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Seismic Safety Design of Sprinkler Systems. Comparison Between NFPA 13 and Italian NTC 2008

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The last main earthquakes in Italy (L'Aquila 2009, Emilia 2012) highlighted the importance of seismic design of facilities and, in particular, of fire protection systems. After the L'Aquila event, the Italian National Fire Department defined specific provisions for reducing seismic vulnerability of fire protection systems, and with the Italian seismic code (NTC 2008) the seismic design of facilities became mandatory. In Italy, in case of sprinkler systems, designers and insurance companies often directly refer to the NFPA 13 standard that also defines provision for installations in seismic areas. Nowadays, this way of doing could produce some problems of compliance with the Italian law. This paper illustrates a comparative analysis between the two standards, highlighting the differences in the seismic action and in the strength verifications. Finally, practical abacus, for identifying the cases in which the NFPA 13 provides solutions that are in compliance with the NTC 2008, are presented.

1. Introduction

After the 2009 L'Aquila earthquake (central Italy) the seismic safety of fire protection systems has become a point of concern and has received specific attention for preventive purposes: for example, Grimaz and Maiolo (2010) illustrates the impact of L'Aquila earthquake on industrial facilities and life-lines, while Grimaz (2010) proposes potential interventions in order to reduce the seismic vulnerability of plants. The Interior Ministry – Italian National Fire Department enacted a guideline with criteria and suggestions for seismic vulnerability reduction of the fire protection systems (CNVVF, 2010). The damage caused by earthquakes in Emilia (Italy) on the 20th and 29th May 2012 confirmed the importance of these guidelines and underlined the relevance of the seismic safety design of facilities and specifically, of sprinkler systems. In the meantime, the seismic design of facilities according to the Italian seismic law (NTC 2008, 2008) has become mandatory. In particular, NTC 2008, section 7.2.4, prescribes that the facilities have to be designed as non-structural components and they have to withstand the seismic action defined by the NTC 2008 for the specific location of installation. Nevertheless, a lot of premises on the Italian territory are protected by sprinkler systems designed according to the NFPA 13 standard (NFPA 13, 2013), since insurance companies prescribe the compliance with this standard. Taking into account that NTC 2008 and NFPA 13 provide different values of seismic action and different values of strength, a sprinkler system designed accordingly to NFPA 13 could be, or could be not, compliant with the NTC 2008 law. This paper illustrates a comparative analysis between the two standards and underlines the differences in the definition of the seismic action and in the strength verifications. As result, practical abacus, for identifying the cases in which NFPA13 provides solutions that are in compliance with NTC 2008, are presented.

2. Seismic action

2.1 Seismic action according to NFPA 13 standard

NFPA 13 (paragraph 9.3.5.9.4) defines the seismic action on a pipe sprinkler system of weight W_a by the relationship:

$$F_p = C_p \cdot W_a \qquad (1)$$

The C_p factor is the seismic coefficient and it can be defined according to appendix E.3 of NFPA 13 by the following Eq(2).

$$C_p = \frac{0.4 \cdot a_p \cdot \left(\frac{2}{3} \cdot F_a \cdot S_S\right)}{\frac{R_p}{I_p}} \cdot \left(1 + \frac{2z}{h}\right) \tag{2}$$

The meaning of the parameters and the values assumed are described in appendix E.3 of NFPA 13 and they are reported below:

- a_p is the component amplification factor (2.5 for piping systems);
- S_S is a measure of the intensity of expected ground shaking (short-period spectral acceleration) and it can be obtained from the Authority having jurisdiction or from a seismic hazard map (for example USGS, 2013);
- R_p is the response modification factor (4.5 for high or limited deformability piping with joints made by threading, bonding, compression coupling, or grooved coupling);
- I_p is the component importance factor (1.5 for fire sprinkler systems);
- z and h are the height of the barycentre of the component of the plant and the height of the structure respectively. Both parameters are measured from the foundation plane (Figure 1); it is assumed $z=h$;
- F_a is the amplification factor based on the intensity of expected ground shaking (S_S). The F_a values do not depend directly on soil classification (NEHRP, 2000). Indeed, for the purpose of the "zone of influence" (ZOI) method adopted by NFPA 13, the values of F_a correspond to the maximum values calculated among all different soil classes (therefore soil classes C or D of NEHRP soil classification). Consequently, F_a values depend only on S_S values, as reported in Table 1.

Table 1: S_S values and consequent F_a factors (from Tab. E.3 of NFPA 13)

S_S	≤ 0.33	0.5	0.75	0.95	1	≥ 1.25
F_a	2.24	1.7	1.2	1.1	1.1	1

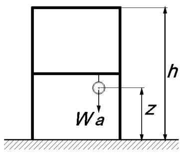

Figure 1: Parameters W_a, z and h.

Considering the above assumptions, Eq(1) becomes:

$$F_p = \frac{2}{3} \cdot F_a(S_S) \cdot S_S \cdot W_a \tag{3}$$

Eq(3) defines the F_p value in terms of Strength Design (SD). The values of F_p (expressed in term of Allowable Stress Design – ASD) are showed also in the table 9.3.5.9.3 of NFPA 13. In that table, the lowest value considered for S_S is 0.33. Finally, it is important to highlight that in order to convert from SD to ASD, it is necessary multiply the SD value by 0.7.

2.2 Seismic action according to NTC 2008

NTC 2008 computes the seismic action on a non-structural element in the paragraph 7.2.3 by assuming the following relationships:

$$F_a = \frac{S_a}{q_a} \cdot W_a \tag{4}$$

$$S_a = S \cdot \frac{a_g}{g} \cdot \left(\frac{3\left(1 + \frac{z}{h}\right)}{1 + \left(1 - \frac{T_a}{T_1}\right)^2} - \frac{1}{2} \right) \geq S \cdot \frac{a_g}{g} \tag{5}$$

where:
- W_a, z and h have the same meaning illustrated for NFPA 13 (Figure 1);
- F_a is the seismic force acting on the barycentre of the component of the plant;
- S_a is the maximum horizontal acceleration that the component has to withstand;
- q_a is the plant structural coefficient. In the following, the value q_a=2 is assumed for sprinkler systems, as this assumption is considered equivalent to the assumption done for R_p parameter (NFPA 13);
- $S=S_S \cdot S_T$ is the site amplification coefficient. It depends on stratigraphy (S_S) and topography (S_T);
- a_g/g is the maximum normalized ground acceleration on a A-type soil class (NTC 2008 classification);
- T_a is the fundamental period of the pipes system, along the considered direction;
- T_1 is the fundamental period of the building where the plant is installed, along the considered direction.

Eq(4) and Eq(5) can be also written as:

$$F_a = \frac{S_a}{q_a} \cdot \mathrm{W_a} = S \cdot \frac{a_g}{g} \cdot \frac{5.5 \cdot \mathrm{C}_{\zeta\tau}}{q_a} \cdot W_a \tag{6}$$

Where:

$$C_{\zeta\tau} = \frac{1}{5.5} \cdot \left(\frac{3\left(1+\frac{z}{h}\right)}{1+\left(1-\frac{T_a}{T_1}\right)^2} - \frac{1}{2} \right) \qquad \text{with} \quad \frac{1}{5.5} \le C_{\zeta\tau} \le 1 \tag{7}$$

The parameter $C_{\zeta\tau}$ can be interpreted as a reductive factor of the seismic action, depending only on $\zeta=z/h$ and $\tau=T_a/T_1$. $C_{\zeta\tau}$ can reach the maximum value of 1 in the case of a sprinkler system at the roof level ($z=h$) and resonance between pipe system and structure ($T_a=T_1$). Figure 2a shows the behavior of $C_{\zeta\tau}$ depending on ζ and τ. Since it is difficult to correctly estimate the value of T_a, it is preferable to assume, to be on the safe side, $T_a=T_1$.
With the above assumptions, Eq(6) becomes:

$$F_a = 2.75 \cdot S \cdot \frac{a_g}{g} \cdot W_a \tag{8}$$

2.3 Relation between NFPA 13 and NTC 2008 seismic action

Considering the assumptions declared in the previous paragraphs, the NFPA 13 design seismic action depends only on the S_S parameter (Eq(3)), while the NTC 2008 design seismic action depends on the term S^*a_g/g (Eq(8)). Figure 2b permits to graphically find the values of S^*a_g/g (NTC 2008) starting from the value of S_S (NFPA 13) and vice versa.

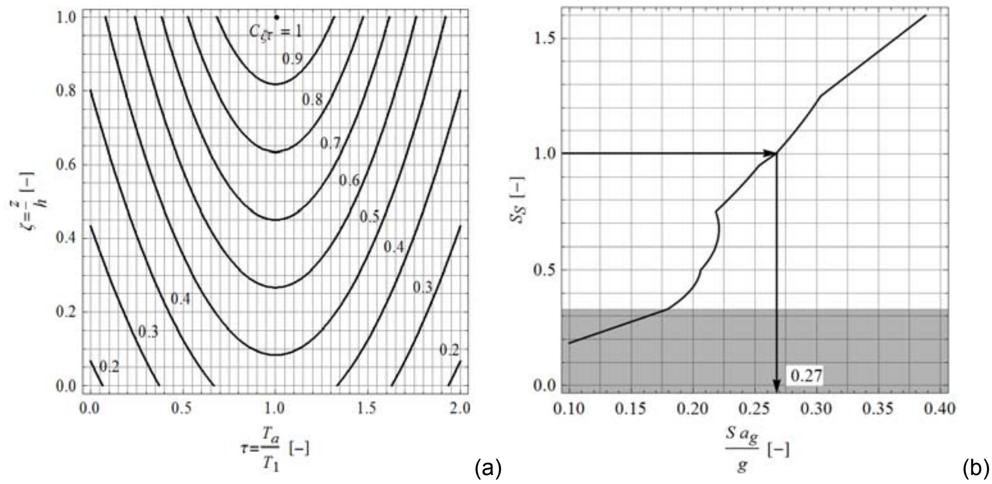

Figure 2: (a) Values of the $C_{\zeta\tau}$ parameter for different values of $\zeta=z/h$ and $\tau=T_a/T_1$. (b) Graphical estimation of the S^*a_g/g (NTC 2008) parameter, starting from the value of S_S (NFPA 13) (in the example, a value of S_S=1 corresponds to S^*a_g/g=0.27). The grey filled area represents the value of S_S lower than 0.33, not considered in the table 9.3.5.9.3 of NFPA 13.

3. Sway-brace design

The sway-brace can be realized by using a tensile-compressive system (so called rigid sway-braced) or a tension-only system (i.e. cables or slender braces). Figure 3 illustrates the two types of sway-braces.

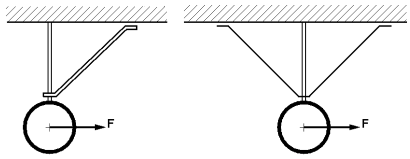

Figure 3: Example of a rigid sway-brace (left) and a tension only sway-brace (right).

3.1 Compressive strength for flexural buckling strength

NFPA 13 and NTC 2008 provide different equations for evaluating the flexural buckling strength. In this paper, the equations are not described, but two figures comparing the strengths with different slenderness (Figure 4a) and the ratio between the two strengths (Figure 4b) are shown.

It is relevant to notice that NFPA 13 is more conservative than NTC 2008, as it provides flexural buckling strength values that are about 88% - 95% of the Italian code. For this reason a steel rigid sway-brace designed accordingly to NFPA 13 is always in compliance with NTC 2008.

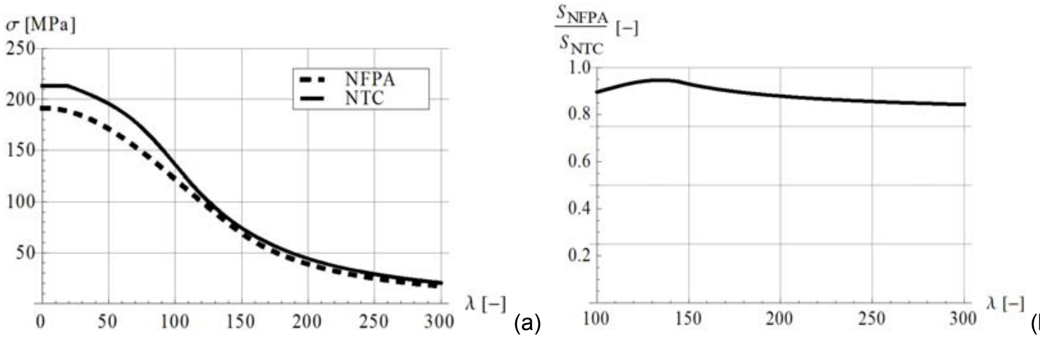

Figure 4: (a) Example of comparison of the buckling stress provided by NFPA 13 and NTC 2008 for different values of slenderness. (b) Ratio between the buckling strength provided by NFPA 13 and NTC 2008 for different values of slenderness.

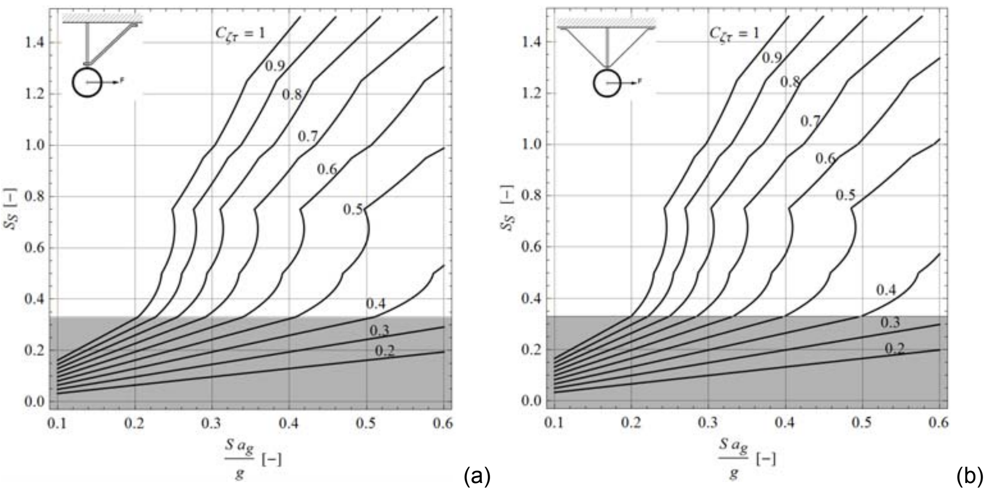

Figure 5: Comparison between S_S (NFPA 13) and $S{*}a_g$ /g (NTC 2008) for different values of $C_{\zeta T}$, (a) in the case of rigid sway-brace with slenderness λ=200 and (b) in the case of tension-only sway-braces. The grey filled area represents the value of S_S lower than 0.33, not considered by table 9.3.5.9.3 of NFPA 13.

3.2 Tensile strength

The equations used by NFPA 13 and NTC 2008 to calculate the tensile strength for steel sway-braces are similar. Actually, the NFPA 13 is more conservative with respect to NTC 2008 by a factor of about 10%, and a steel tension-only sway-brace designed accordingly to NFPA is always in compliance with NTC 2008. However, a tension-only system is often realized by a cable with a design-strength defined by the manufacturer; in this case no difference exists between NTC 2008 and NFPA 13 in terms of strength.

4. Comparison between NFPA 13 and NTC 2008: abacus

In order to make easier knowing when the NFPA 13 seismic design is compliant with NTC 2008, the Authors propose to use the abacus in Figure 5. Figure 5a refers to rigid sway-braces while Figure 5b to tension-only sway-braces. If the S_S values of the NFPA 13 design are known, and for a given $C_{\zeta T}$ (Eq(7) or Figure 2a), it is possible to graphically identify the corresponding values of $S*a_g/g$ of NTC 2008.

5. Example of comparison

In the following, the parameters for the design of a sprinkler system according to NFPA 13 in three different Italian cities are compared with the parameters for a design compliant with NTC 2008 (Table 2). The comparison permits to answer the question: “In case of a sprinkler system designed with rigid (or tension-only) sway-braces according to NFPA 13 (and therefore for a specific S_S value), which is the correspondent value of ground acceleration ($S*a_g/g$) for NTC 2008?”
Table 2 shows the three analyzed cities: Bologna, Udine and Tolmezzo (UD) (all in Northern Italy). In the comparison, an installation of the sprinkler system at the roof level is assumed ($z=h$), and the conservative assumption $T_a=T_1$ is adopted. These hypotheses lead to $C_{\zeta T}=1$. The values of short-period spectral acceleration (S_S) for NFPA 13 come from the “worldwide seismic design map” (USGS, 2013). Using the two abacus in Figure 5, it is possible to obtain the maximum $S*a_g/g$ values ensuring that the NFPA 13 seismic design is compliant with NTC 2008.

Table 2. Correspondence between S_S (NFPA 13) and $S*a_g/g$ (NTC 2008) for rigid and tension-only sway-braces, for three case study (derived from Figure 5)

City	S_S	$S*a_g/g$ (rigid sway-braces)	$S*a_g/g$ (tension-only sway-braces)
Bologna (BO)	1.06	0.32	0.31
Tolmezzo (UD)	1.22	0.34	0.33
Udine (UD)	1.02	0.31	0.30

Table 3 and 4 show the $S*a_g/g$ demand for rigid and tension-only sway-braces, respectively. The values are divided considering both the different NTC 2008 soil classes (A, B, C, D that are different from NEHRP 2000 definitions) and four levels of importance of structures (Reference Life: V_R = 50, 75, 100 and 150 years). The filled cells with bold values, represent the cases in which the NFPA 13 is not compliant with NTC 2008. For example, a sprinkler system designed in Bologna according to NFPA 13 has S_S=1.06, and consequently $S*a_g/g$ of 0.32 for rigid and 0.31 for tension-only sway-braces; this sprinkler system is always compliant with the NTC 2008 code for all the soil classes. However, a sprinkler system with tension-only sway-braces designed in Udine according to NFPA 13 (S_S=1.02) has a correspondent $S*a_g/g$ value of 0.31 and then it is compliant with NTC 2008 in case of soil A, B and C for factories (with V_R = 50 years), soil A and B for schools (V_R = 75 years) and civil protection offices (V_R = 100 years), and it is never compliant with NTC 2008 in case of hospitals (V_R = 150 years) (Table 4).

Table 3. $S*a_g/g$ parameter for A, B, C and D soil Italian classification (from NTC 2008). The filled cells with bold values are the cases in which the NFPA 13 seismic design of rigid sway-braces is not compliant with NTC 2008 law (compare with values in Table 2).

Premises and City	V_R (y)	$S*a_g/g$ (soil A)	$S*a_g/g$ (soil B)	$S*a_g/g$ (soil C)	$S*a_g/g$ (soil D)
Factory in Bologna (BO)	50	0.17	0.20	0.24	0.30
Factory in Tolmezzo (UD)	50	0.24	0.28	0.32	**0.36**
Factory in Udine (UD)	50	0.21	0.25	0.29	**0.34**
School in Udine (UD)	75	0.24	0.28	**0.33**	**0.37**
Civil protection offices in Udine (UD)	100	0.27	0.31	**0.35**	**0.38**
Hospital in Udine (UD)	150	**0.32**	**0.35**	**0.39**	**0.39**

Table 4. Sa_g/g parameter for A, B, C and D soil Italian classification (from NTC 2008). The filled cells with bold values are the cases in which the NFPA 13 seismic design of tension-only sway-braces is not compliant with NTC 2008 law (compare with values in Table 2).*

Premises and City	V_R (y)	S*a_g/g (soil A)	S*a_g/g (soil B)	S*a_g/g (soil C)	S*a_g/g (soil D)
Factory in Bologna (BO)	50	0.17	0.20	0.24	0.30
Factory in Tolmezzo (UD)	50	0.24	0.28	0.32	**0.36**
Factory in Udine (UD)	50	0.21	0.25	0.29	**0.34**
School in Udine (UD)	75	0.24	0.28	**0.33**	**0.37**
Civil protection offices in Udine (UD)	100	0.27	**0.31**	**0.35**	**0.38**
Hospital in Udine (UD)	150	**0.32**	**0.35**	**0.39**	**0.39**

6. Conclusions

This paper briefly presents some criteria for the seismic design of sprinkler systems, both according to NFPA 13 and to NTC 2008. The comparison between the two standards highlights the differences and points out the possibility that a design according to NFPA 13 might not comply with NTC 2008. Being NTC 2008 a law, the compliance with NTC 2008 must be verified for installations in Italy. Nevertheless, sprinkler systems are often designed according to NFPA 13, and therefore a specific verification of compliance with NTC 2008 is necessary. The results and in particular the abacus (Figure 5) presented in this paper can be used by designers and Authorities to make easier this verification.

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