 5) Where can one **define the first yield** then?
 - a. In a **reinforced concrete column**, the _____ behavior often begins when the _____ occurs at a very small displacement.
 - b. For a reinforced concrete column, typically the first yield is defined as the displacement at which the _____ **in the column starts to** _____.
 - c. However this may result in a very **small** _____ and therefore a very **large** _____.

Structural Response and Plastic Hinges:

- 1) When a **structure deforms nonlinear**, it is ideal to control/design for areas of _____ behavior.
- 2) To **accommodate the plastic behavior**, special _____ requirements are established.
 - a. For regions of interest, reduced _____ **reinforcement spacing** is made to ensure enhanced ductility in a reinforced concrete element.
 - b. This is done to ensure that the regions of interest behave as _____.
- 3) The **various detailing** represent different **global ductility** of the structure and is a function of the **construction style** and **material**.
 - a. **More on this when design codes are presented.**
- 4) Within two general classes of structures, it is ideal to localize the plastic hinging into defined regions.
 - a. **Buildings** – adopt a philosophy of _____.
 - i. **Plastic hinges** are ideally located at the _____ and at the _____ of the building.
 - b. **Bridges** – plastic hinges are ideally located at _____.

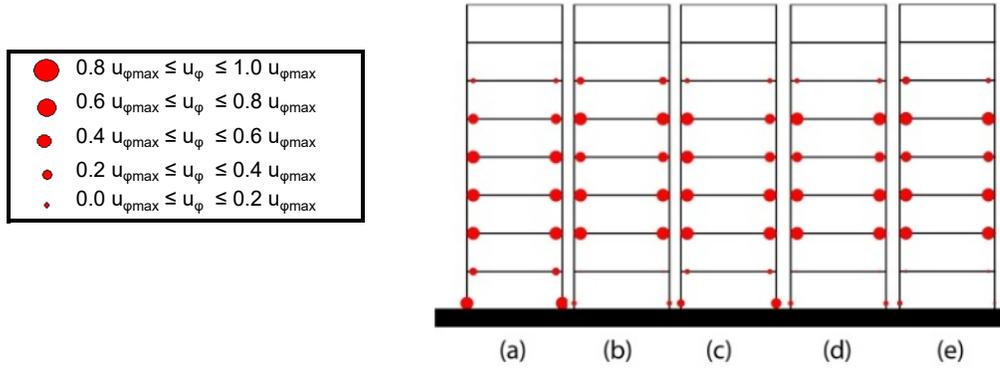


Figure 5. Location of developed average maximum plastic hinges induced from time history analyses in an eight story reinforced concrete special moment resisting frame building. Note is this a function of the ground motion scaling, where the following methods were performed: (a) code, (b) fundamental, (c) range, (d) sweep and (e) baseline (BL)¹.

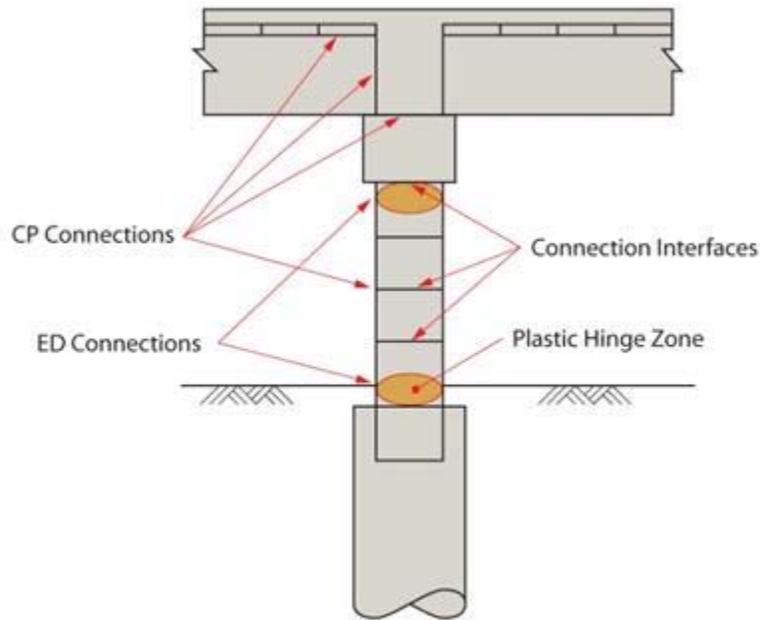


Figure 6. Plastic hinge locations in a bridge bent system for high seismic regions².

¹ Figure obtained from: Wood, R.L. and Hutchinson, T.C. (2012) "Effects of Ground Motion Scaling on Nonlinear Higher Mode Building Response." *Earthquakes and Structures*, 3(6): 869-887.

² Figure obtained from: Marsh, M. L., Stringer, S. J., Stanton, J. F., Eberhard, M. O., Haraldsson, O. S., Tran, H. V., et al. (2013) *Precast Bent System for High Seismic Regions*. (No. FHWA-HIF-13-037-C). Federal Highway Administration. Washington, DC. 84p.

Nonlinear Models:

1) **Common models** for nonlinearity include:

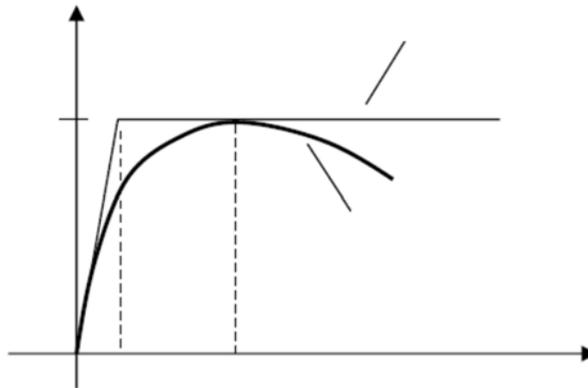
2) _____

3) _____

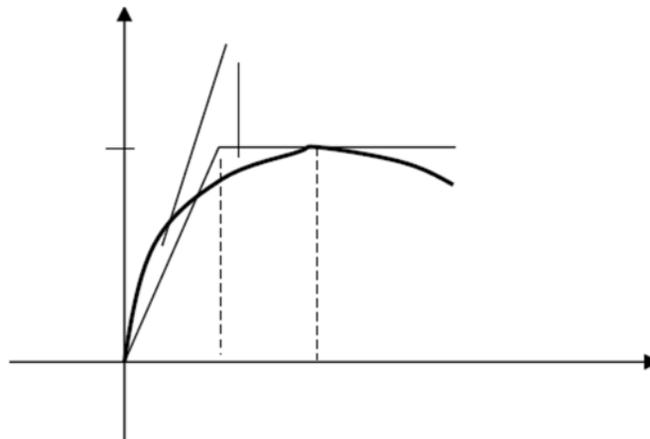
4) _____

Equivalent Elastic-Perfectly Plastic Structures:

- 1) Often it may be desirable to define an **equivalent elastic-perfectly plastic system** for a structure that has **continuously varying nonlinearity**.
- 2) This is needed such that **an _____** as derived for an elastic-perfectly plastic system can be applied.
- 3) Three methods to construct equivalent elastic-perfectly plastic structures can be demonstrated via the sketches below.
- 4) **Maximum resistance equal to that of the original structure**, sketch:

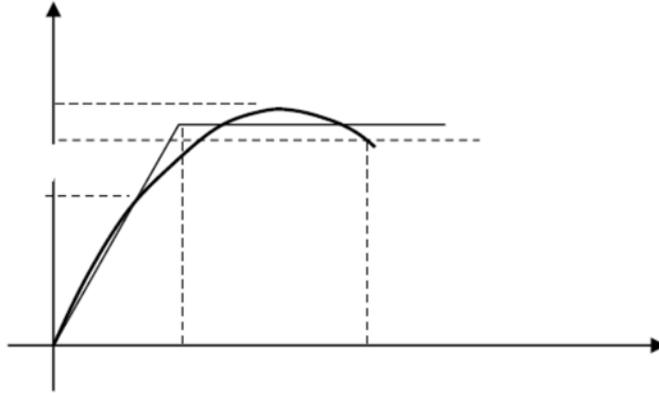


- a. This is considered **less conservative** since it over-estimates the _____ capability of the structure.
 - b. An analyst must still determine the maximum _____ as well as the yield displacement _____.
- 5) **Equal energy dissipation capacity** or equal area, sketch:



- a. This is **more representative** of the _____.

- b. However the **post-peak** _____ of the structures is not considered.
 - c. Often times, a structure may still be considered _____ and _____ even if it passed it peak strength.
- 6) **Displacement based on certain percentage of post-peak strength**, sketch:



- a. The post-peak behavior is utilized in this scenario.
- b. The value of ____ depends on the **type of structure** and the level of desired _____.
- c. For many structures, including _____ and _____, _____ can be taken as _____.
- d. This results in a yield strength of the equivalent elastic-plastic structure can be somewhere between _____ and _____ as well as contain approximately the same _____ as the original structure.