2C09
Design for seismic and climate changes

Lecture 19: Performance-based seismic design

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Sustainable Constructions
under Natural Hazards and Catastrophic Events

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Lecture outline

19.1 Need for performance based design

19.2 Performance objectives

19.3 Structural performance levels

19.4 Seismic hazard levels

19.5 Modelling and performance criteria

Modern seismic design codes

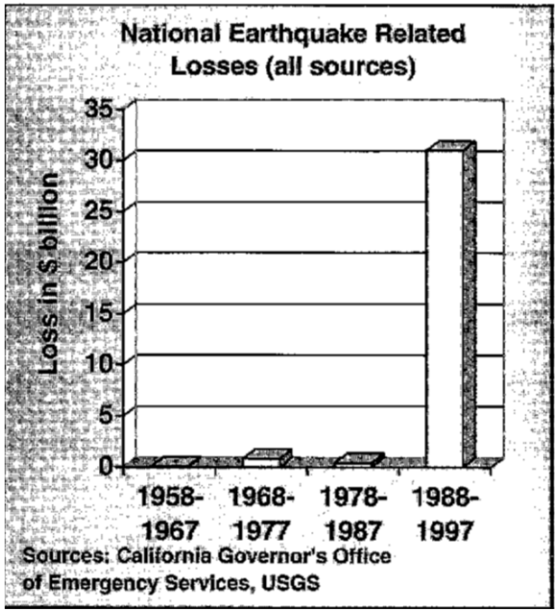
Design codes	Reality
Recommends regulate and simple structures.	Most structures do not fulfil code regularity requirements.
Structural response modelled using a elastic static analysis. Ductility of the structure quantified through the behaviour factor *q*.	Most structures will respond in the inelastic range during a design earthquake, the response being affected by the dynamic nature of the seismic action.
Check at the SLS by limiting lateral drifts.	- Only non-structural components are targeted. - Other response quantities may be more relevant (acc.)
…	…

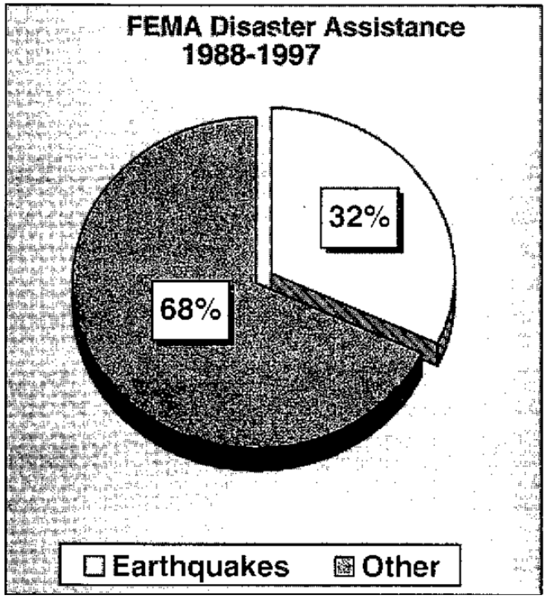
Modern seismic design codes

- Modern seismic design codes are prescriptive and try to be simple.
- Though the objective of the seismic design codes is to provide certain performance levels, the ability of the structure to attain a certain performance level is NOT evaluated as a part of a traditional design process.
- The real performance of code-designed buildings can be better than the minimum requirements, or worse.
- Building owners and tenants have generally the perception that structures designed to modern codes have a high safety level, and their damage is not probable.

Need for performance based seismic design

- **Earthquakes produced at the end of the 20th century (e.g. 1994 Northridge earthquake and 1995 Kobe earthquake):**
  - **Has forced recognition that damage, sometimes severe, can occur in buildings designed in accordance with the code.**
  - **Property and insured losses as a result of the Northridge Earthquake, recognized as the most costly earthquake in U.S. history, led to an awareness that the level of structural and nonstructural damage that could occur in code-compliant buildings may not be consistent with public notions of acceptable performance.**





Need for performance based seismic design

- Increased losses are due to several factors:
  - A larger density of the building stock in seismically active areas
  - An increasingly older building stock
  - Larger costs of business interruption
  - Larger share of losses due to failure of nonstructural components and contents (in case of high-tech industries and medical facilities).
- However, there is a major misperception on the part of many owners, insurers, lending institutions and government agencies about the expected performance of a code conforming building.
- Current codes clearly serve an essential and effective role in protecting building occupants. The design basis of the code is intended to provide a basic level of safety and a relatively economical means by which to construct buildings.
- Stakeholders are demanding that practical and cost-effective means be developed to address the issues of damage control and loss reduction.

Need for performance based seismic design

- Developments in the field of earthquake engineering

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- Need for seismic performance assessment methods able to provide stakeholders informations on expected level of building damage

+

- Acknowledgement of the fact that prescriptive design approach used for new buildings are NOT suitable for evaluation of existing ones (which do not satisfy a series of requirements for regularity, detailing, etc.)

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- Development of Performance Based Seismic Design methods (PBSD)

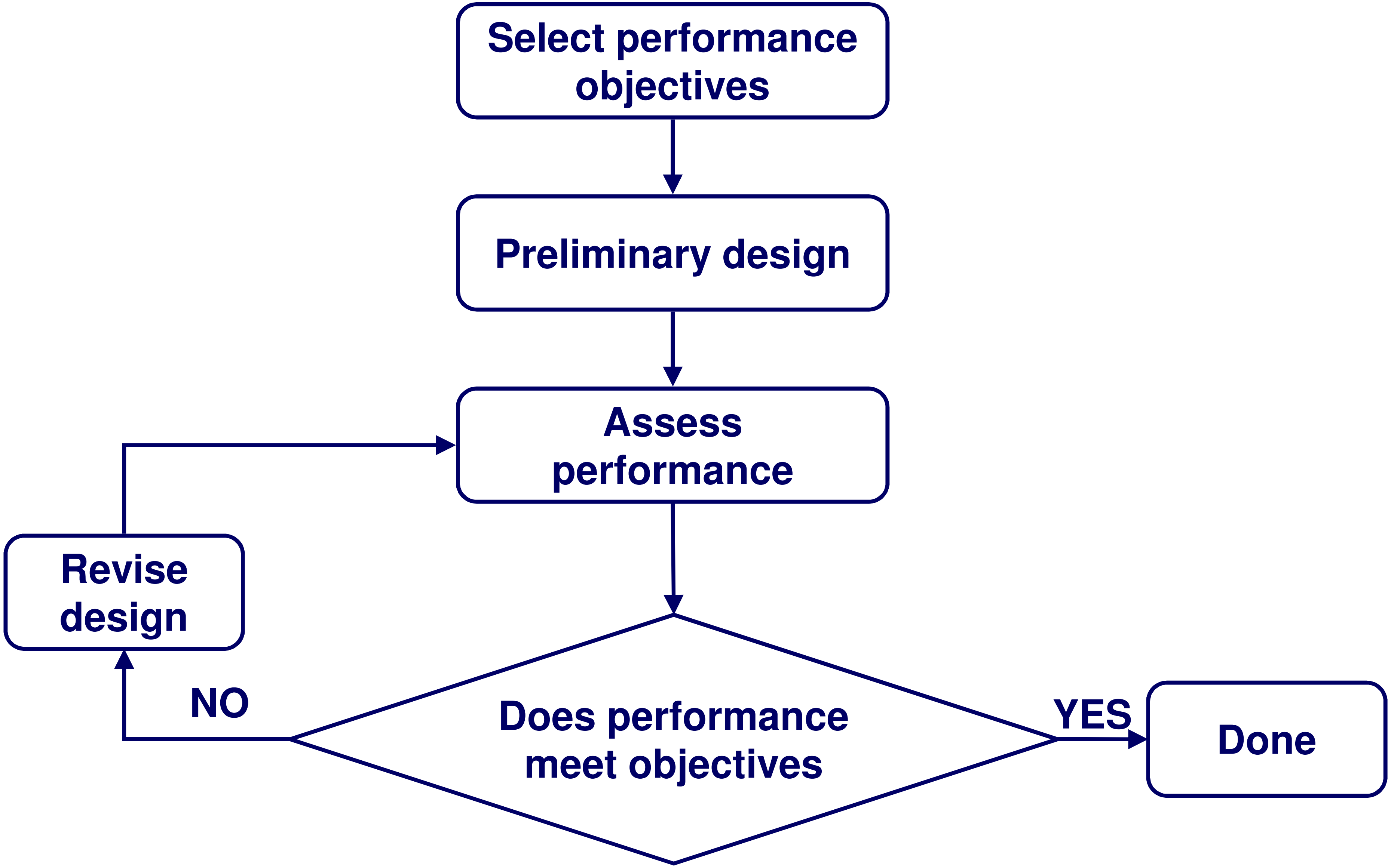
Performance based seismic design

- **Performance based seismic design (PBSD) offers engineers the possibility to design in a reliable way structures meeting a given performance level. At the same time, PBSD lets stakeholders to quantify financially (or otherwise) the risk to which their properties are prone, and to choose a performance level according to their needs, keeping a minimum level of safety.**

- **In PBSD identification and evaluation of seismic performance of the building is part of the design process.**

- **PBSD is an iterative process.**

Performance based seismic design



Performance based seismic design

- Performance-based design begins with the selection of design criteria stated in the form of one or more performance objectives.
- Each performance objective is a statement of the acceptable risk of incurring specific levels of damage, and the consequential losses that occur as a result of this damage, at a specified level of seismic hazard.
- Losses can be associated with
  – structural damage,
  – nonstructural damage, or
  – both.
- They can be expressed in the form of
  – casualties,
  – direct economic costs,
  – and downtime (time out of service)

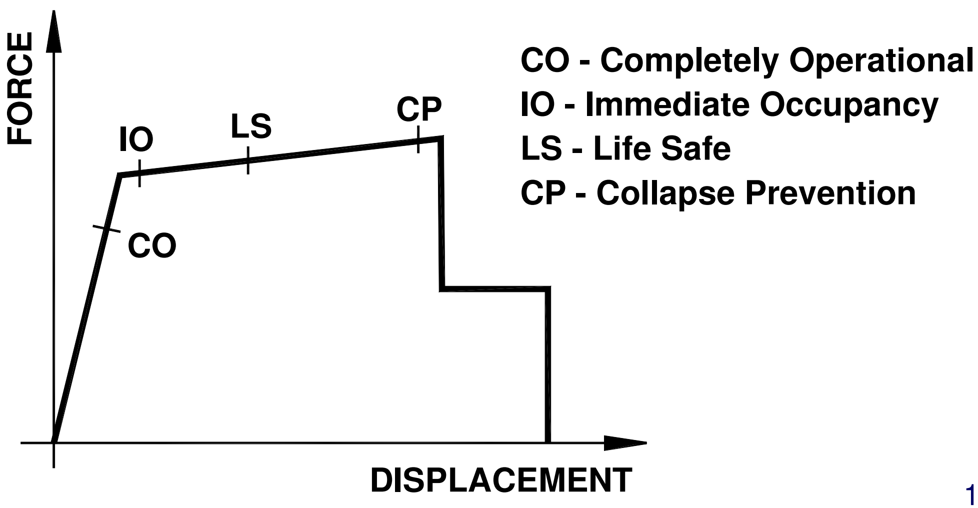
Performance based seismic design

- Generally, a team of decision makers, including the
  - building owner,
  - design professionals, and
  - building officials,

  will participate in the selection of performance objectives for a building.
- This team may consider the needs and desires of a wider group of stakeholders including prospective tenants, lenders, insurers and others who have impact on the value or use of a building, but may not directly participate in the design process.
- The basic questions that should be asked are:
  - What events are anticipated?
  - What level of loss/damage/casualties is acceptable?
  - How often might this happen?

Performance based seismic design

- The notion of acceptable performance follows a trend generally corresponding to:
  - Little or no damage for small, frequently occurring events
  - Moderate damage for medium-size, less frequent events
  - Significant damage for very large, very rare events
- Once the performance objectives are set, a series of simulations (analyses of building response to loading) are performed to estimate the probable performance of the building under various design scenario events.
- In the case of extreme loading, as would be imparted by a severe earthquake, simulations may be performed using nonlinear analysis techniques.



Performance based seismic design

- PBSD is an iterative process
- In some cases it may not be possible to meet the stated objective at reasonable cost, in which case, some relaxation of the original objectives may be appropriate.
- PBSD provides a systematic methodology for assessing the performance capability of a building, system or component.
- It can be used to:
  - verify the equivalent performance of alternatives,
  - deliver standard performance at a reduced cost,
  - or confirm higher performance needed for critical facilities.
- PBSD establishes a vocabulary that facilitates meaningful discussion between stakeholders and design professionals on the development and selection of design options.

Performance based seismic design

- PBSD provides a framework for determining what level of safety and what level of property protection, at what cost, are acceptable to stakeholders based upon the specific needs of a project.
- Performance-based seismic design can be used to:
  - Design individual buildings with a higher level of confidence that the performance intended by present building codes will be achieved.
  - Design individual buildings that are capable of meeting the performance intended by present building codes, but with lower construction costs.
  - Design individual buildings to achieve higher performance (and lower potential losses) than intended by present building codes.
  - Design individual buildings that fall outside of code-prescribed limits with regard to configuration, materials, and systems to meet the performance intended by present building codes.
  - Assess the potential seismic performance of existing structures and estimate potential losses in the event of a seismic event.
  - Assess the potential performance of current prescriptive code requirements for new buildings, and serve as the basis for improvements to code-based seismic design criteria so that future buildings can perform more consistently and reliably.

Performance objectives

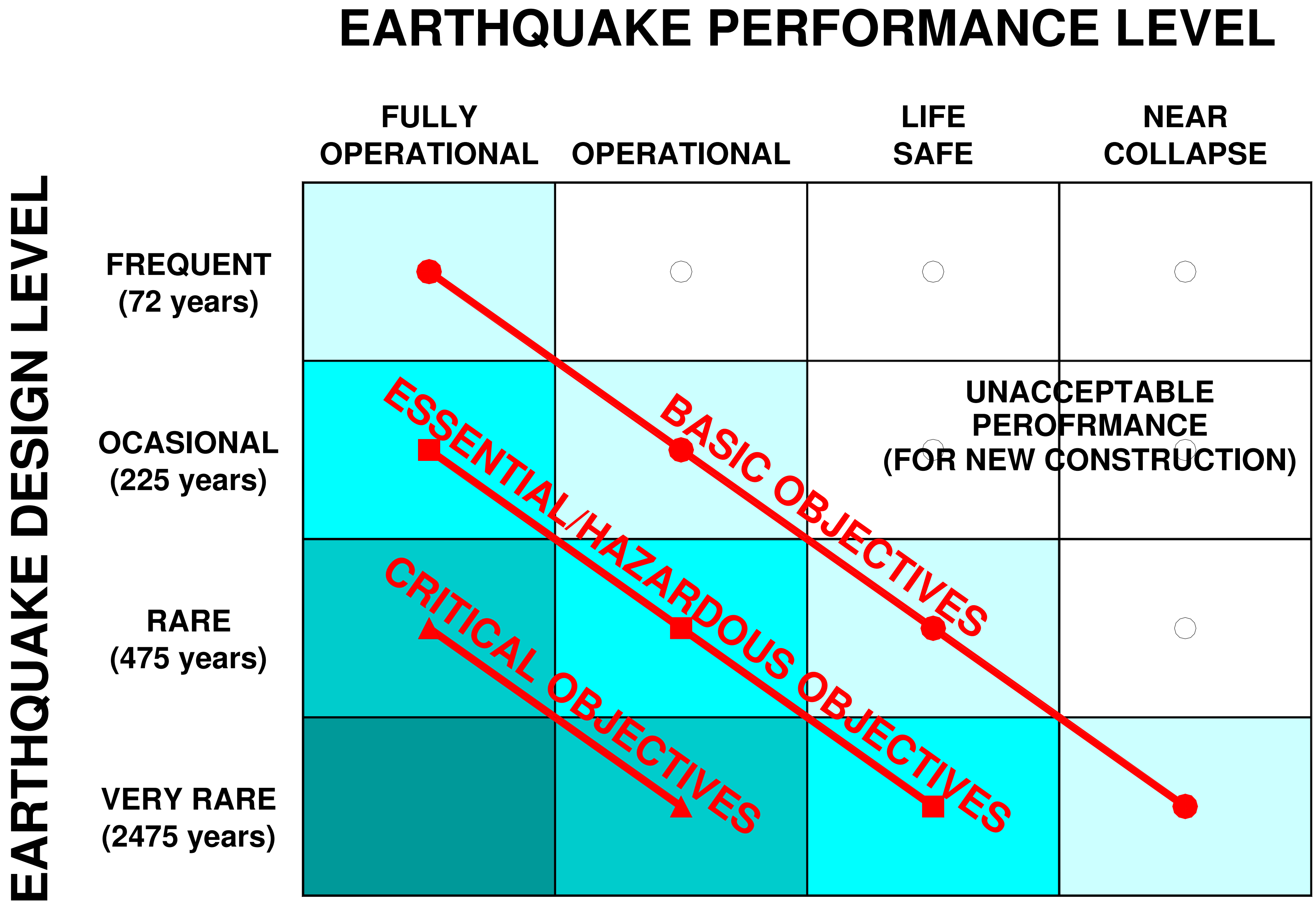
- **A performance objective is an acceptable risk of experiencing a specific damage level (with associated losses) for a specific level of seismic hazard**

- **The concept of performance objective is equivalent to the one of limit state**

- **For a building to fulfil a performance objective, it is necessary that it fulfils a given seismic performance level associated to a certain seismic hazard level**

- **Generally design or evaluation of a building implies fulfilling of more performance objectives (limit states), depending on importance class and the requirements of the stakeholder**

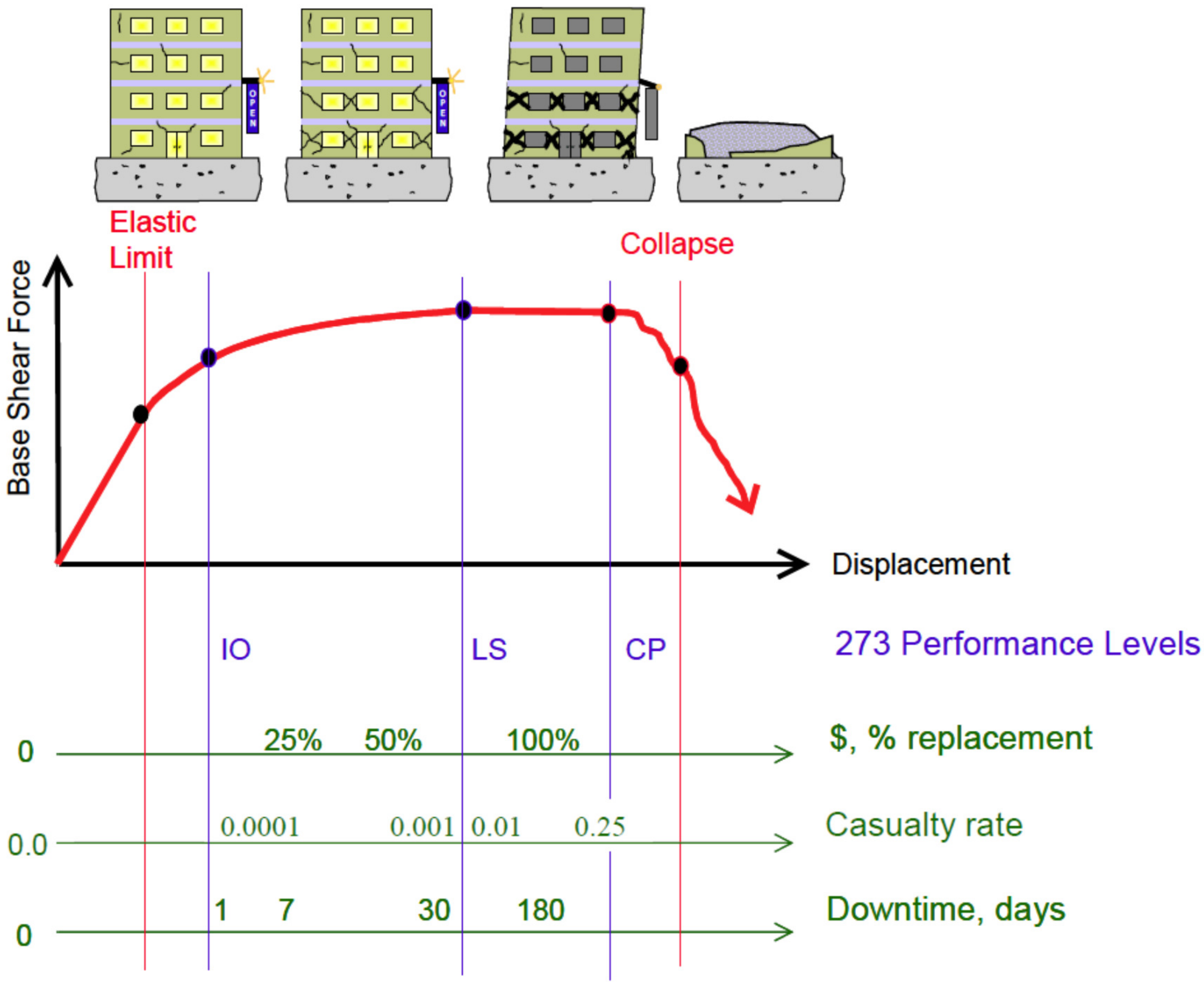
Choosing performance objectives



Performance levels

- **Performance level of a building can be expressed quantitatively through:**
  - **Safety offered to building inhabitants during and after an earthquake**
  - **The cost and feasibility of building repair**
  - **Time during which is out of use due to repair**
  - **Economic, architectural and historical impact on the community**
- **Performance level depends directly on the level of degradations that the building is likely to experience**
- **Building performance is a combination of the performance of both <u>structural</u> and <u>nonstructural components</u>**
- **Building performance levels are discrete damage states selected from among the infinite spectrum of possible damage states that buildings could experience as a result of earthquake response.**

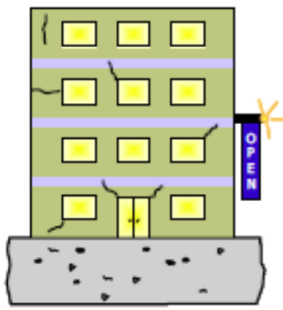
Performance levels



Structural performance levels (FEMA 356)

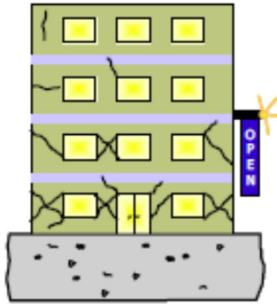
- **Structural Performance Levels (FEMA 356):**
  - Immediate Occupancy (S-1),
  - Life Safety (S-3),
  - Collapse Prevention (S-5),
  - Not Considered (S-6).

- **Immediate Occupancy (S-1):**
  - the post-earthquake damage state that remains safe to occupy, essentially retains the pre-earthquake design strength and stiffness of the structure
  - The risk of lifethreatening injury as a result of structural damage is very low, and although some minor structural repairs may be appropriate, these would generally not be required prior to reoccupancy.



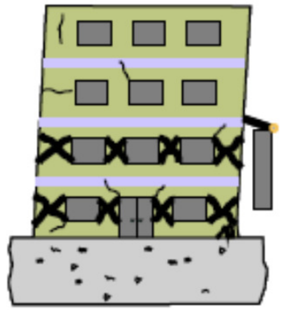
Structural performance levels (FEMA 356)

- **Life Safety (S-3):**
  - Significant damage to the structure has occurred, but some margin against either partial or total structural collapse remains.
  - Some structural elements and components are severely damaged, but this has not resulted in large falling debris hazards, either within or outside the building.
  - Injuries may occur during the earthquake; however, the overall risk of life-threatening injury as a result of structural damage is expected to be low.
  - It should be possible to repair the structure; however, for economic reasons this may not be practical. While the damaged structure is not an imminent collapse risk, it would be prudent to implement structural repairs or install temporary bracing prior to reoccupancy.



Structural performance levels (FEMA 356)

- **Collapse Prevention (S-5):**
  - The building is on the verge of partial or total collapse.
  - Substantial damage to the structure has occurred, potentially including significant degradation in the stiffness and strength of the lateral-force resisting system, large permanent lateral deformation of the structure, and – to a more limited extent – degradation in vertical-load-carrying capacity.
  - However, all significant components of the gravity load-resisting system must continue to carry their gravity load demands.
  - Significant risk of injury due to falling hazards from structural debris may exist.
  - The structure may not be technically practical to repair and is not safe for reoccupancy, as aftershock activity could induce collapse.



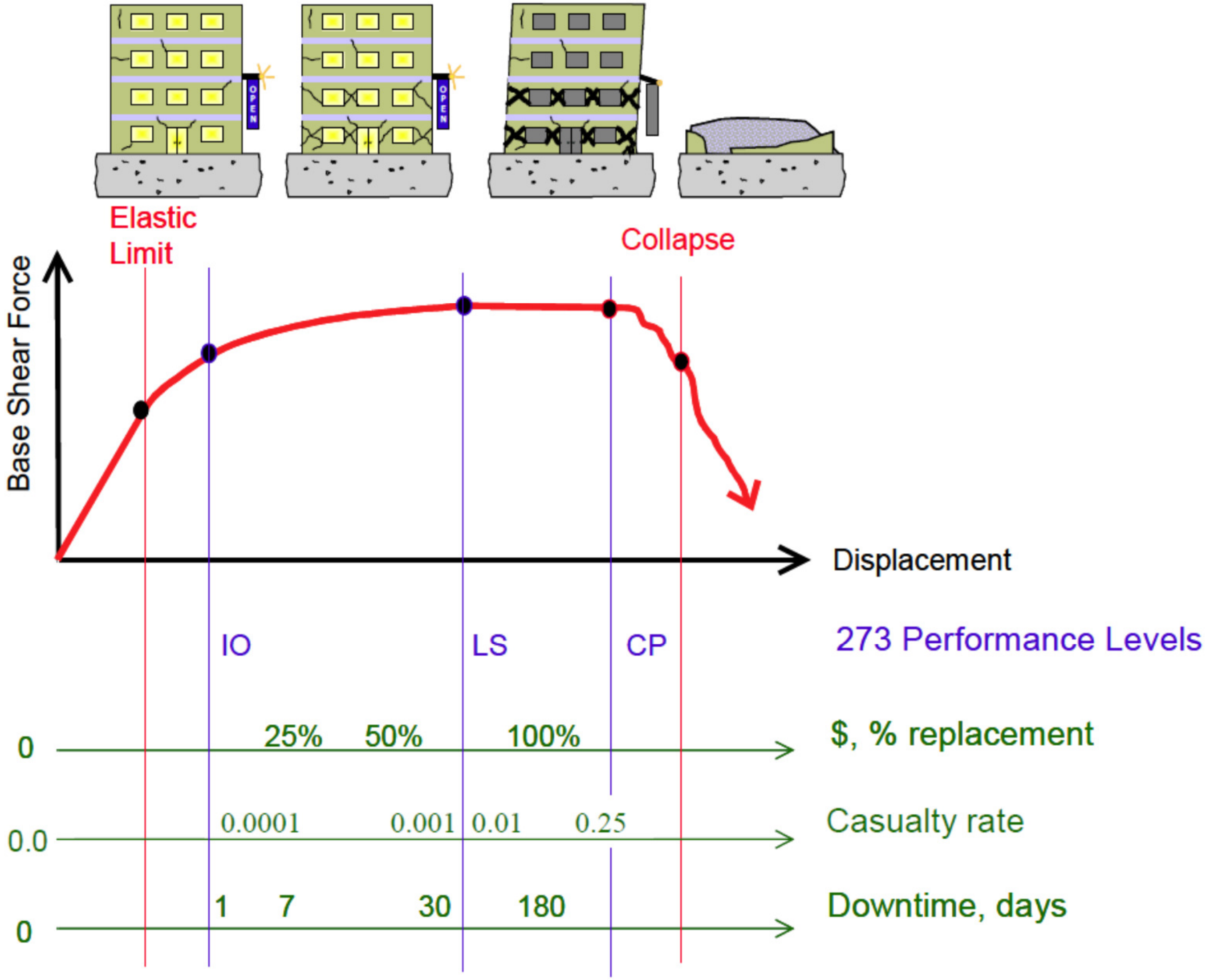
Structural performance levels (FEMA 356)

- **Not Considered (S-6):**
  - A building rehabilitation that does not address the performance of the structure
  - Some owners may desire to address certain nonstructural vulnerabilities in a rehabilitation without addressing the performance of the structure itself. Such rehabilitation programs are sometimes attractive because they can permit a significant reduction in seismic risk at relatively low cost.

- **Additionally to the four discrete performance levels, FEMA 356 includes two intermediate Structural Performance Ranges, which represent intermediate levels of structural performance:**
  - the Damage Control Range (S-2) and
  - the Limited Safety Range (S-4)

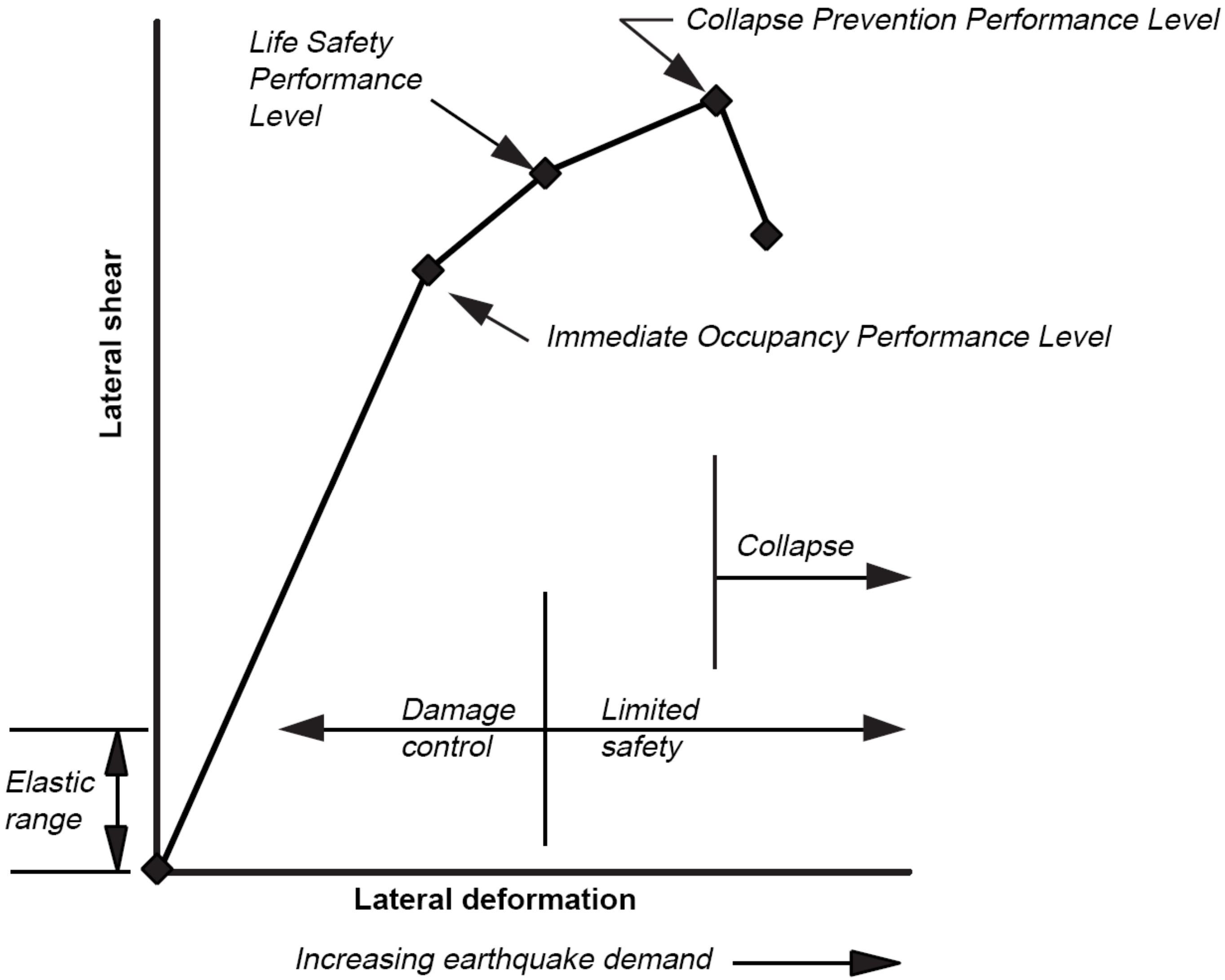
Structural performance levels (FEMA 356)

- **Structural performance levels: ductile response**



Structural performance levels (FEMA 356)

- **Structural performance levels: brittle response**



Structural performance levels (FEMA 356)

- **Examples of qualitative characterisation of structural performance levels in FEMA 356**

		Structural Performance Levels		
Elements	**Type**	**Collapse Prevention S-5**	**Life Safety S-3**	**Immediate Occupancy S-1**
Steel Moment Frames	Primary	Extensive distortion of beams and column panels. Many fractures at moment connections, but shear connections remain intact.	Hinges form. Local buckling of some beam elements. Severe joint distortion; isolated moment connection fractures, but shear connections remain intact. A few elements may experience partial fracture.	Minor local yielding at a few places. No fractures. Minor buckling or observable permanent distortion of members.
	Secondary	Same as primary.	Extensive distortion of beams and column panels. Many fractures at moment connections, but shear connections remain intact.	Same as primary.
	Drift	5% transient or permanent	2.5% transient; 1% permanent	0.7% transient; negligible permanent
Braced Steel Frames	Primary	Extensive yielding and buckling of braces. Many braces and their connections may fail.	Many braces yield or buckle but do not totally fail. Many connections may fail.	Minor yielding or buckling of braces.
	Secondary	Same as primary.	Same as primary.	Same as primary.
	Drift	2% transient or permanent	1.5% transient; 0.5% permanent	0.5% transient; negligible permanent

Non-structural performance levels (FEMA 356)

- **Nonstructural components include:**
  - architectural components such as partitions, exterior cladding, and ceilings; and
  - mechanical and electrical components, including HVAC systems, plumbing, fire suppression systems, and lighting.
  - partially – occupant contents and furnishings (such as inventory and computers) :
- **Although structural engineers typically have relatively little input to the design of these items, the way in which they perform in an earthquake can significantly affect the operability and even fitness for occupancy of a building following an earthquake.**
- **Even if a building’s structure is relatively undamaged, extensive damage to lights, elevators, and plumbing and fire protection equipment could render a building unfit for occupancy.**

Non-structural performance levels (FEMA 356)

- There are three basic issues related to the performance of nonstructural components:
  - Security of component attachment to the structure and adequacy to prevent sliding, overturning, or dislodging from the normal installed position
  - Ability of the component to withstand earthquake induced building deformations without experiencing structural damage or mechanical or electrical fault
  - Ability of the component to withstand earthquake induced shaking without experiencing structural damage or mechanical or electrical fault.

Non-structural performance levels (FEMA 356)

- Non-structural performance levels(FEMA 356):
  - Operational (N-A),
  - Immediate Occupancy (N-B),
  - Life Safety (N-C),
  - Hazards Reduced (N-D), and
  - Not Considered (N-E).

Non-structural performance levels (FEMA 356)

- **Operational (N-A):**
  - The nonstructural components are able to support the pre-earthquake functions present in the building.
  - Most nonstructural systems required for normal use of the building – including lighting, plumbing, HVAC, and computer systems – are functional, although minor cleanup and repair of some items may be required.
  - It requires considerations beyond those that are normally within the sole province of the structural engineer.
  - In addition to assuring that nonstructural components are properly mounted and braced within the structure, it is often necessary to provide emergency standby utilities.
  - It also may be necessary to perform rigorous qualification testing of the ability of key electrical and mechanical equipment items to function during or after strong shaking.

Non-structural performance levels (FEMA 356)

- **Immediate Occupancy (N-B):**
  - Damage to nonstructural components, but building access and life safety systems generally remain available and operable, provided that power is available.
  - Minor window breakage and slight damage could occur to some components.
  - Presuming that the building is structurally safe, occupants could safely remain in the building, although normal use may be impaired and some cleanup and inspection may be required.
  - In general, components of mechanical and electrical systems in the building are structurally secured and should be able to function if necessary utility service is available. However, some components may experience misalignments or internal damage and be nonoperable.
  - Power, water, natural gas, communications lines, and other utilities required for normal building use may not be available.
  - The risk of life-threatening injury due to nonstructural damage is very low.

Non-structural performance levels (FEMA 356)

- **Life Safety (N-C)**
  - Damage to nonstructural components but the damage is non-life threatening.
  - Potentially significant and costly damage has occurred to nonstructural components but they have not become dislodged and fallen, threatening life safety either inside or outside the building.
  - Egress routes within the building are not extensively blocked, but may be impaired by lightweight debris.
  - HVAC, plumbing, and fire suppression systems may have been damaged, resulting in local flooding as well as loss of function.
  - While injuries may occur during the earthquake from the failure of nonstructural components, overall, the risk of life-threatening injury is very low.
  - Restoration of the nonstructural components may take extensive effort.

Non-structural performance levels (FEMA 356)

- **Hazards Reduced(N-D)**
  - Damage to nonstructural components that could potentially create falling hazards, but high hazard nonstructural components are secured and will not fall into areas of public assembly.
  - Extensive damage has occurred to nonstructural components, but large or heavy items that pose a high risk of falling hazard to a large number of people—such as parapets, cladding panels, heavy plaster ceilings, or storage racks—are prevented from falling.
  - The intent of this Performance Level is to address significant nonstructural hazards without needing to rehabilitate all of the nonstructural components in a building.
- **Not Considered (N-E)**
  - Does not address nonstructural components.
  - In some cases, the decision to rehabilitate the structure may be made without addressing the vulnerabilities of nonstructural components. It may be desirable to do this when rehabilitation must be performed without interruption of building operation.

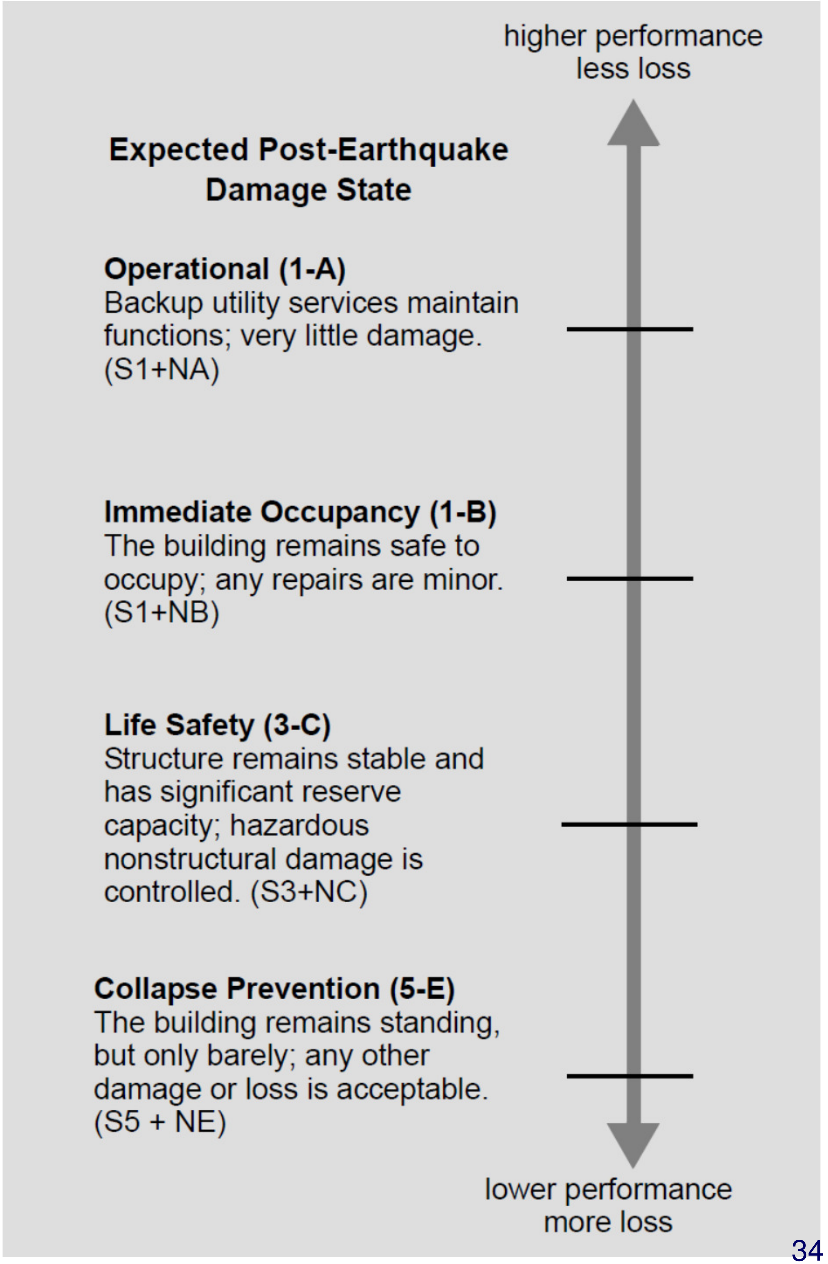
Non-structural performance levels (FEMA 356)

- **Examples of qualitative characterisation of non-structural performance levels in FEMA 356**

Component	Nonstructural Performance Levels			
	Hazards Reduced[2] N-D	Life Safety N-C	Immediate Occupancy N-B	Operational N-A
Cladding	Severe distortion in connections. Distributed cracking, bending, crushing, and spalling of cladding elements. Some fracturing of cladding, but panels do not fall in areas of public assembly.	Severe distortion in connections. Distributed cracking, bending, crushing, and spalling of cladding elements. Some fracturing of cladding, but panels do not fall.	Connections yield; minor cracks (<1/16" width) or bending in cladding.	Connections yield; minor cracks (<1/16" width) or bending in cladding.
Glazing	General shattered glass and distorted frames in unoccupied areas. Extensive cracked glass; little broken glass in occupied areas.	Extensive cracked glass; little broken glass.	Some cracked panes; none broken.	Some cracked panes; none broken.
Partitions	Distributed damage; some severe cracking, crushing, and racking in some areas.	Distributed damage; some severe cracking, crushing, and racking in some areas.	Cracking to about 1/16" width at openings. Minor crushing and cracking at corners.	Cracking to about 1/16" width at openings. Minor crushing and cracking at corners.
Ceilings	Extensive damage. Dropped suspended ceiling tiles. Moderate cracking in hard ceilings.	Extensive damage. Dropped suspended ceiling tiles. Moderate cracking in hard ceilings.	Minor damage. Some suspended ceiling tiles disrupted. A few panels dropped. Minor cracking in hard ceilings.	Generally negligible damage. Isolated suspended panel dislocations, or cracks in hard ceilings.

Performance levels (FEMA 356)

- **Building performance levels are obtained by considering:**
  - **A structural performance level and**
  - **A non-structural performance level.**
- **Examples:**
  - **Operational(1-A) = (S1+NA)**
  - **Immediate occupancy (1-B) = (S1+NB)**
  - **Life safety (3-C) = (S3+NC)**
  - **Collapse prevention (5-E) = (S5+NE)**



Performance levels (FEMA 356)

- **Examples of qualitative characterisation of nbuilding performance levels in FEMA 356**

	Target Building Performance Levels			
	Collapse Prevention Level (5-E)	**Life Safety Level (3-C)**	**Immediate Occupancy Level (1-B)**	**Operational Level (1-A)**
Overall Damage	Severe	Moderate	Light	Very Light
General	Little residual stiffness and strength, but load-bearing columns and walls function. Large permanent drifts. Some exits blocked. Infills and unbraced parapets failed or at incipient failure. Building is near collapse.	Some residual strength and stiffness left in all stories. Gravity-load-bearing elements function. No out-of-plane failure of walls or tipping of parapets. Some permanent drift. Damage to partitions. Building may be beyond economical repair.	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. Elevators can be restarted. Fire protection operable.	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. All systems important to normal operation are functional.
Nonstructural components	Extensive damage.	Falling hazards mitigated but many architectural, mechanical, and electrical systems are damaged.	Equipment and contents are generally secure, but may not operate due to mechanical failure or lack of utilities.	Negligible damage occurs. Power and other utilities are available, possibly from standby sources.
Comparison with performance intended for buildings designed under the *NEHRP Provisions,* for the Design Earthquake	Significantly more damage and greater risk.	Somewhat more damage and slightly higher risk.	Less damage and lower risk.	Much less damage and lower risk.

Seismic hazard levels

- The level of the seismic action at a site can be expressed probabilistically in terms of:
  - reference return period, T_R
  - reference probability of exceedance, P_R in T_L years

- Relation between T_R, P_R, and T_L:

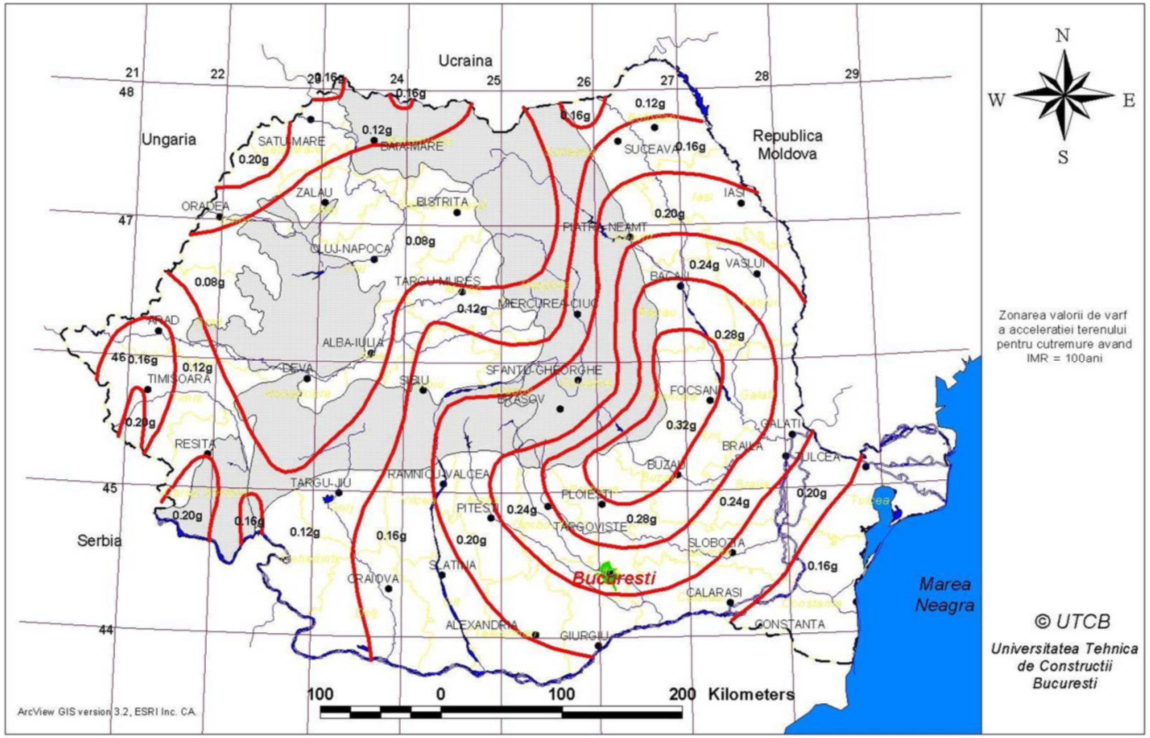
$$T_R = -\frac{T_L}{\ln(1 - P_R)}$$

- Seismic hazard levels in FEMA 356

Earthquake Having Probability of Exceedance	Mean Return Period (years)
50%/50 year	72
20%/50 year	225
10%/50 year	474
2%/50 year	2,475

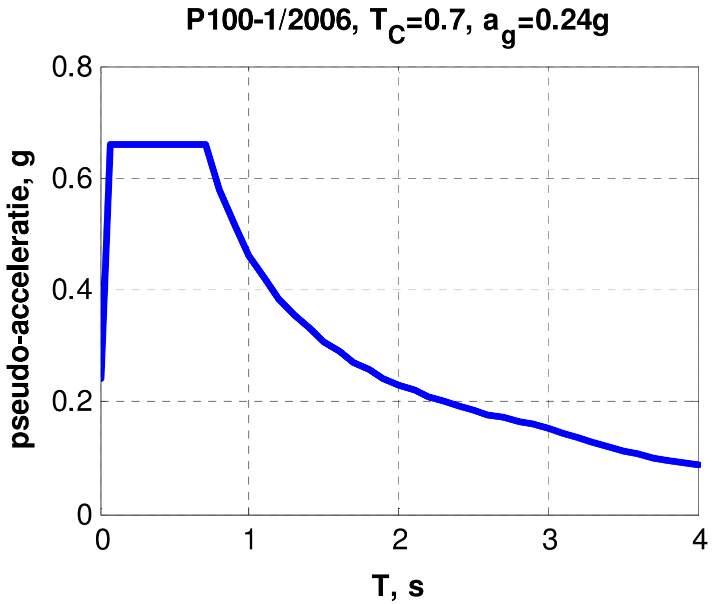
Seismic hazard levels

- **The seismic hazard is described in terms of a single parameter, i.e. the value of the reference peak ground acceleration a_g (for a given return period)**
- **Ex: Eurocode 8: 2004 uses at ULS**
  - **T_R = 475 years**
  - **P_R = 10% in T_L = 50 years**

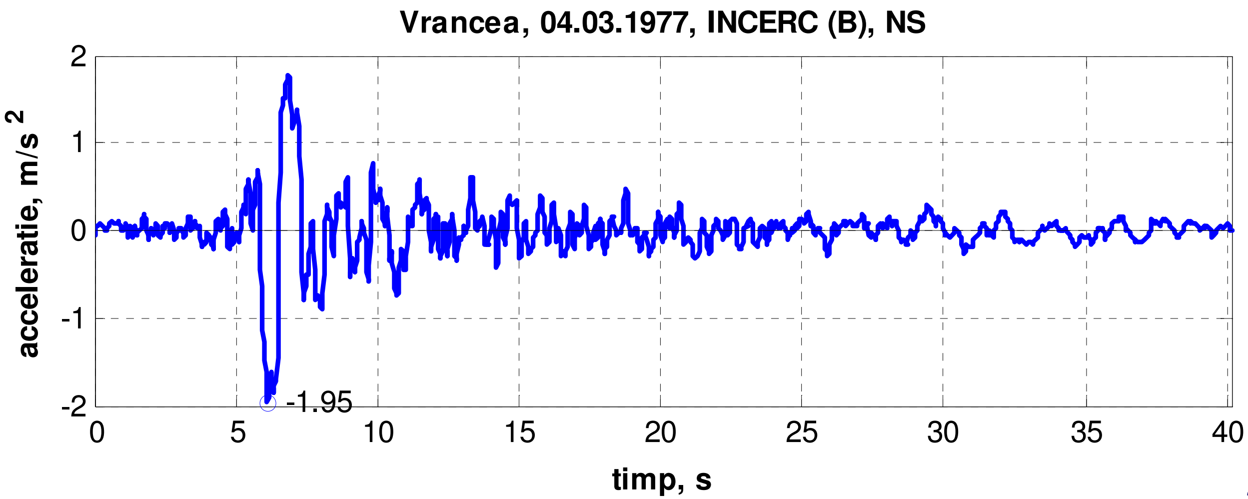


Seismic hazard levels

- Seismic action at a site is defined using:
  - Elastic response spectra (pseudo-acceleration)



  - accelerograms



Performance objectives in FEMA 356

- FEMA 356 uses 16 discrete performance objectives (a - p)
- They can be combined in sets of performance objectives:
  - Basic Safety Objective
  - Enhanced Objectives
  - Limited Objectives

Table C1-1 Rehabilitation Objectives

		Target Building Performance Levels			
		Operational Performance Level (1-A)	Immediate Occupancy Performance Level (1-B)	Life Safety Performance Level (3-C)	Collapse Prevention Performance Level (5-E)
Earthquake Hazard Level	50%/50 year	a	b	c	d
	20%/50 year	e	f	g	h
	BSE-1 (~10%/50 year)	i	j	k	l
	BSE-2 (~2%/50 year)	m	n	o	p

Performance objectives in FEMA 356

- **Basic Safety Objective (BSO)**
  - **Is intended to approximate the earthquake risk to life safety traditionally considered acceptable in design**
  - **Life safety (3-C) for 10%/50 years [k] and Collapse prevention (5-E) for 2%/50 years [p]**

Table C1-1 Rehabilitation Objectives

		Target Building Performance Levels			
		Operational Performance Level (1-A)	**Immediate Occupancy Performance Level (1-B)**	**Life Safety Performance Level (3-C)**	**Collapse Prevention Performance Level (5-E)**
Earthquake Hazard Level	50%/50 year	a	b	c	d
	20%/50 year	e	f	g	h
	BSE-1 (~10%/50 year)	i	j	k	l
	BSE-2 (~2%/50 year)	m	n	o	p

Performance objectives in FEMA 356

- **Enhanced Objectives**
  - Rehabilitation that provides building performance exceeding that of the BSO
  - Building Performance Levels that exceed those of the BSO (Method 1)
  - Earthquake Hazard Levels that exceed those of the BSO (Method 2)
  - Combination between M1 and M2
- **Examples:**
  - k + p + any of a, e, i, b, f, j, or n
  - o or n or m

Table C1-1 Rehabilitation Objectives

Earthquake Hazard Level		Target Building Performance Levels: Operational Performance Level (1-A)	Immediate Occupancy Performance Level (1-B)	Life Safety Performance Level (3-C)	Collapse Prevention Performance Level (5-E)
	50%/50 year	a	b	c	d
	20%/50 year	e	f	g	h
	BSE-1 (~10%/50 year)	i	j	k	l
	BSE-2 (~2%/50 year)	m	n	o	p

Performance objectives in FEMA 356

- **Limited Performance Objectives: building performance less than that of the BSO**
- **Examples:**
  - Life safety (3-C) for 10%/50 years [k]
  - Collapse Prevention (5-E) for 2%/50 years [p]

Table C1-1 Rehabilitation Objectives

		Target Building Performance Levels			
		Operational Performance Level (1-A)	Immediate Occupancy Performance Level (1-B)	Life Safety Performance Level (3-C)	Collapse Prevention Performance Level (5-E)
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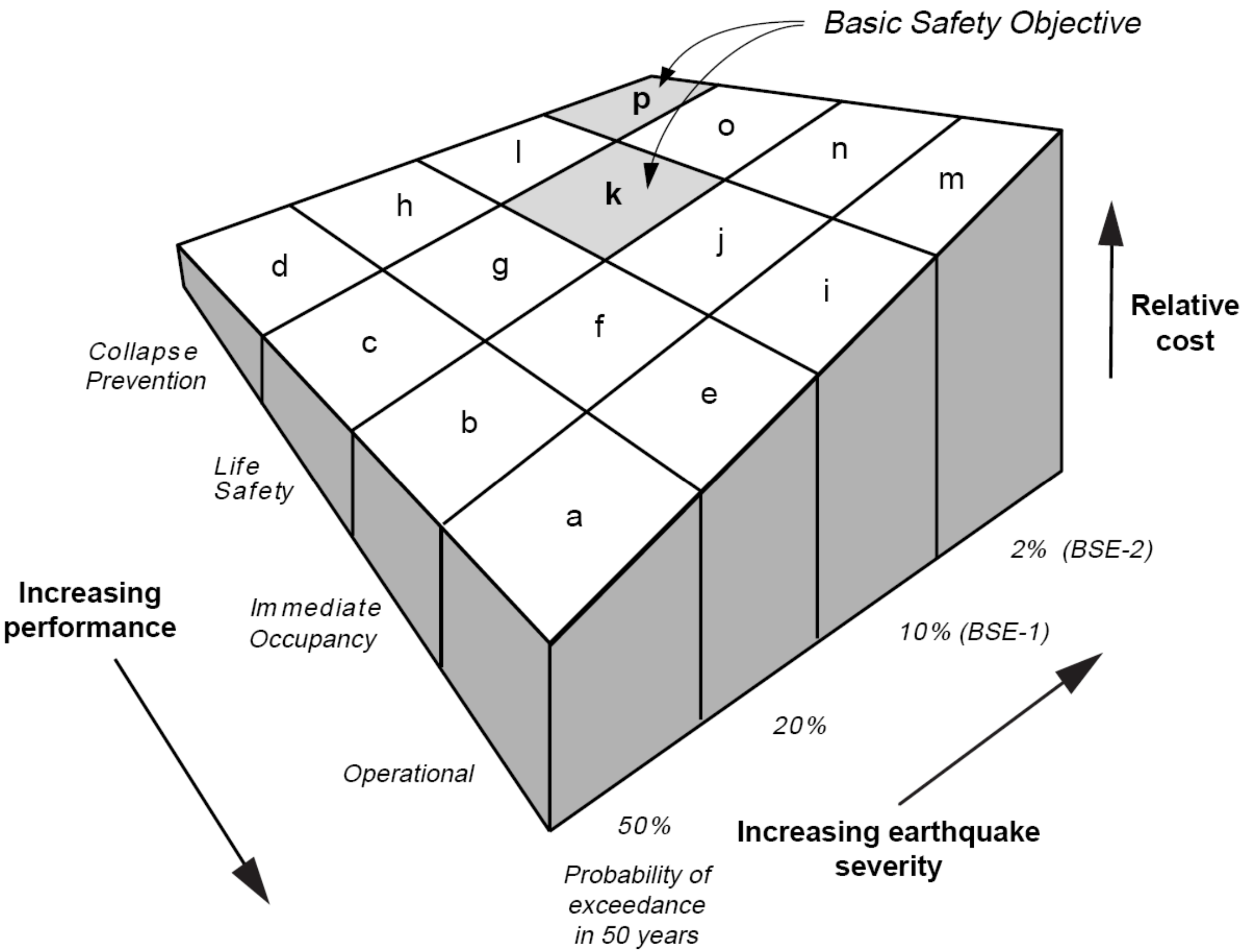
	20%/50 year	e	f	g	h
	BSE-1 (~10%/50 year)	i	j	k	l
	BSE-2 (~2%/50 year)	m	n	o	p

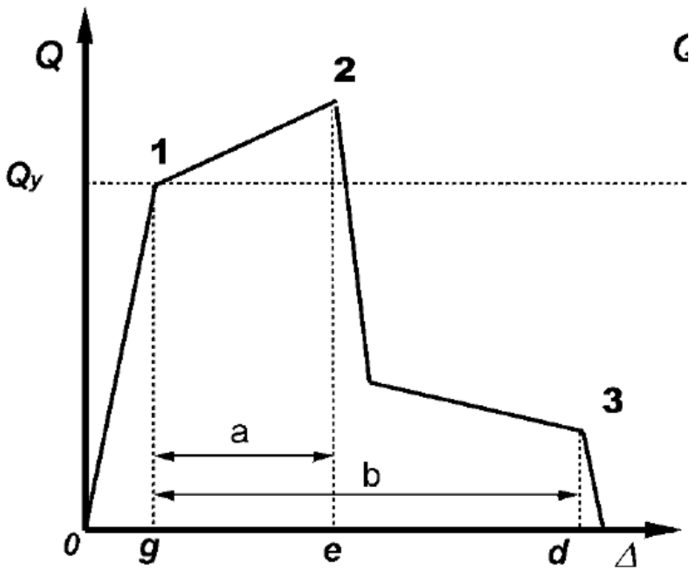
Performance objectives in FEMA 356

- **Selection of performance objectives affects the cost of the building**



Modelling of components: ductile / brittle actions

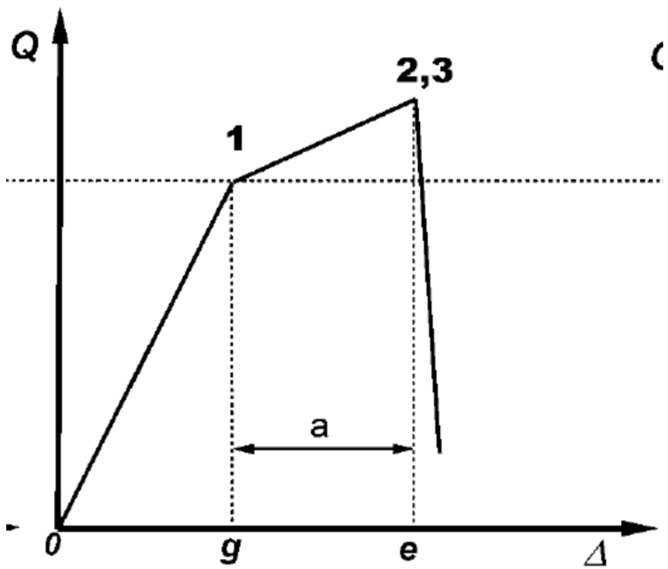
- **Type 1 curve (deformation-controlled or ductile):**
  - elastic range (point 0 to point 1 on the curve) followed by
  - a plastic range (points 1 to 3)
  - non-negligible residual strength and ability to support gravity loads at point 3
  - Primary component actions shall be classified as deformation-controlled if <u>e > 2g</u>.



Type 1 curve

Modelling of components: ductile / brittle actions

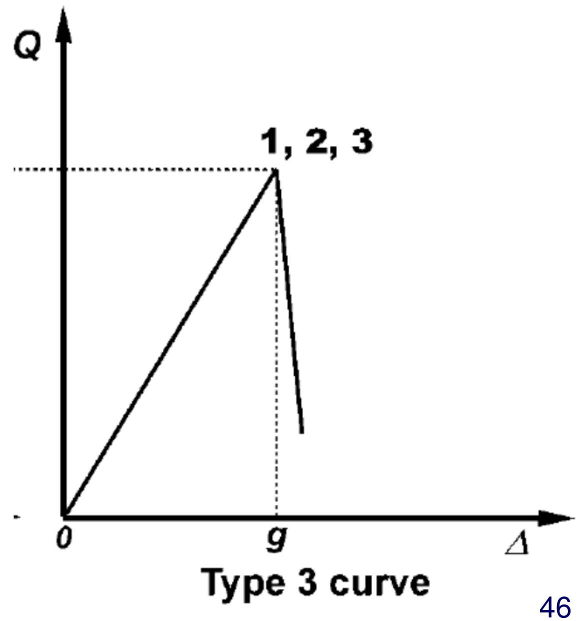
- **Type 2 curve (deformation-controlled or ductile):**
  - **an elastic range (point 0 to point 1 on the curve)**
  - **plastic range (points 1 to 2)**
  - **loss of strength and loss of ability to support gravity loads beyond point 2.**
  - **deformation-controlled if the plastic range is such that e > 2g; otherwise, they shall be classified as force controlled.**



Type 2 curve

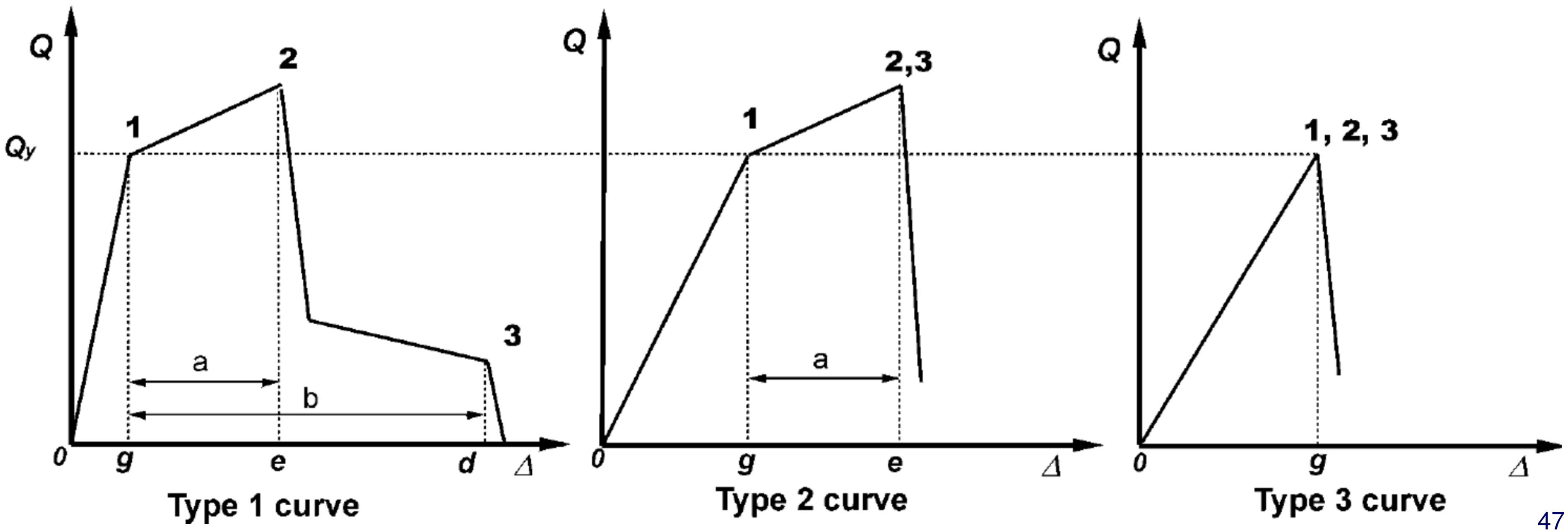
Modelling of components: ductile / brittle actions

- **Type 3 curve (brittle or nonductile behavior):**
  - an elastic range (point 0 to point 1 on the curve)
  - loss of strength and loss of ability to support gravity loads beyond point 1.
  - force-controlled (brittle) behaviour



Modelling of components: ductile / brittle actions

- **A given component may have a combination of both force- and deformation-controlled actions.**
- **Type of response (ductile / brittle) affects:**
  - **Modelling of structural component**
  - **Performance criteria**



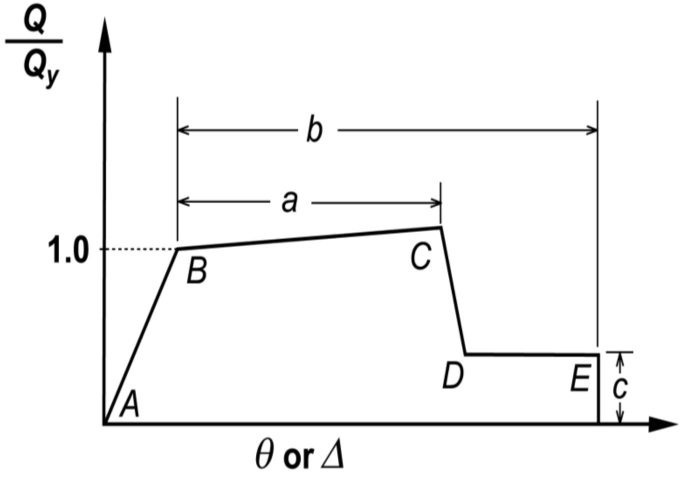
Modelling of components: ductile / brittle actions

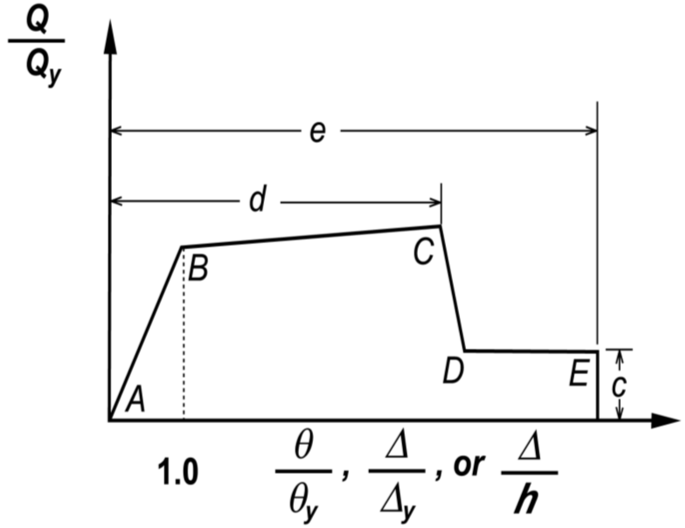
- **Examples of ductile / brittle actions:**

Type of structure	Component	Ductile actions	Brittle actions
Steel moment resisting frames	beams	Bending (M)	Shear (V)
	columns	M	Axial (N), V
	joints	V (in general)	-
Steel concentrically braced frames	braces	N	-
	beams	-	N
	columns	-	N
Steel eccentrically braced frames	links (short)	V	M, N
	braces	-	M, N, (V)
	beams	-	M, N, V
	columns	-	M, N, V

Modelling of components

- **Modelling of ductile components:**
  - A-B segment: elastic response
  - B-C segment: strain hardening
  - C-D segment: strength degradation
  - D-E segment: residual strength
- **Modelling and performance criteria can be specified in terms of:**
  - Absolute deformations (θ or Δ) or
  - Normalised deformations (θ/θ_y or Δ/Δ_y)



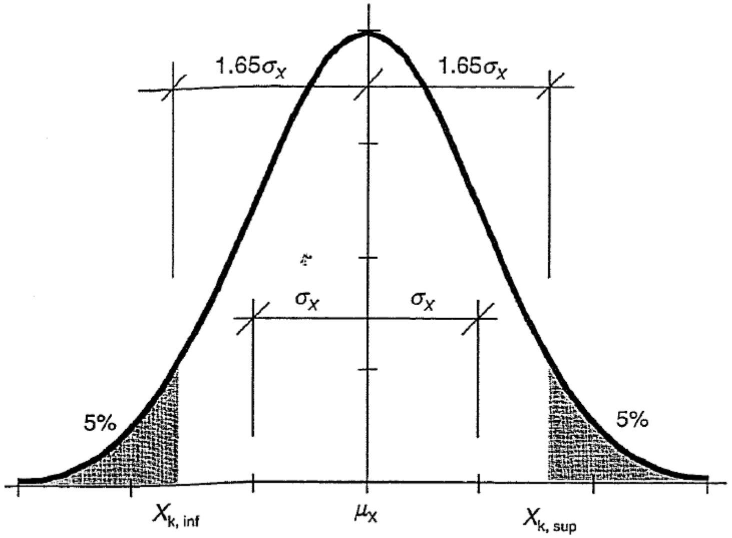


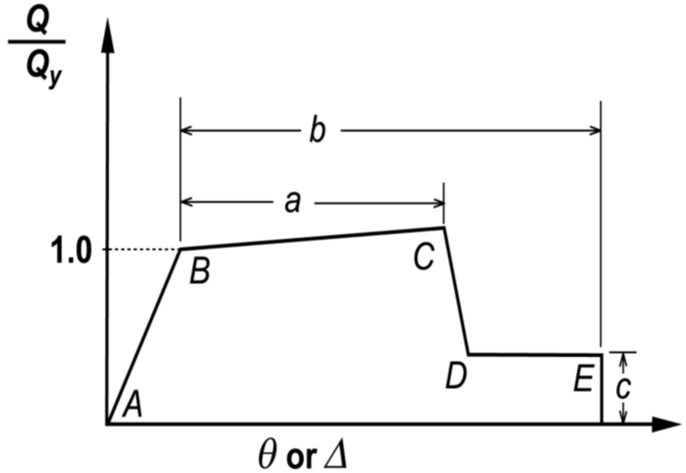
Modelling of components

- **Account should be taken of variability of mechanical properties of structural components should be made.**

- **<u>Brittle</u> components are modelled using <u>characteristic</u> values of strength (mean minus one standard deviation)**

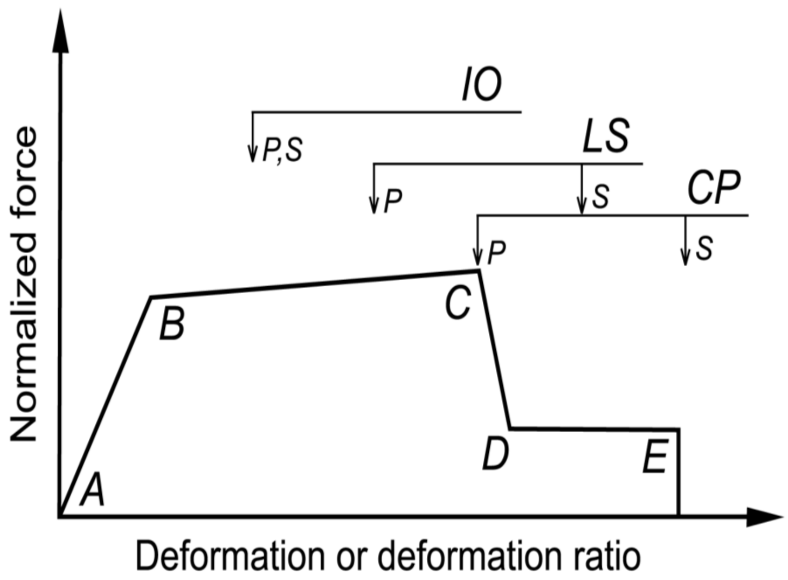
- **<u>Ductile</u> components are modelled using <u>mean</u> values of strength (statistical mean)**





Performance criteria: components

- The degree to which a structural components fulfil a performance criteria is established based on the demand to capacity ratios.
- Generally, modelling of components and their performance criteria are obtained from experimental tests, depending on:
  - Type of structural component (primary / secondary)
  - Performance level considered
- For usual materials and structural types, data from literature or codes can be used (e.g. FEMA 356, EN 1998-3)



Performance criteria: components

- **Principle of checking the performance:**
  Ed ≤ Rd
  Effect of action (demand) ≤ Capacity of the component
- **In case of elastic analysis methods, performance criteria are checked in terms of forces**
- **In case of plastic analysis methods, performance criteria are checked in terms of deformations for ductile components and in terms of forces for brittle components**

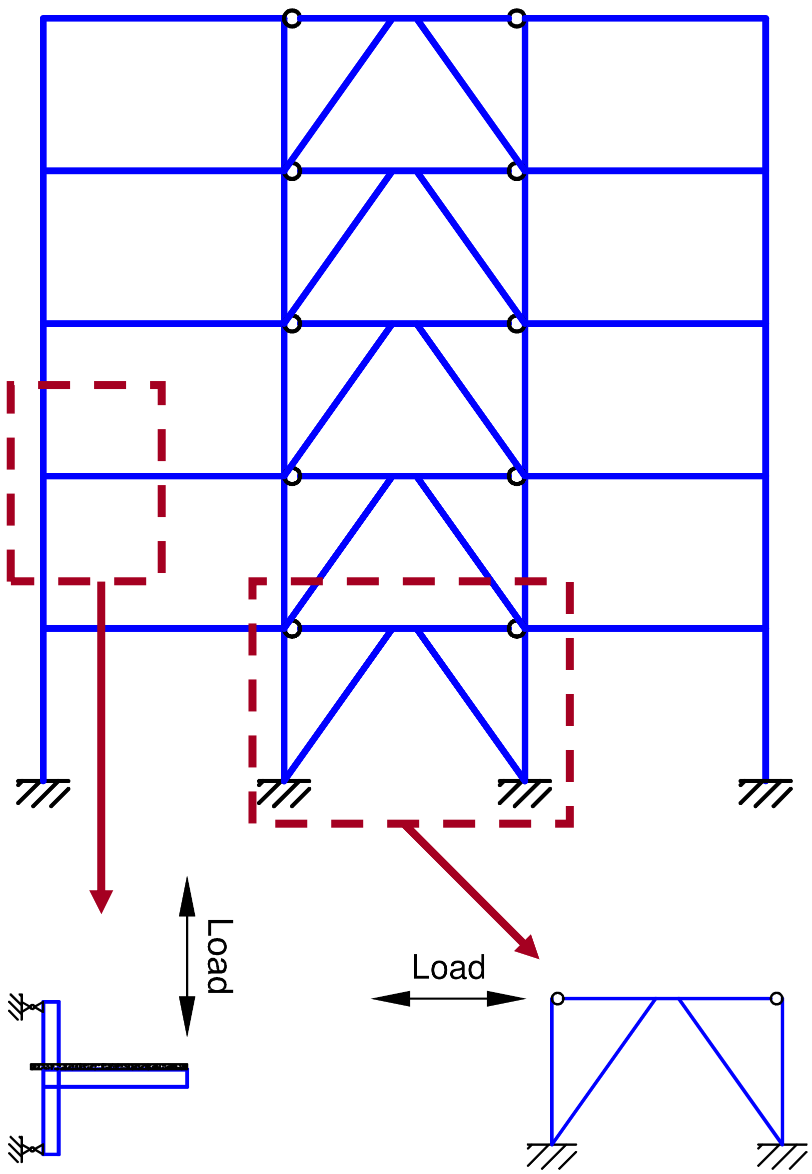
- **Codes for existing buildings (FEMA 356, EN 1998-3):**
  - **Ductile components: design deformation ≤ capacity**
  - **Brittle components: design force ≤ strength determined using characteristic material properties**

Performance criteria: components

- **Generally, modelling of components and their performance criteria are obtained from experimental tests**
- **Generally, experimental tests are performed on sub-assemblies representative for the specific component.**
- **Experimental test should reproduce the state of stress and boundary conditions that the component experiences within the structure.**
- **The objective of experimental test is to determine the force-deformation response (stiffness, strength and ductility) of the sub-assembly under seismic action. Based on them, design models and performance criteria are established.**

Performance criteria: components

- **Dual frame**
  - Eccentrically braced frame and
  - Moment resisting frame
- **Experimental sub-assembly:**
  - Portal frame for characterisation of the eccentrically braced frame
  - Beam-column joint for characterisation of moment resisting frames



Performance criteria: components

- **Tests on beam to column steel joints**

Performance criteria: components

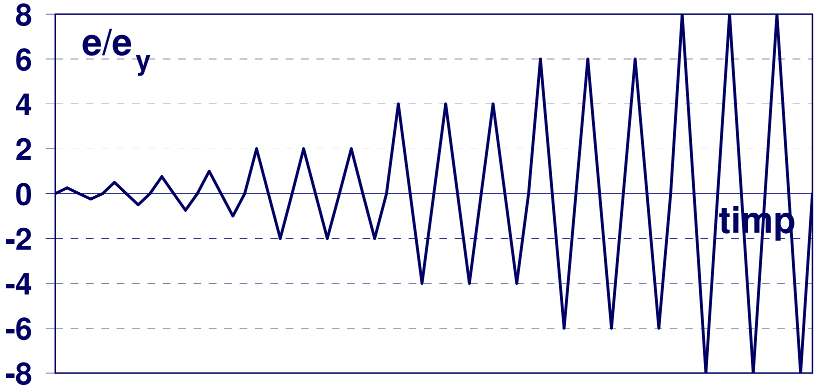
- **Tests on eccentrically braced frame**

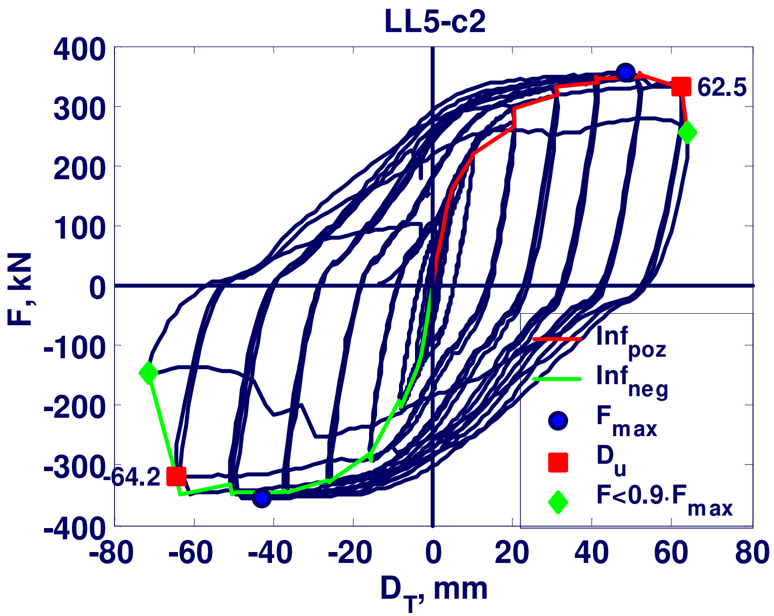
Performance criteria: components

- **Tests on steel braces**

Performance criteria: components

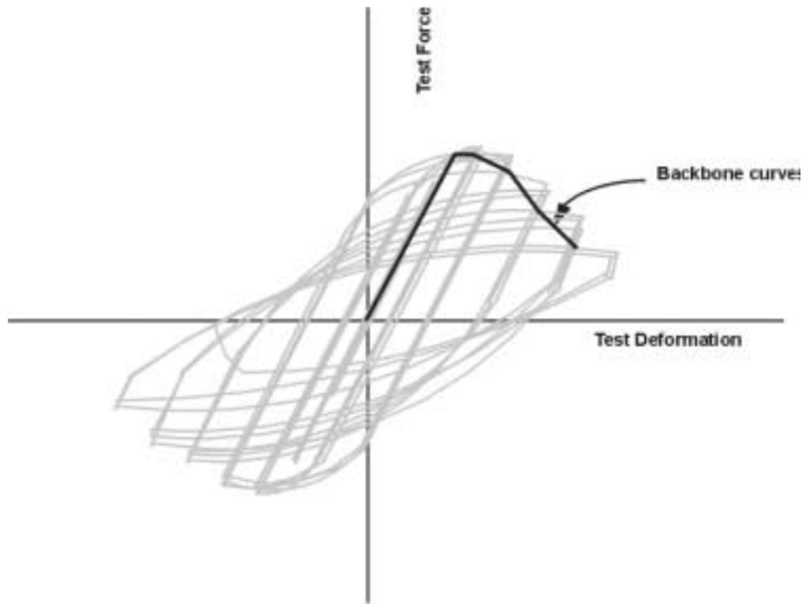
- **FEMA 356 requires that performance criteria of a structural component be obtained as the <u>mean</u> of at least <u>three identical tests</u>.**
- **Sub-assembly should be subjected to cyclic loading with progressively increasing deformation amplitudes, until the component losses its capacity to resist seismic or gravity loads.**

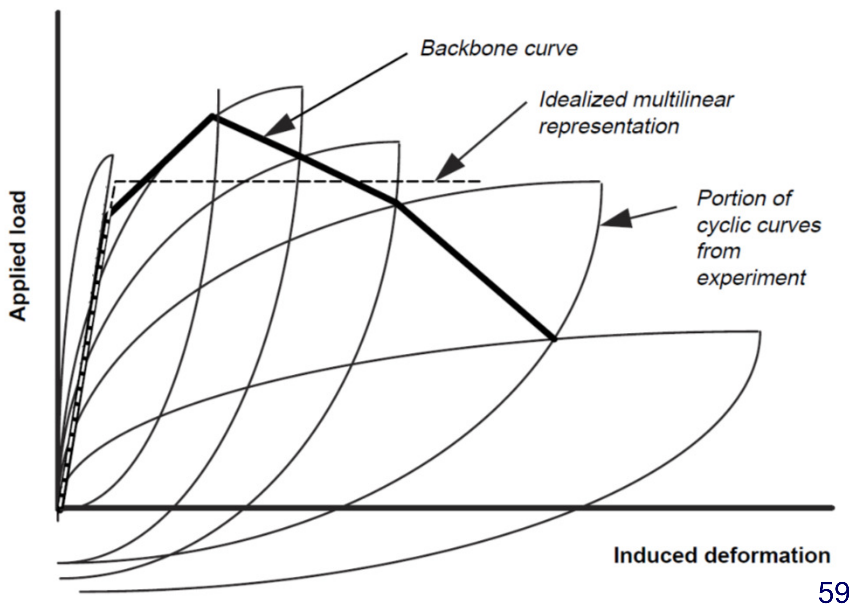




Performance criteria: components

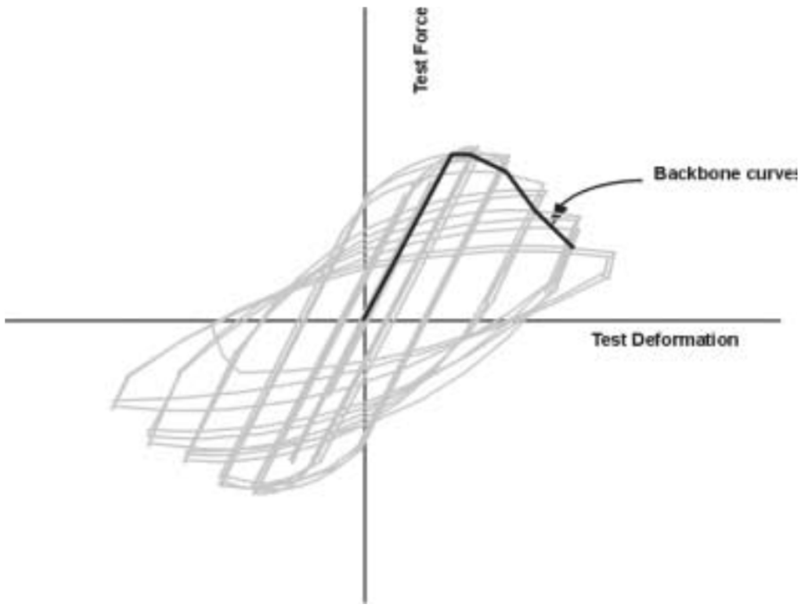
- **General procedure for determination of modelling parameters and performance criteria:**
  1. The cyclic force-deformation curve is obtained from the test.
  2. The "backbone" curve is generated from the cyclic hysteresis, accounting for strength degradation in cycles of equal amplitude.
  3. The average backbone curve is determined.
  4. The initial stiffness is determined.
  5. The component is classified as ductile or brittle

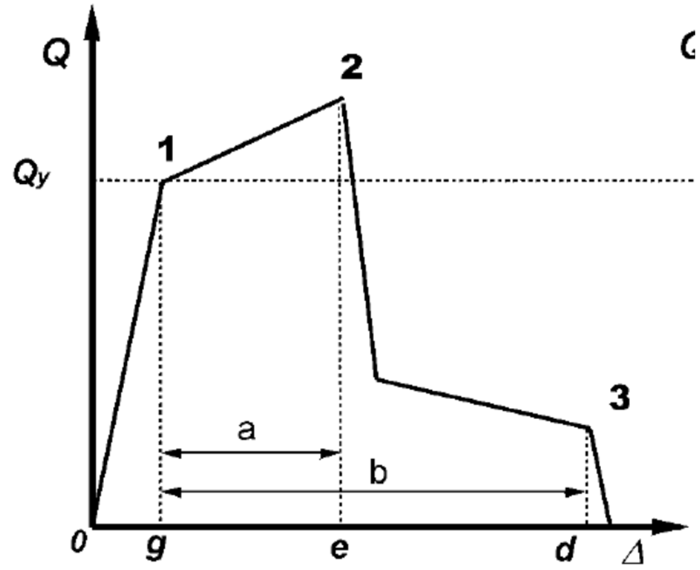




Performance criteria: components

6. For brittle components, strength is determined as the minimum value of the yield force.
7. Performance criteria for ductile components:
   - Immediate occupancy (IO): the deformation at which permanent, visible damage occurred in the experiments but not greater than 0.67 times the deformation limit for Life Safety
   - Life Safety (LS): 0.75 times the deformation at point 2 on the curves
   - Collapse Prevention (CP): The deformation at point 2 on the curves but not greater than 0.75 times the deformation at point 3





Examples of modelling parameters and performance criteria (FEMA 356)

Table 5-6 Modeling Parameters and Acceptance Criteria for Nonlinear Procedures—Structural Steel Components

Component/Action	Modeling Parameters: Plastic Rotation Angle, Radians a	Modeling Parameters: Plastic Rotation Angle, Radians b	Modeling Parameters: Residual Strength Ratio c	Acceptance Criteria (Plastic Rotation Angle, Radians): IO	Primary LS	Primary CP	Secondary LS	Secondary CP
Beams—flexure								
a. $\frac{b_f}{2t_f} \le \frac{52}{\sqrt{F_{ye}}}$ and $\frac{h}{t_w} \le \frac{418}{\sqrt{F_{ye}}}$	$9\theta_y$	$11\theta_y$	0.6	$1\theta_y$	$6\theta_y$	$8\theta_y$	$9\theta_y$	$11\theta_y$
b. $\frac{b_f}{2t_f} \ge \frac{65}{\sqrt{F_{ye}}}$ or $\frac{h}{t_w} \ge \frac{640}{\sqrt{F_{ye}}}$	$4\theta_y$	$6\theta_y$	0.2	$0.25\theta_y$	$2\theta_y$	$3\theta_y$	$3\theta_y$	$4\theta_y$
c. Other	Linear interpolation between the values on lines a and b for both flange slenderness (first term) and web slenderness (second term) shall be performed, and the lowest resulting value shall be used							

Performance criteria: structure

- **The structure shall be provided with at least one continuous load path to transfer seismic forces, induced by ground motion in any direction, from the point of application to the final point of resistance.**

- **All primary and secondary components shall be capable of resisting force and deformation actions within the applicable acceptance criteria of the selected performance level.**

References / additional reading

- FEMA 356, 2000, "Prestandard and commentary for the seismic rehabilitation of buildings", prepared by the American Society of Civil Engineers for the Federal Emergency Management Agency, Washington, D.C.
- EN 1998-3: 2004 "Eurocode 8 - Design of structures for earthquake resistance Part 3: Assessment and retrofitting of buildings".
- FEMA 349, 2000, Action Plan for Performance-based Seismic Design, prepared by the Earthquake Engineering Research Institute for the Federal Emergency Management Agency, Washington, D.C.
- FEMA 445, 2006. Next-Generation Performance-Based Seismic Design Guidelines Program Plan for New and Existing Buildings. Prepared by ATC for FEMA, Washington D.C.

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