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Comparison of the Seismic Code Provisions for Non-Structural Components for Selected Countries

Helene Tischer[1*], Damian N. Grant[2], Jamie Dennis[3] and Michele Malaspina[4]

[1]Associate, Arup, Montreal, QC, Canada
[2]Associate Director, Arup, London, United Kingdom
[3]Senior Engineer, Arup, Amsterdam, Netherlands
[4]Engineer, Arup, Amsterdam, Netherlands
[*]helene.tischer@arup.com (Corresponding Author)

ABSTRACT

Past earthquakes have shown that, even if a structure behaves appropriately, failure or damage to non-structural components can have an impact on the safety of building occupants and represent considerable financial loss. Failure of these elements can also interrupt the function of the building and severely affect its recovery time.

Most modern building codes have recognized this by including requirements for the design of non-structural components and their attachments, at least to ensure a minimum level of safety. However, from a practitioner's point of view, these requirements sometimes are not considered with the same care as the structural design, especially in moderate seismic zones.

This paper aims to contribute to the better understanding on the topic by describing some general principles of seismic design of building operational and functional components, and by comparing the minimum requirements for Canada, the United States, Japan, China, New Zealand, the Eurocode, Turkey and Italy. For all countries, codes or guidelines define the seismic force to be applied using simplified equations. Given the simplified procedure these equations are based on, the results are generally conservative, but differences in the magnitude of the force to be considered was observed between codes. In all cases, the seismic force equation depends on the location's expected ground motions and component's weight, as well as amplification factors due to the building's and the component's characteristics. In this paper the different formulations are reviewed, highlighting the differences in how each of these factors are taken into account in design for each code.

Keywords: operational and functional components, non-structural components, code comparison

INTRODUCTION

Non-structural components are all parts and content of a building that are not classified as structural. They are also referred to as operational and functional components, to avoid the misconception that they will not have to resist any forces. While they do not contribute to the load resistance, they are essential to allow the intended use of the building. They can be broadly classified in three categories:

1. Architectural components (both external and internal) such as partitions, ceilings, parapets or cladding;
2. Building services (mechanical, electrical and plumbing components), such as pumps, chillers, air handling units, piping or ductwork;
3. Building contents, including for example furniture, industrial storage racks, computer and desktop equipment, kitchens or machine shop equipment.

Past earthquake events have shown that, even if the structure behaves appropriately, failure or damage to non-structural components has a profound impact on the safety of building occupants and damage to property. Examples of observed scenarios include harm to occupants because of falling shelving units, blockage of safety exits by collapsed partition walls or interrupted services because of equipment that has toppled over. Figure 1 shows some moderate damage to non-structural components of an office after the 2014 Napa (California, USA) earthquake, with a magnitude of 6.0. While the structure of the building remained intact, ceiling tiles fell off, filing cabinets toppled over and contents of a shelving unit fell out. The displaced elements make circulation through the space difficult and could potentially impact evacuation and rescue missions.

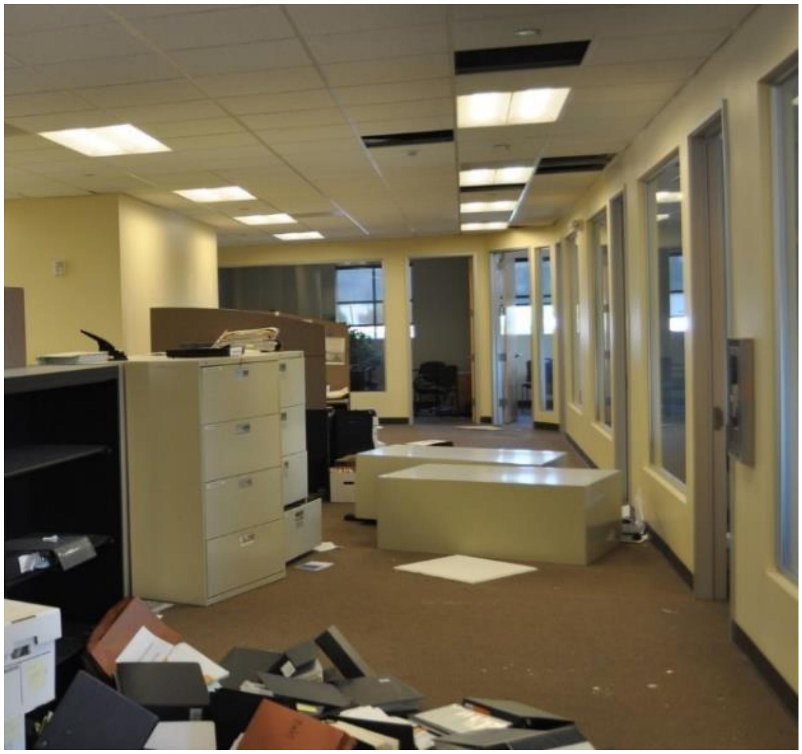

Figure 1. Damage to non-structural components in Napa after the 2014 earthquake.

On the other hand, the value of non-structural elements in a building most times exceed the cost of the structure by a large margin which makes their protection paramount from an economical perspective, especially in regions of high seismicity with frequent earth movements. Failure of non-structural components can also interrupt the function of the building and severely affect its recovery time, something especially critical in essential facilities like hospitals, first responders or telecommunication providers.

Most modern building codes now include requirements for the design of non-structural components and their attachments, at least to ensure a minimum level of safety. This level corresponds to "life safety" performance or similar for codes covered in this paper. The aim is to preserve the life of occupants of the building, but extensive and sometimes irreparable damage is accepted for an earthquake with a small probability of occurrence. Note that better performance is expected for certain essential facilities through the use of an importance factor. This paper analyzes the seismic force calculated following a number of international codes to comply with these minimum requirements.

For certain types of buildings that need to remain functional after an earthquake, as for example hospitals, the above requirements are not sufficient. This has led to the development of guidelines and design principles that exceed the minimum code requirements, known as performance-based design. This approach has indeed become more and more common in recent years. In this type of analysis performance objectives are defined, which can be described as levels of acceptable damage associated to earthquakes of different magnitudes. These performance objectives need to be established on a case-by-case basis; hospitals, for example, generally need to stay functional even after a large earthquake, while a family dwelling could be designed with less stringent requirements. Performance-based design is mandatory for certain jurisdictions and occupancies, but it can also be adopted by building owners or occupants on a voluntarily basis to ensure a better performance of the building's non-structural components. These regulations are outside of the scope of the present paper.

SEISMIC ACTION AFFECTING NON-STRUCTURAL COMPONENTS

During an earthquake, seismic waves affect the base of a building, creating both motion and distortion in the structure and its contents. These two main actions are often used to classify non-structural elements in acceleration- or deformation-sensitive components, as can be shown in the examples of Figure 1. To characterize the intensity of the action, the characteristics of the earthquake wave at the base of the structure need to be assessed (dependent on a variety of geological aspects, as magnitude of the earthquake, distance to the epicentre, and amplification due to local soil characteristics). The supporting building will also amplify the wave, depending on characteristics of the structure and the location within the building of the studied component. As a rule, the higher up in a structure a component is located, the more seismic actions are amplified.

Deformation-sensitive components are those that are affected by deformations imposed by the structure. The largest deformations typically occur between floors but can also occur between a floor and the roof. A typical example of a deformation-sensitive component is a masonry wall, see the top of Figure 1. If the wall and its attachments have not been designed properly, the relative deformation (δ in the figure) will create large forces in the wall and potentially lead to its failure. Any element that is attached at two levels can be classified as deformation-sensitive.

Acceleration-sensitive components are those that are subjected to inertial forces from the earthquake. Unlike deformation-sensitive components, this effect does not require the component to be attached at different locations. Damage can rather be explained by the inertial forces generated from the shaking of the supporting structure, as for example a top-heavy piece of equipment toppling over. Equipment in general can most often be classified as acceleration-sensitive. Most of the time, the inertial forces produced are critical in the horizontal directions, but some components can also be sensitive to vertical accelerations, as for example those with horizontal cantilever portions.

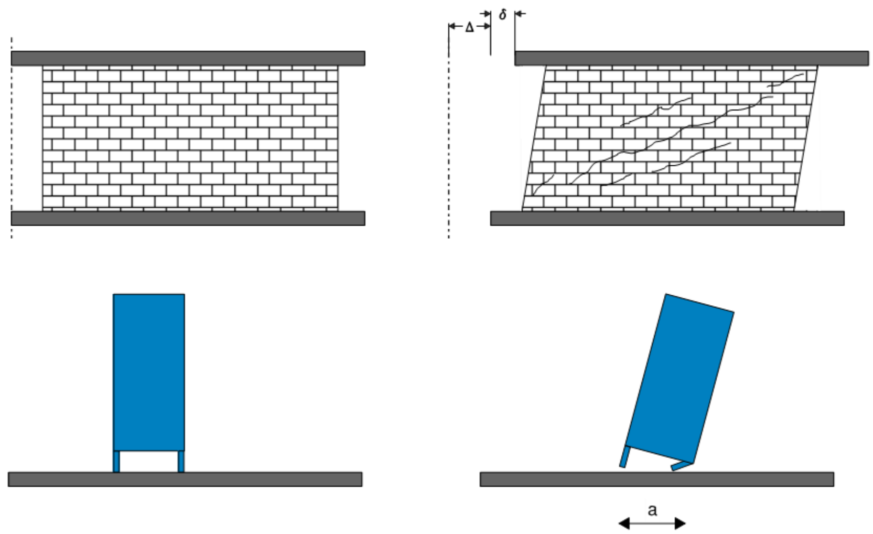

Figure 2. Displacement sensitive (top) and acceleration sensitive (bottom) non-structural components

Finally, the interaction between a non-structural component and its surrounding elements, either structural or non-structural, can produce two potentially damaging effects: relative motions or impacts.

Relative motions typically can induce damage in service lines connecting different elements, such as pipes or cables. While the failure of these elements might not induce any damage to the main equipment studied, if not designed properly the services will be interrupted and equipment will be non-operational, potentially for a prolonged period.

Impacts between components, including pounding, swinging, rolling and sliding, can damage either the studied component or the surrounding structure. An example of this type of failure is a spring isolated equipment falling off its support and damaging an adjacent partition wall.

MECHANISMS TO RESIST SEISMIC ACTIONS

Deformation-sensitive components can either be protected by separating the components from the surrounding structure, or by integrating the component to the main structure. The first approach is often preferred for its simplicity. For partition walls, for example, it is standard practice to allow the relative in-plane movement between the wall and the slab above, restraining only the out-of-plane movement to stabilize the wall in that direction (see Figure 3 for a typical condition with a masonry wall meeting a slab edge).

For acceleration-sensitive components, adequate connection between the component and the surrounding structure are paramount to resist the inertial forces, including anchors, plates, braces and snubbers (isolated equipment). The connections will have to be examined for their resistance. Their ductility and rigidity are also important to limit dynamic amplification of the accelerations between the supporting structure and the component.

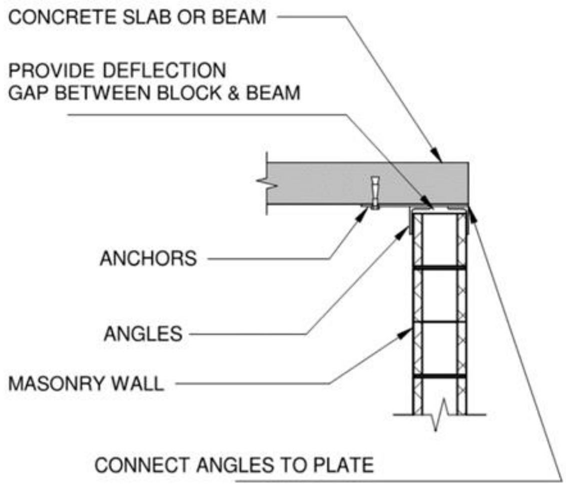

Figure 3. Masonry wall to slab connection restraining only out-of-plane movement

To avoid damage to service lines or other components because of relative motions, flexible joints or flexible sections of piping can be used and cables can be installed with additional slack. As with deformation-sensitive components, alternatively service lines can also be designed to be rigid and strong enough to connect different non-structural components (i.e., different parts of a machine or different equipment) without failure. Finally, impact forces are usually avoided by providing a large enough gap between elements that no contact will be produced, or by providing impact-absorbing connections.

In summary, to ensure an adequate performance of non-structural components, the following measures should be taken:

- Ensure that the component is properly attached to the supporting structure and that there is no risk of overturning at the code prescribed earthquake intensity;
- Separate the component from the surrounding structure to avoid deformations being imposed on it by the deformation of the main structure (preferred option), or integrate the component to the structural system.
- Assess and address the potential for impact (often referred to as pounding) between the component and the surrounding structural and non-structural elements;
- Design service lines so that they can undergo the expected relative movement between different attachment points without damage.

Each component must be evaluated independently to ensure risks are identified and mitigated.

COMPARISON BETWEEN CODE REQUIREMENTS

The requirements for calculation of seismic loading for non-structural components are discussed for the code summarized in Table 1.

Table 1. Reference Codes and Regulations.

Abbreviation	Location	Code	Reference
NBCC2020	Canada	National Building Code of Canada, 2020 edition	[1]
NBCC2015	Canada	National Building Code of Canada, 2015 edition	[2]
ASCE7-16	United States	ASCE/SEI 7: Minimum Design Loads and Associated Criteria for Buildings and Other Structures, 2016 edition	[3]
EC8-04	Europe	Eurocode 8: Design of Structures for Earthquake Resistance: Part 1-1: General Rules, Seismic Actions and Rules for Buildings, 2004 edition	[4]
BCJ	Japan	Guidelines for Seismic Design and Construction of Building Equipment, 2014 edition	[5]
NZS1170.5:2004	New Zealand	New Zealand Loading Code, 2004 edition	[6]
TEC2018	Turkiye	Turkish Seismic Code, 2018 edition	[7]
NTC2018	Italy	Italian Building Code, 2018 edition	[8]
GB50011-2010	China	Chinese Code for Seismic Design of Buildings, 2016 edition	[9]

The review shows that the prescriptions for seismic design of non-structural components included in codes and standards from different parts of the word have a similar organization. Minimum seismic design forces are calculated based on simplified equations. The studied component and its connections are then designed to resist a combination of horizontal and vertical seismic actions (vertical actions waived in certain cases), as well as gravity loads. The simplified equations to calculate the seismic horizontal component force can be summarized as follows:

$$V_c = F_1 F_2 F_3 F_4 F_5 \mathrm{W} \tag{1}$$

Where:

Vc: horizontal component of the seismic force to be applied to the component

F_1: Seismic hazard unput and soil characteristics factor

F_2: Floor acceleration amplification factor (related to height of component installation within the building)

F_3: Component dynamic response factor

F_4: Component ductility factor

F_5: Component importance factor

W: Weight of the component

Some of the factors above are not present in all codes, and some codes will combine several of these into one parameter, or have several components to one of the factors above. Additionally, some codes will include a numeric factor to further modify the force. Finally, codes might prescribe minimum and maximum value either for some of the factors, or for the resulting seismic force. In the next sections, each one of the factors will be discussed in more detail.

PARAMETERS AFFECTING SEISMIC FORCE

Seismic hazard input and soil characteristics

Seismic ground accelerations are typically taken from hazard maps reported for a reference rock or hard soil ground condition within national standards, reflecting the variation in seismic hazard across the jurisdiction of the code. These values are then modified to account for the site-specific soil conditions, which can amplify or reduce the accelerations depending if the site corresponds to soft soil or harder rock. It is to note that all studied codes use this approach, except GB50011-2010 that disregards local soil conditions.

While the codes studied account for the seismic ground accelerations and local site conditions to calculate the expected seismic force on non-structural components as described above, most of them ignore other geological configurations that affect seismic shaking such as topographic effects (amplification of ground shaking along the edge of ridges) or soil basin edge effects. In the codes considered for the review, only the Italian code explicitly consider topographic effects, and none consider basin edge effects. Earthquake induced tsunami effects or landslide loads are beyond the scope of this study.

Floor acceleration amplification

Seismic floor accelerations increase along the building height, with the maximum amplification at the roof. All studied codes recognize this including a factor dependent on the height in the calculation of the seismic load, although the treatment given varies.

NBCC2020, NBCC2015, ASCE7-16, EC8-04, GB50011-2010 and BJC include a linear increase of lateral acceleration with increasing floor height. NZS1170.5:2004 includes a piecewise linear increase of lateral acceleration. NTC2018 suggests using floor acceleration response spectra, but is open to alternative simplified solutions, providing an alternative formula in the commentary for frame buildings that is based on linear increase of lateral acceleration with increasing floor height. Finally, TEC2018 requires an equivalent lateral load analysis to evaluate the accelerations along the height of the building.

In theory, there is a possible reduction in acceleration for deep basements that may have a positive impact on the forces acting on the component when compared to those on the ground floor. However, any possible reduction would require a detained understand of specific ground conditions on a site-by-site basis, and there is no provision for taking this reduction into account included in the studied codes.

Component dynamic response

The dynamic response of the component to the floor excitation can amplify the acceleration experienced by the component if there is resonance between the component's and the building's period. This phenomenon is accounted for by all codes reviewed, although different approaches are followed:

- ASCE7-16 uses tabulated a_p values to account for the dynamic response based on the component type. Values are typically 1.0 for stiff components and 2.5 for flexible components, where stiff components are those with a period below 0.06s. The background for these factors is a study by the National Centre for Earthquake Engineering Research (NCEER) [10], which based the amplification factor on the ratio between non-structural component period and building period. The use of bespoke a_p values based on this study is also allowed, in which case both rigid and very flexible components would have an a_p value of 1 (cases where the ratio of the component period over the building period is less than 0.5 or higher than 2.0).
- NBCC2020 and NBCC2015 use the same approach as ASCE7-16, with tabulated amplification values A_r, for a range of different types of non-structural systems. Values are either 1.0 for rigid components or 2.5 for flexible components, with rigid components being those with a period below 0.06s. Note that A_r gets combined with other factors in the parameter S_p, which is capped.
- EC8-04's approach is explicitly based on the ratio between non-structural component and building periods.
- BCJ provides discrete, tabulated amplification factors that vary between 1 and 2.
- NZS1170.5:2004 gives an approach based on non-structural component period only.
- TEC2018 adopted the same tabulated amplification factors, a_p, as ASCE7-16.
- NTC2018 suggests the use of floor acceleration response spectra when enough information on the building is known. In cases where little information is available, it proposes an alternative approach explicitly based on the ratio between non-structural component and building periods.
- GB50011-2010 gives two discrete amplification values, 1.0 and 2.0, depending on the ratio between non-structural component and building periods.

While all codes recognize that the component dynamic acceleration factor depends on the relationship between the period of the building and the period of the component, several include simplified procedures based on tabulated values, recognizing that the calculation of the component's period is difficult to achieve. A reasonable agreement is shown between most of the codes in terms for maximum dynamic amplification values, varying between 2.0 and 2.5 for all codes, except for the NTC2018 which provides a maximum dynamic amplification value of 5 in case of stiff components at resonance with soil and building.

One key difference between codes is that tabulated values, as in ASCE7-16, are conservative for long period components since the amplification factor is not reduced for components that are flexible with respect to the building they are housed in. The minimum value for the factor also differs. While usually it is 1.0, EC8-04 and NZ1170.5 allow a value of less than 1.0 for very flexible equipment or mounting, allowing to take full advantage of seismic isolation of the equipment, where possible.

Finally, the NZS1170.5 is the only code that ignores the lack of amplification for very short periods, increasing the design force by a factor 2.0 for all components with a period smaller than 0.7s, while taking advantage of energy dissipation for components with very long periods, similar to EC8-04.

Component's ductility

If a non-structural component or its mountings can sustain permanent deformation without a reduction in strength, the seismic design forces can be reduced based on this ductility. All studied codes allow for this reduction explicitly, except BCJ. Some of them will also take into account the overstrength of the element and its attachments in this factor.

All codes including this factor will reduce seismic forces by dividing the seismic coefficient by a factor greater than 1. The exceptions are the NZS1170.5, multiplying by a factor smaller than 1.0, and the GB50011-2010, which multiplies the expression by a factor ranging from 0.6 to 1.2 for a similar effect. It is to note that all studied codes except NZS1170.5 include tabulated values for this factor based on the type of component evaluated (excluding BCJ, which does not allow for it). NZS1170.5 suggest the use of a reduction factor equal to 1.0 unless more information on the post-elastic response of the non-structural component can be justified in the design phase.

Component's importance

The component importance factor depends on the consequence of its failure, depending on the presence of hazardous substances in the component, the number of injuries or fatalities that could be associated with the failure of the element, and the importance of the component's ability to function for post-earthquake operation of the facility that houses it. ASCE7-16, NSZ1170.5 and GB50011-2010 use prescriptive values following this approach.

In lieu of explicitly investigating the component's importance, some codes use the building importance. The building importance factor is related to the overall consequence of building failure, and typical values are 1.0 for a normal building and 1.5 for essential facilities. TEC2018 and NTC2018 follow this approach.

The EC8-04 as well as NBCC2020 and NBCC2015 take into consideration both the importance of the component and the importance of the building. Finally, the BCJ does not explicitly consider this parameter.

Summary

Table 2 summarizes the different factors that affect the seismic component force for the studied codes and guidelines.

Table 2. Summary, factor affecting the seismic component force.

Code	Seismic Input and soil	Location of component in building	Component Dynamic Response	Component Ductility	Component Importance
NBCC2020	$S(0.2)$ factor	Linear amplification with height, from 1.0 at the base to 3.0 at the roof	A_r factor: discrete value of 1.0 or 2.5	R_p factor: ranges from 1.0 to 5.0	I_E (building importance) and C_p factor: 1.0 for ordinary, 1.5 for toxic or explosive materials, 0.7 for flat bottom tanks at or below ground
NBCC2015	F_a and $S_a(0.2)$ factors	Linear amplification with height, from 1.0 at the base to 3.0 at the roof	A_r factor: discrete value of 1.0 or 2.5	R_p factor: ranges from 1.0 to 5.0	I_E (building importance) and C_p factor: 1.0 for ordinary, 1.5 for toxic or explosive materials, 0.7 for flat bottom tanks at or below ground
ASCE7-16	S_{DS} factor	Linear amplification with height, from 1.0 at the base to 3.0 at the roof	a_p factor, discrete value of 1.0 or 2.5 (except 1.25 for exterior wall fasteners)	R_p factor: ranges from 1.5 to 12.0	I_p factor: either 1 or 1.5 depending on the component's importance
EC8-04	α and S factors	Linear amplification of acceleration with height, from 1 at base to ~2.5 at roof	Amplification related to the period ratio T_a/T_1, with a maximum value of ~2.2 on roof	q_a factor: varies between 1.0 and 2.0	α considers the building's importance, γ_a factor: 1.0 for ordinary, 1.5 for important components
BCJ	K_o and Z factors	k_{Hi} factor: linear amplification with height, from 1 at the base to 3.33 at the roof	Amplification related to component, mounting and anchorage stiffness. Discrete value of 1.0 (stiff) and 2.0 (flexible)	Not explicitly considered	Not explicitly considered
NZS1170.5:2004	$C(0)$ factor	Linear amplification with height, from 1.0 at the base to 3.0 at 20% of total height (or 12m), constant of 3.0 above	Amplification related to component period. Varies between 2.0 (stiff) and 0.5 (flexible)	C_{ph} factor: varies between 1 for brittle components and 0.45 for very ductile components	R_p factor: varies between 1.0 and 3.6. Parts necessary for the operational continuity of the structure have R_p=1.0 or higher depending on the

					structure limit state and return period factor
TEC2018	S_{DS} factor	Proportional to the displacement obtained with an equivalent lateral load analysis. Minimum allowed is 0.75 times peak ground acceleration	a_p factor, discrete value of 1.0 or 2.5	R_p factor: ranges from 1.5 to 12.0	I_p factor referring to the importance factor of the building, 1.0 for standard and 1.5 for important buildings
NTC2018	α and S factors	Floor acceleration response spectra or linear amplification with height, from 1.0 at the base to 2.0 at the roof	Amplification related to the ratio between the component and the building's period. Maximum ratio is 5 for stiff components in resonance	q_a factor: varies between 1.0 and 2.0	α considers the building's importance
GB50011-2010	α_{max} factor (not influenced by soil characteristics)	ζ_2 factor: linear amplification with height, from 1.0 at the base to 3.0 at the roof	ζ_1 factor: amplification related to the ratio between the component and the building's period. Varies between 1.0 and 2.0	η factor: varies between 0.6 and 1.2	γ factor: 1.0 for standard and 1.4 for important components

CONNECTIONS

One key aspect of the seismic design of non-structural components is their attachment to the supporting structure, and in most building codes these attachments are the focus of provisions covering seismic design of non-structural components. These attachments must be designed by a locally accredited structural engineer and represented on structural drawings (not necessarily the same structural drawings and engineer as the building), and this for all locations covered in this document. There is no generic way of attaching equipment, since it will depend on several factors including the location and size of the furnished attachment points, characteristics of surrounding structure and the loads to resist.

Most of the studied codes contain additional requirements to assure the anchorage of the component is elastic, increasing the seismic force. For NBCC2015 and NBCC2020 prescribe a ductility factor of 1.0 or 1.5 for anchors. A similar approach is used for EC8-04. ASCE7-16 includes an overstrength factor that varies between 1 and 2.5. NZS1170.5 requires a ductility of 1 to be used for anchors, and further reduce the capacity of the anchors by a 0.75 factor. TEC2018 and NTC2018 also require the ductility factor to be set to 1.0 and use an additional amplification factor of 1.5. Finally, BCJ and GB50011-2010 do not explicitly consider any modification for anchorage forces.

Note that companion concrete codes required to design anchorages, often prescribe additional considerations for the load that should be applied to them to ensure they behave elastically during the design earthquake.

SAMPLE CALCULATIONS

Two sample calculations were performed to compare the numeric values obtained for the design forces using the studied codes[1]: an unbraced masonry parapet at roof level, and an instrumentation cabinet at the ground floor.

For both examples, a peak ground acceleration (PGA) of 0.5g was assumed. Where codes require the short period spectral acceleration as input instead, a ratio of 2.5 was assumed between this parameter and the PGA [11]. Soil was assumed to be of good quality (hard rock or similar). As for the building, it was assumed to be a 20m high, reinforced concrete frame building

[1] GB50011-2010 was excluded.

of high importance (hospital). The component in itself was assumed to not be relevant for post-earthquake operability of the building. The weight of the parapet was assumed to be 1950kg/m3, and its dimensions 1.0m high by 0.20m thick and 5.0m long. For the instrumentation cabinet, a weight of 200kg was assumed.

Furthermore, some of the codes require more specific information. Reasonable assumptions were made in those cases.

Results obtained are shown in Table 3, where the component force has been normalized by the component weight. Some comments are included to explain the differences of the results.

Table 3. Sample calculations for component horizontal force

Code	V_c/W Parapet	V_c/W Cabinet	**Comments**
NBCC2020, NBCC2015	1.16	0.39	Importance of the building considered. Relatively high ductility when compared to some other codes.
ASCE7-16	0.80	0.20	Does not consider the building's importance factor. Relatively high ductility when compared to some other codes.
EC8-04	2.46	0.53	Importance of building considered. Dynamic amplification dependent of building period.
BCJ	3.20	0.96	Does not consider the ductility of the component.
NZS1170.5:2004	2.55	0.55	Ductility factors are relatively low when compared to other codes.
TEC2018	3.00	0.45	Importance of building considered. Lateral force method is required to estimate the lateral acceleration of the building.
NTC2018	4.05	1.00	Larger dynamic amplification factor assumed compared to the other codes, since resonance between the component's and the building's period was assumed.

As can be seen, the numeric results vary significantly from one code to the other, which can be explained by the differences in the used procedures, that do not always include the same factors, or calculate these using different procedures. While the sample presented here is not enough for general conclusions, and other factors that will affect the design of the elements have not been considered, it is apparent that different codes can lead to dissimilar results.

CONCLUSIONS

Adequate seismic design of non-structural components and their attachment to the main structure is paramount to assure a building's safety, and to limit damages to valuable building content. This has been recognized by building legislation globally. This paper compares 10 different codes and guidelines, applicable in eight distinct jurisdictions. From this comparison, it can be concluded that:

- The prescriptions for seismic design of non-structural components have a similar organization for all studied codes and guidelines. Minimum seismic design forces are calculated based on simplified equations that are dependent of the seismic hazard input, local soil characteristics, floor amplification related to the height of the component within the building, the component's dynamic response factor, its ductility, its importance (or the importance of the building as a whole), as well as the component's weight.
- Treatment of the seismic hazard and soil characteristics are similar between all codes. Only one did not consider local soil conditions. Almost no code explicitly considers topographic effects, and none considers basin edge effects.
- All studied codes require the floor acceleration amplification to be increased along the height of the buildings, and for most cases the increase is linear.
- All codes reviewed account for the dynamic amplification of the response if the component and the building are in resonance. Approaches differ, varying from a simplification based on tabulated responses to methods that require deep understanding of the dynamic behavior of the component and the building.
- All codes except one allow to reduce the component seismic force based on the expected ductility of the studied element.
- All codes expect one include factors to account for the component's importance, as related to the consequence of its failure, the building's importance, based on its use, or both.

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