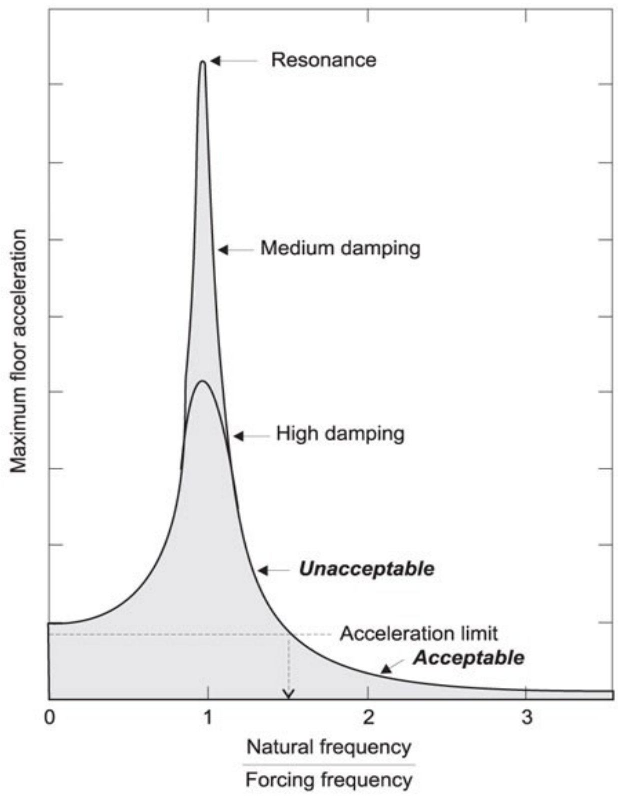
1 Theoretical basis

1.1 Resonance frequencies and coupled soil-structure interaction

Shear waves (S) are the main cause of the damages borne by the buildings during a seismic event. In fact, as the compressive waves act against the structures along a vertical plane, the shear ones stress the building along the horizontal plane, where buildings are usually more vulnerable. Forced by shear stress, buildings are induced to oscillate with frequencies which are characteristic of the buildings themselves. Buildings have a fundamental frequency of vibration which is function of the building rigidity and mass:

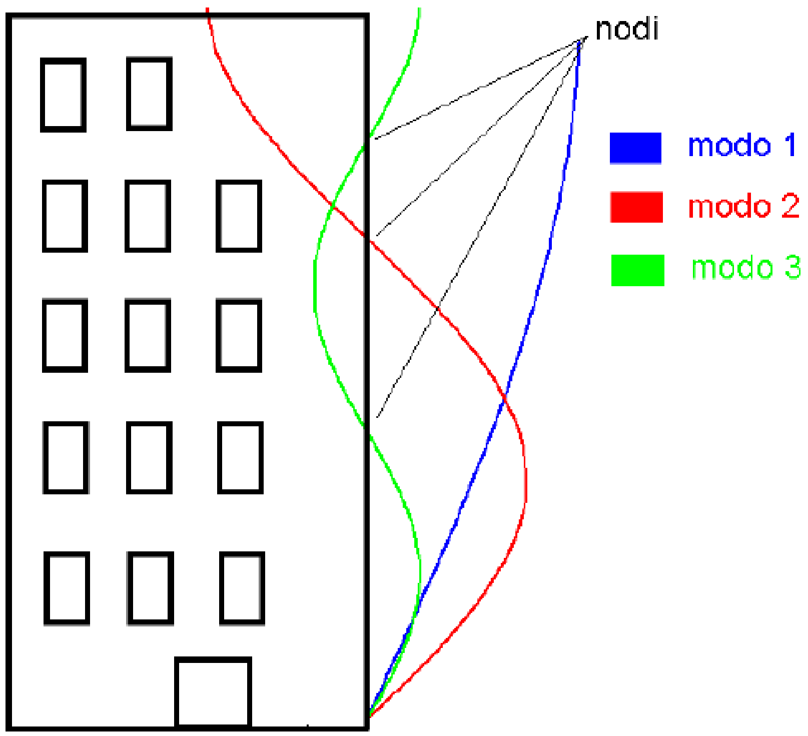
$$f = \frac{1}{2\pi}\sqrt{k/m};$$

Consequently the fundamental frequency is direct function of rigidity and inverse function of mass.

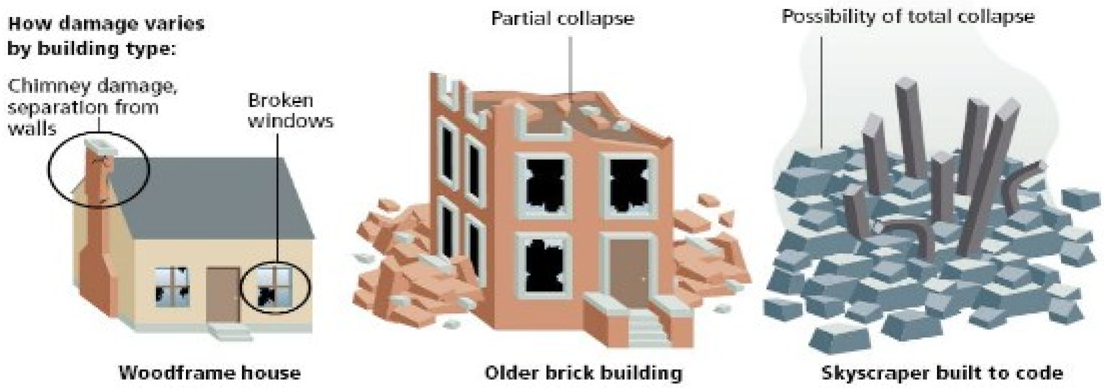


The 'seismic hazard' term means the predisposition of a building to bear damages due to a seismic event. It was demonstrated that the seismic hazard of a recently-built building is only marginally correlated to its structural characteristics. More onerous it's the effect of the seismic amplification of the site, which increases in a remarkable way the intensity of the seismic forces acting against a building.

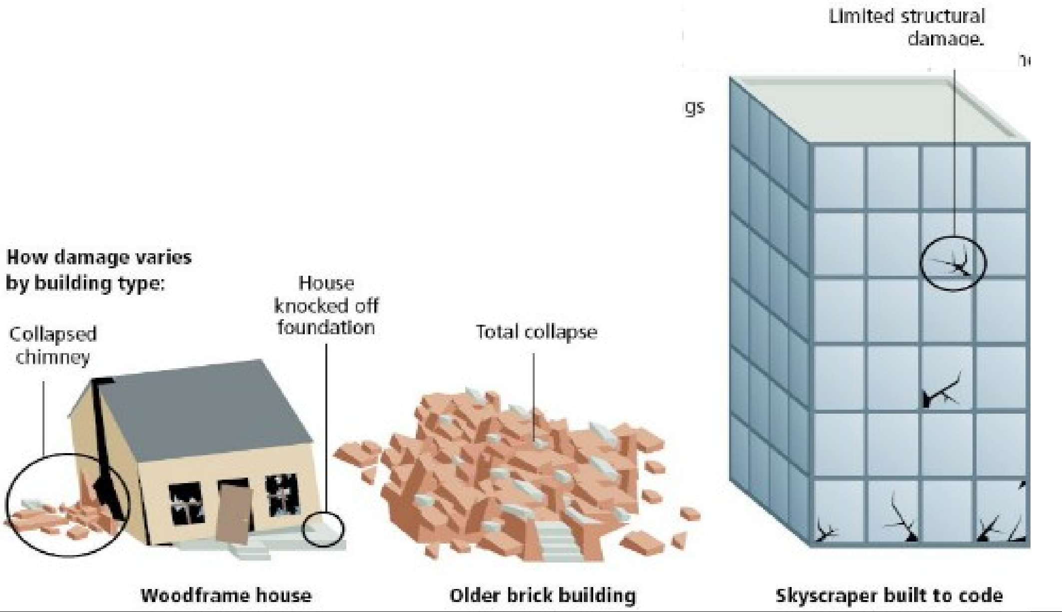
Seismic amplification depends on the ratio between the resonance frequencies of the ground and the building during the earthquake. In detail, if the resonance frequency of the building is comparable to the subsoil one, it rises a coupled soil-building interaction which takes to a catastrophic amplification of the seismic forces. Therefore more the ratio between the ground and building frequencies is close to one, higher are the seismic forces which act upon the structure and, consequently, more important are the predictable damages. The coupled-resonance effects become unbearable for the structural safety, when the ratio falls in the interval 0.67 – 1.50. The coupled-resonance effect allows to explain the phenomenon of the selective damages which can often be detected inside the areas hit by an earthquake. Varying the geological context, the resonance frequencies of the ground consequently change. Buildings having similar resonance frequencies could be subject to different level of damage, because built up on different geological contexts.
In addition to the fundamental mode, buildings can vibrate in a more complex way, on the basis of the superior modes.



Da S.Castellaro, 2010



Mexico City 1985: High-rise buildings suffered more high-level damages than the low-rise ones. Resonance frequency of the gorund is close to 1 Hz.



Haiti 2010: Low-rise buildings suffered more high-level damages than the high-rise ones. Resonance frequency of the ground is close to 10 Hz.

1.2 Direct measurement of the resonance frequencies

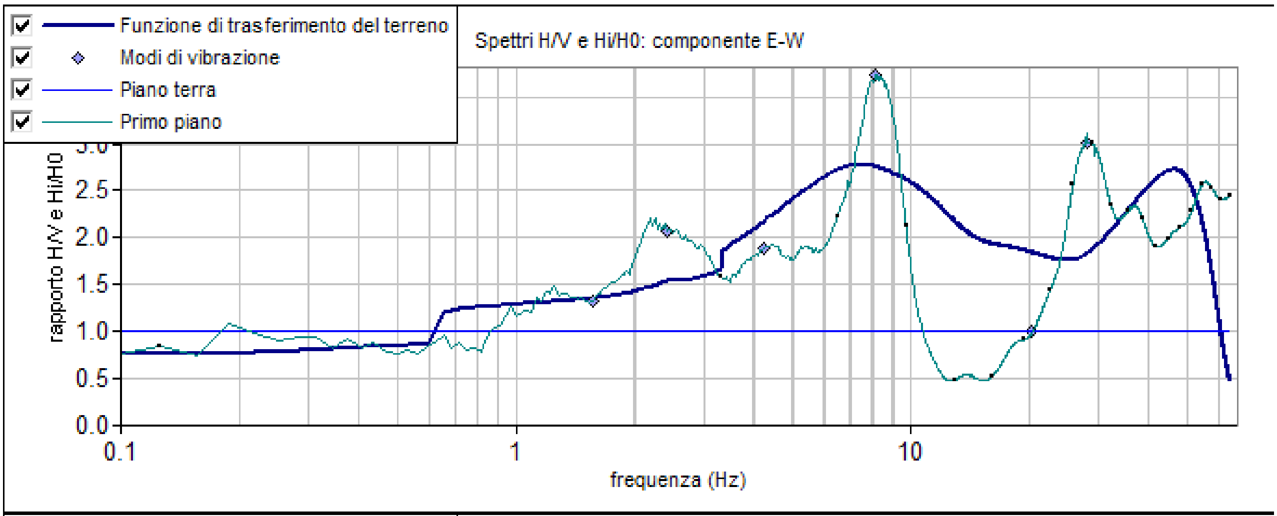
In scientific literature they exist many formulas to estimate of the fundamental frequency of a building. The simplest one is the following::

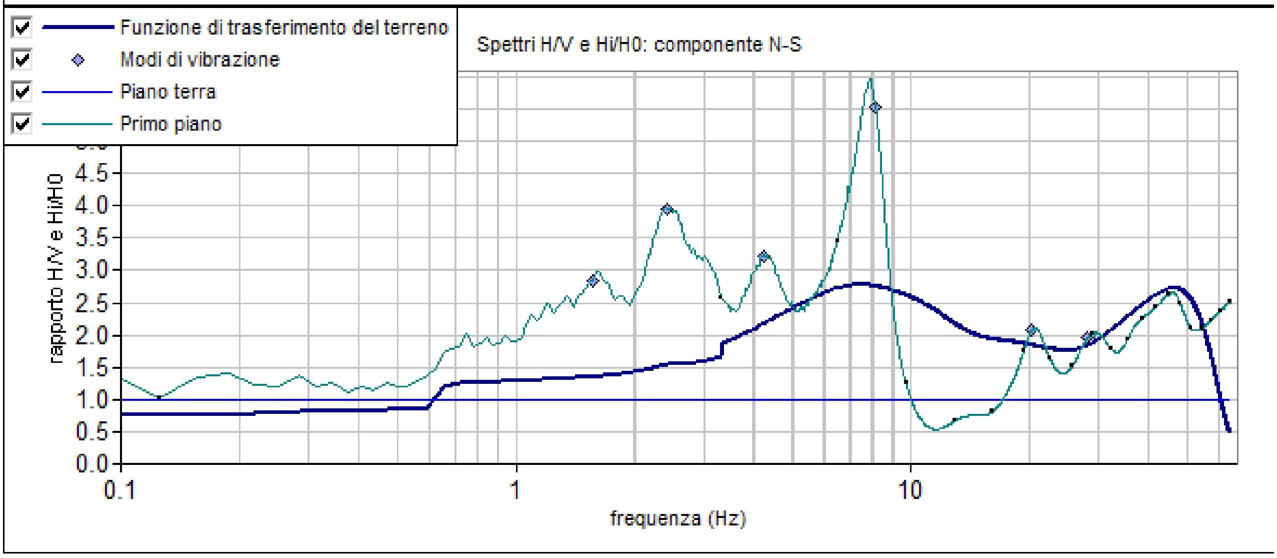
$$Fz = 10 / n.storey$$

These formulas have several limits. They are usually applicable to single regular-shaped buildings, having a homogeneous mass distribution and heights which fall inside to a specifically interval of values. Where these conditions are not satisfied, they tend to give wrong results. These expressions actually provide only an approximate value of the resonance frequency, as they are usually affected by a error close to 20% or more, even where they are applied to an ideal case.

Resonance frequencies of buildings and ground can be directly measured, as an alternative, through the use of accelerometer or velocimeter sensors. At least two measurements inside the examined building have to be executed, the first one on the lowest floor and the second one on the top floor, arranging the sensors along the same vertical line. The comparison between the measurements executed on the several floors directly gives the fundamental frequency of the examined building and possibly those associated to the superior modes.

Having as reference datum an earthquake, though of low magnitude, the building response will be surely closer to the real one under extreme condition. The use of the microtremors, consist of environmental vibrations, usually of anthropic origin, provides an estimate of the fundamental frequency in seismic condition. It has to take in account that, during an earthquake of high magnitude, the fundamental frequency tends to shift toward the low frequencies, though the shifting is contained within few percentage points.


Funzione di trasferimento del terreno
Modi di vibrazione
Piano terra
Primo piano
Spettri H/V e Hi/H0: componente E-W
rapporto H/V e Hi/H0
2.5
2.0
1.5
1.0
0.5
0.0
0.1
1
10
frequenza (Hz)


Funzione di trasferimento del terreno
Modi di vibrazione
Piano terra
Primo piano
Spettri H/V e Hi/H0: componente N-S
rapporto H/V e Hi/H0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.1
1
10
frequenza (Hz)

1.3 Technique of measurement and instruments.

The SRF (Floor Spectral Ratio) techniques is based on the direct measure of the fundamental frequencies of the buildings, using the environmental microtremors, to the purpose of estimating the seismic effects of the site and the vulnerability of the structure.
The term 'environmental noise' means the set of vibrations which spread themselves inside the ground due to natural and anthropic sources. Since the '70s it has been known that the microtremors tend to excite both the ground and the buildings natural frequencies of vibration, allowing to identify them. From a practical point of view, what is measured, in a predefined interval of frequencies, usually 0.1-100 Hz, is the propagation velocity of the microtremors both along the horizontal and vertical planes (H and V), taking in account that such vibrations are mainly composed by surface waves. The FSR technique needs the use of a triaxial velocimeter or accelerometer, that's a device which can record microtremors along the two horizontal directions (X and Y) and along the vertical one(Z) in a wide interval of frequencies (0.1-100 Hz) and for a time interval long enough (10-20 minutes). The recorded measurements are then processed and redrawn in the form of spectra Hi/H0, where Hi and H0 are, respectively, the mean value of the horizontal components on the i-th floor and the mean value of the horizontal component on the lower storey.
Practically, having regular-shaped buildings with a homogeneous mass distribution, at least two measurements have to be executed, the first one on the lowest floor and the second one on the top floor, arranging the sensors along the same vertical line. A best resolution can be achieved, making measurements on all the floors of the examined building. The maximum recorded peak Hi/H0, processed through the FSR technique, directly gives the fundamental frequency of vibration of the building. The seismic amplification of the site can be taken in account, importing the transfer function of the ground calculated through a numerical model of the subsoil or, as an alternative, executing a measurement outside the building using the HVSR technique.
The measurement instrument has to be positioned, arranging it parallel to the two main axes of the structure. Therefore the measures inside the building allow to estimate two spectra Hi/H0, concerning, respectively, the two main axes of the structure. In case of buildings having irregular shape and with an dishomogeneous mass distribution more verticals must be executed.

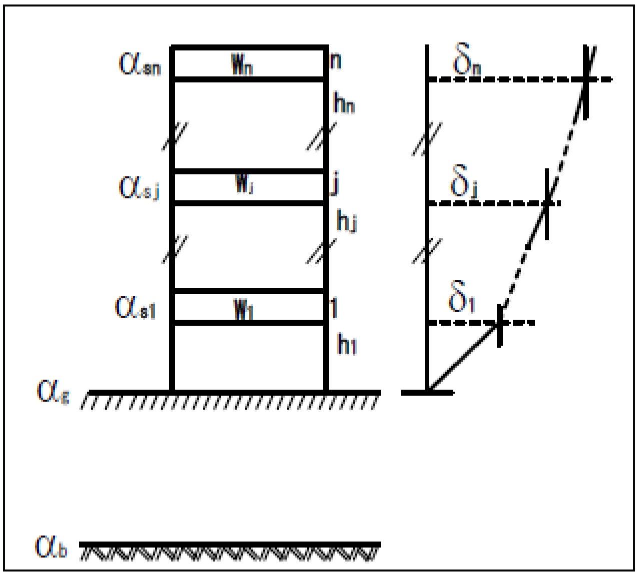
1.4 Estimating the seismic hazard.

Estimating the seismic hazard of a building, starting by the data acquired using the FSR technique, can be executed through Nakamura method (1997). The horizontal displacement due to the seismic action on the j-th storey of the building can be expressed by the following formula:

$$\delta_j = \frac{\alpha_{s\,j}}{(2\pi F_s)^2} \quad (1)$$

where α_{sj} is given by: $\alpha_{sj} = A_{sj} A_g \alpha_b$

and where A_{sj} and A_g are the spectral amplifications of the structure and of the ground, relating to the frequency F_s, and α_b is the product of the seismic acceleration in the bedrock ($a_{bedrock}$), by a corrective coefficient *e*: $\alpha_b = a_{bedrock} e$



The variable *e* usually assumes values included in the interval 0.65-1.00

The maximum interstory drift ratio ($IDS_{max\%}$) on the j-th floor relating to a specific frequency is given by the following expression:

$$\gamma_j = \frac{\delta_j - \delta_{j-1}}{h_j} = \frac{\alpha_{s\,j} - \alpha_{s\,j-1}}{4\pi^2 F_s^{\,2} h_j} \quad (2)$$

where h_j is the interstory height.

The equivalence between existing damage scales and HRC-Scale for general RC structures

<table>
<tr><th>DI_{HRC}</th><th>HRC</th><th>HAZUS 1999 [17]</th><th>VISION 2000 [18]</th><th>FEMA 273 [19]</th><th>EMS98 [20]</th><th>MSK [2]</th><th>AIJ [5]</th><th>ATC-13 [7]</th><th>ATC-21 [21]</th><th>EPPO [22]</th></tr>
<tr><td>0</td><td>None</td><td colspan="9">No damage limit state</td></tr>
<tr><td>10</td><td>Slight</td><td rowspan="4">Slight damage</td><td rowspan="2">Fully operational</td><td rowspan="3">Immediate occupancy</td><td rowspan="2">Grade 1</td><td rowspan="2">D1</td><td rowspan="2">Light</td><td>Slight</td><td rowspan="4">Green Tag</td><td rowspan="4">Green Tag</td></tr>
<tr><td>20</td><td rowspan="3">Light</td><td rowspan="2">Light</td></tr>
<tr><td>30</td><td rowspan="3">Operational</td><td rowspan="2">Grade 2</td><td rowspan="2">D2</td><td rowspan="3">Minor</td></tr>
<tr><td>40</td><td rowspan="2">Damage control</td><td rowspan="3">Moderate</td></tr>
<tr><td>50</td><td rowspan="3">Moderate</td><td rowspan="3">Moderate damage</td><td rowspan="3">Grade 3</td><td rowspan="3">D3</td><td rowspan="4">Yellow Tag</td><td rowspan="4">Yellow Tag</td></tr>
<tr><td>60</td><td rowspan="2">Life safe</td><td rowspan="2">Life safe</td><td rowspan="2">Moderate</td></tr>
<tr><td>70</td><td rowspan="2">Heavy</td></tr>
<tr><td>80</td><td rowspan="2">Extensive</td><td rowspan="3">Extensive damage</td><td rowspan="2">Near collapse</td><td>Limited safety</td><td rowspan="3">Grade 4</td><td rowspan="3">D4</td><td rowspan="2">Major</td></tr>
<tr><td>90</td><td rowspan="2">Collapse prevention</td><td rowspan="2">Major</td><td rowspan="2">Red Tag</td><td rowspan="2">Red Tag</td></tr>
<tr><td>100</td><td>Partial Collapse</td><td>Collapse</td><td>Partial collapse</td></tr>
<tr><td></td><td>Collapse</td><td colspan="9">Collapse limit state</td></tr>
</table>

After Rossetto e Elnashai (2003)

The correlations between $IDS_{max\%}$ and the degree of damaging of the building have been developed by several Authors [Rossetto e Elnashai (2003), Calvi (1999)], allowing to identify the threshold values between a level of damage and the next one as a function of the building tipology.

Particularly Rossetto e Elnashai (2003) suggest the following correlations between $IDS_{max\%}$ and the parameter DI_{HRC} (HRC damage index):

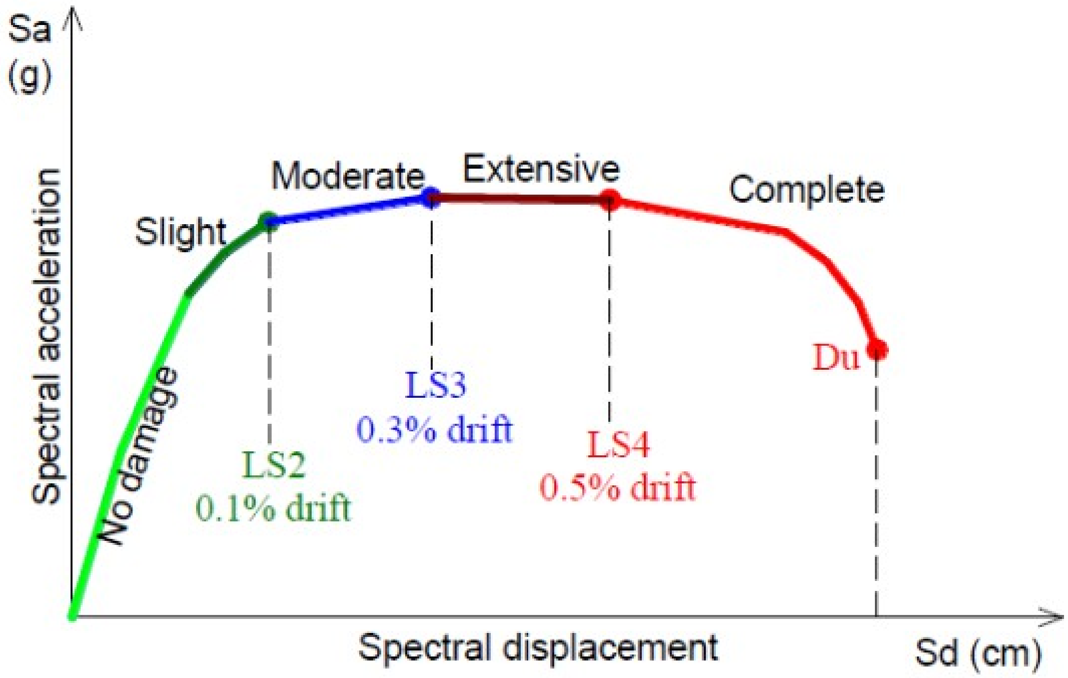
$$DI_{HRC} = 34.89Ln(ISD_{max\%}) + 39.39,\ \mathrm{R}^2 = 0.991 \text{ for non-ductile MRF}$$

$$DI_{HRC} = 22.49Ln(ISD_{max\%}) + 66.88,\ \mathrm{R}^2 = 0.822 \text{ for infilled frames}$$

$$DI_{HRC} = 39.31Ln(ISD_{max\%}) + 52.98,\ \mathrm{R}^2 = 0.985 \text{ for shear-wall systems}$$

$$DI_{HRC} = 27.89Ln(ISD_{max\%}) + 56.36,\ \mathrm{R}^2 = 0.760 \text{ for general structures}$$

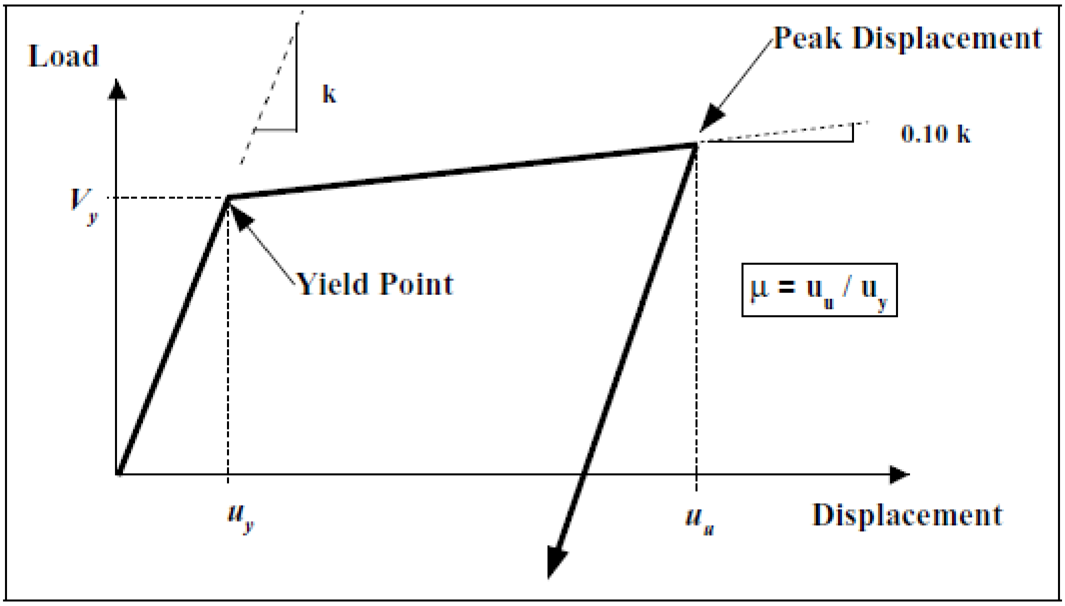
In case of unreinforced masonry buildings Calvi (1999) suggests the following scheme:



The Nakamura method allows to identify the yield point of the capacity curve of the building, that's the point beyond which the structure passes from an elastic behavior to an anelastic behavior. The yield point corresponds to the displacement value where DI_{HRC}=20. Choosing an empirical bilinear model for the capacity curve, where it's supposed that the angular coefficient of the curve beyond the yield point K' corresponds to the 10% of the angular coefficient in the elastic interval K, that's

$$K' = 0.10\ K$$

it can extrapolate the behavior of the building in case of seism of medium-strong magnitude



Numerically, the seismic hazard of the structure, relative to a specific seism, can be expressed by a Hazard Index, given by the ratio between the seismic acceleration needed to reach a predetermined level of damaging, usually the Life Safe level, and the seismic acceleration of the reference earthquake.

Approximately, it can refer to the following table.:

Very high hazard	High hazard	Moderate hazard	Low hazard
$0<IR\leq0.2$	$0.2<IR\leq0.6$	$0.6<IR\leq1.0$	$IR>1.0$