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Seismic Safety Design of Sprinkler Systems. Comparison Between FM Global and NTC 2008

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The recent main earthquakes in Italy (Emilia, 2012, Abruzzo, 2009) highlighted the importance of seismic design of plants in particular in the industrial sector. Indeed, in such cases, the indirect costs due to the out of services of the plants and the consequent production losses are very high and greater than the direct costs of reconstruction/reparation of the plant. For this reason, often, the insurance companies require that the principal plants (such as the sprinkler system) should be seismically designed. In case of an earthquake, the seismic design of sprinkler systems has to ensure the strength and the stability in order to avoid accidental ruptures and onerous out of services. In Italy, the seismic design of the plants became mandatory after July 2009 with the entering into force of the NTC 2008 standard. Nevertheless, foreign insurance standards, such as FM Global, are usually adopted in Italy for the seismic design of sprinklers. This practice raises the following question: “Is a sprinkler designed according to the requirements of FM standards compliant with the NTC 2008?”.
This paper illustrates a comparative analysis between FM Global and the NTC 2008, highlighting the differences in terms of seismic action and strength. Finally, practical abacuses, for identifying the cases in which the FM-Global provides solutions that are in compliance with the NTC 2008 are presented.

1. Introduction

Fire risk is one of the main concerns of the safety managers in workplaces. Fire protection systems, and sprinklers, in particular, are widely used as effective countermeasure both for controlling the fire propagation and for facilitating the evacuation of people. Grimaz et al., 2014a and Grimaz and Tosolini, 2013 illustrate the role of these systems in the definition of fire safety and in the evacuation, respectively. For the workplaces located in a seismic area, the earthquake effects must be considered also in terms of fire safety. Indeed, the seismic damage on industrial facilities could cause both damage on structures and on content (direct damage) but also out-of-services of plants and production losses (indirect damage). Grimaz and Maiolo (2010) highlighted this aspect after the recent earthquakes in Italy (Abruzzo, 2009 and Emilia, 2012). Moreover, it is worth noting that an earthquake could, at the same time, provoke fires and/or compromise the operability of the fire protection systems. An out-of-service of the fire protection system could have heavy consequences especially if the seismic action provokes a leakage of flammable or explosive substances. This means that a fire protection system, and in particular sprinklers, must be designed both to withstand the seismic action and to maintain its efficiency after the event, avoiding accidental activation too.
In order to ensure that a sprinkler system performs correctly after an earthquake, insurance companies require the plant to be compliant with specific standards. In the Italian territory, insurance companies often require the compliance with NFPA 13 or FM Global (2010); anyway, it is possible to observe that these standards could be not always compliant with the specific national seismic code. Following an outline similar to Grimaz et al. (2014b), where the comparison between NFPA 13 and NTC 2008 standards for the design of sprinkler systems was described, in this paper the Authors illustrate a comparative analysis for the Italian territory between FM Global standard and NTC 2008.

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2. Seismic action

2.1 Seismic action according to FM Global standards

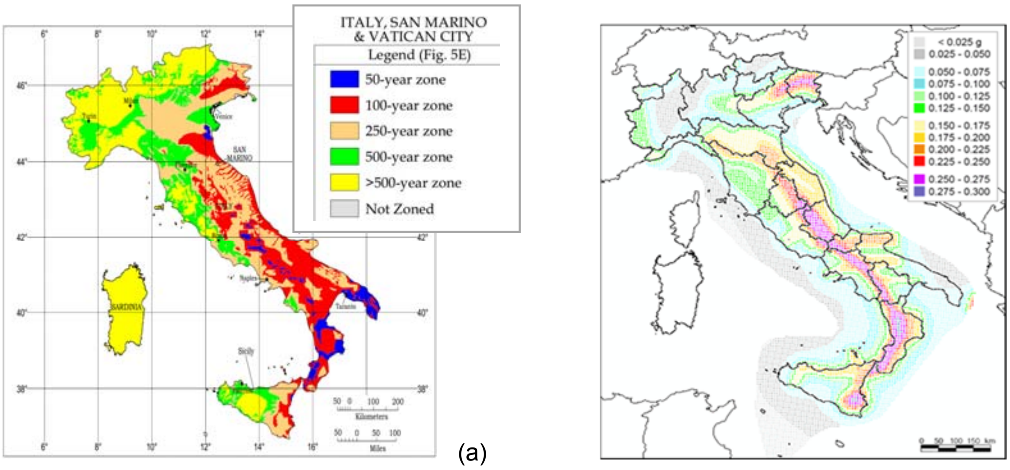
FM Global (in the following FM) 2-8, in the §2.2.1.8 defines the seismic action on a pipe sprinkler system of weight W_a by the relationship:

$$F_p = \mathrm{G} \cdot W_a \qquad (1)$$

Where

- W_a is the seismic weight of the considered zone of influence of the pipe system;
- G is the expected horizontal acceleration;
- F_p is the horizontal seismic force acting on considered pipe system.

The expected horizontal acceleration *"G"* depends on the earthquake zones, as defined in paragraph C.7 of FM 1-2 (2010). FM Earthquake Zone Map (FM 1-2, §C.7.3) of Italy differs from the hazard map of NTC 2008 developed for the Italian territory (Figure 1). FM Earthquake Zone Map provides the mean return period of ground motion that could cause "reasonable damage to structures without significant seismic protection" (FM 1-2, §C.7). FM 2-8 (2010), §2.2.1.2.2 suggests to adopt a minimum G parameter of 0.75 for the "50-year earthquake zones", 0.5 in the "100-year earthquake zones", and 0.4 in the "250" and "500-year earthquake zones".



(a) (b)

Figure 1. (a) FM Earthquake Zone Map of Italy (from Fig. 5E of FM 1-2). Blue zones: G = 0.75. Red zones: G=0.50. Orange, green and yellow zones: G=0.40. (b) Seismic hazard map of NTC 2008 for the determination of the parameter a_g/g.

The G factors defined by FM are based on the Allowable Stress Design (ASD) analysis method, this implies that a coefficient 0.7 has to be used to convert the G parameter values for the application in the Strength Design (SD) method. Therefore, the FM seismic action expressed in term of SD becomes:

$$F_p = \frac{1}{0.7} \cdot \mathrm{G} \cdot W_a \qquad \text{(SD method)} \qquad (2)$$

2.2 Seismic action according to NTC 2008

NTC 2008 computes the seismic action on a non-structural element as reported in §7.2.3. The evaluations were explained in Grimaz et al., 2014b and are shortly reported in Eq. (3) and (4). For an exhaustive description of the meaning of the symbols in the equations, refer to Grimaz et al., 2014b.

$$F_a = \frac{S_a}{q_a} \cdot \mathrm{W_a} = S \cdot \frac{a_g}{g} \cdot \frac{5.5 \cdot \mathrm{C}_{\zeta\tau}}{q_a} \cdot W_a \qquad (3)$$

Where:

$$C_{\zeta\tau} = \frac{1}{5.5} \cdot \left(\frac{3\left(1 + \frac{z}{h}\right)}{1 + \left(1 - \frac{T_a}{T_1}\right)^2} - \frac{1}{2} \right) \qquad \text{with} \quad \frac{1}{5.5} \leq C_{\zeta\tau} \leq 1 \qquad (4)$$

The parameter $C_{\zeta\tau}$ can be interpreted as a reductive factor of the seismic action, depending only on $\zeta=z/h$ and $\tau=T_a/T_1$. $C_{\zeta\tau}$ is maximum in the case of a sprinkler system at the roof level ($z=h$) and resonance between pipe system and structure ($T_a=T_1$).

2.3 Comparison between FM Global and NTC 2008 seismic action

The comparison between FM and NTC 2008 aims at evaluating which is the value of $S \cdot a_g/g$ in the NTC 2008 seismic action (Eq. (3)) that produces the same seismic action of FM calculated with the specific *G* parameter (Eq. (2)). Comparing Eq. (2) and Eq. (3) it results:

$$\left\{S \cdot \frac{a_g}{g}\right\}_{eq} = \frac{G}{1.93 \cdot C_{\zeta\tau}} \qquad (5)$$

Where $\{S^*a_g/g\}_{eq}$ is the NTC 2008 parameter equivalent to FM values.

If we consider, for example, $z=h$ and $T_a=T_1$ (therefore $C_{\zeta T}=1$), the FM parameters G=0.4, 0.5 and 0.75, produces the same seismic action of the NTC 2008 parameters $S \cdot a_g/g$ =0.21, 0.26 and 0.39.

3. Comparison between FM Global and NTC 2008 strength

Sway-brace can be realized by using a rigid (tensile-compressive system) or tension-only system (see Figure 2).

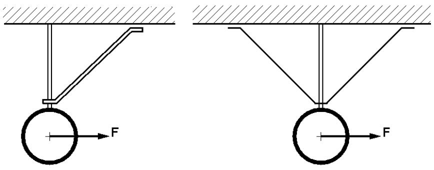


Figure 2: example of a rigid sway-brace (left) and a tension only sway-brace (right).

As for NFPA 13, FM Global computes the strength of sway-brace referring to the AISC (2005) standard and in terms of ASD. This implies that it is necessary to calculate the strength in terms of SD to compare the results with NTC 2008 (i.e. divide the ASD value by 0.7).

3.1 Tensile strength by AISC (Strength Design)

The tensile strength (expressed in terms of SD) is defined by relationship D2-1 of the AISC:

$$\mathrm{R_d} = \frac{1}{0.7} \cdot \mathrm{R_a} = \frac{1}{0.7} \cdot \frac{A \cdot F_y}{1.67} = \frac{A \cdot F_y}{1.17} \qquad (6)$$

Where

- A is the gross section;
- F_y is the yield stress.

3.2 Compressive strength for flexural buckling by AISC (Strength Design)

The compressive strength for flexural buckling (expressed in terms of ASD) is given by the relationship E3-1 of the AISC:

$$\mathrm{R_d} = \frac{1}{0.7} \cdot \mathrm{R_a} = \frac{1}{0.7} \cdot \frac{A \cdot F_{cr}}{1.67} = \frac{A \cdot F_{cr}}{1.17} \qquad (7)$$

Where:

$$F_{cr} = \begin{cases} F_y \cdot 0.658^{\frac{F_y}{F_e}} & \lambda \leq 4.71 \cdot \sqrt{\dfrac{E}{F_y}} \\ 0.877\, F_e & \lambda > 4.71 \cdot \sqrt{\dfrac{E}{F_y}} \end{cases}$$

and

$$F_e = \frac{\pi^2 E}{\lambda^2}$$

3.3 Tensile strength by NTC 2008 (Strength Design)

The tensile strength $N_{t,Rd}$ has to be computed according to the following equation (NTC 2008, §4.2.4.1.2):

$$N_{t,Rd} = \frac{A \cdot f_{yk}}{\gamma_{M0}} = \frac{A \cdot f_{yk}}{1.05} \qquad (8)$$

Where

- A is the cross section of the sway-brace pipe;

- f_{yk} is the characteristic yield stress of the material;
- γ_{M0} = 1.05 is the strength safety factor (NTC 2008, Table 4.2.5).

3.4 Compressive strength for flexural buckling by NTC 2008 (Strength Design)
The evaluation of the sway-brace compressive strength requires the verification the flexural buckling strength. In particular, the buckling strength ($N_{B,Rd}$) of the brace has to be computed according to Eq. (9) (NTC 2008, §4.2.4.1.3.1):

$$N_{B,Rd} = \frac{\chi \cdot A \cdot f_{yk}}{\gamma_{M1}} \tag{9}$$

Where:

- $\chi = \frac{1}{\Phi+\sqrt{\Phi^2-\bar{\lambda}^2}} \leq 1$ is the buckling reduction factor;
- $\Phi = \frac{1}{2}\left(1 + \alpha\left(\bar{\lambda} - \frac{2}{10}\right) + \bar{\lambda}^2\right)$;
- α is the imperfection factor (NTC 2008,§ 4.2.4.1.3). It depends on the section of the brace adopted. Typical values of α are 0.21, 0.34 and 0.49, for the instability curves *a*, *b*, *c*, respectively;
- $\bar{\lambda} = \sqrt{\frac{A \cdot f_{yk}}{N_{cr}}} = \cdots = \sqrt{\frac{f_{yk}}{E}}\frac{\lambda}{\pi}$ is the dimensionless slenderness;
- $N_{cr} = \frac{\pi^2 \cdot E \cdot A}{\lambda}$ is the elastic critical buckling force;
- $\lambda = K \cdot \frac{L}{r}$ is the slenderness of the pipe;
- K is the effective length factor (generally K = 1);
- L is the length of the sway-brace pipe;
- r is the radius of gyration of the sway-brace pipe;
- A is the cross section of the sway-brace pipe;
- f_{yk} is the characteristic yield stress of the material;
- E is the Young modulus of the material;
- γ_{M1} = 1.05 is the buckling safety factor (Table 4.2.5).

3.5 Comparison between the strength
For tensile strength (Strength Design), FM Global and NTC 2008 use similar equation. The main difference is caused by the adopted safety factors. FM Global strength design is more conservative with respect to NTC 2008 of a factor of about 10%. As a consequence, for the same seismic action, a steel tension-only sway-brace designed according to FM is always in compliance with NTC 2008. Note that for tension-only sway-braces, FM does not permit slenderness greater than 300 (therefore cable systems are not permitted) while NTC 2008 does not give any limitation.
For flexural buckling strength, FM is more conservative than NTC 2008 for low values of the α parameter and high slenderness. For example, for a slenderness λ=200 and hot formed brace (instability curve *"a"*, Figure 3), it provides a strength of about 88% of the Italian code. As a consequence, for the same seismic action a class *"a"* rigid sway-brace designed according to FM is always in compliance with NTC 2008. Note that both FM and NTC 2008, for rigid sway-brace, limit the maximum slenderness to 200.

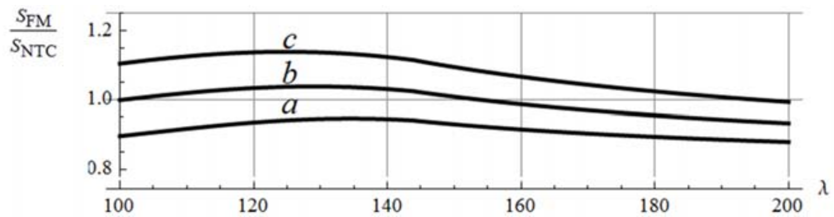
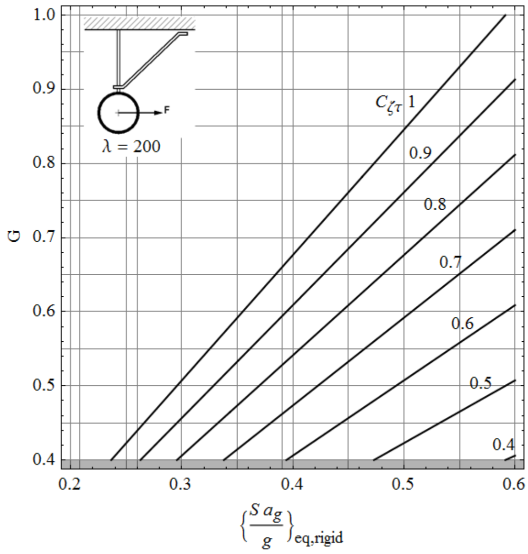


Figure 3: Ratio between the buckling strength provided by FM and NTC 2008 for different values of slenderness and for the three instability curves "a", "b" and "c".

4. Comparison between FM Global and NTC 2008: design abacus

In order to simply identify the cases in which FM Global seismic design is compliant with NTC 2008, the Authors propose to use the abacus in Figure 4. Figure 4a refers to rigid sway-braces (slenderness λ=200, instability curve “a”) while Figure 4b to tension-only sway-braces. If the *G* values of the FM design are known, and for a given $C_{\zeta T}$ (see Eq. (4) or Grimaz et al., 2014b), it is possible to graphically identify the corresponding values of $S{\cdot}a_g/g$ of NTC 2008.



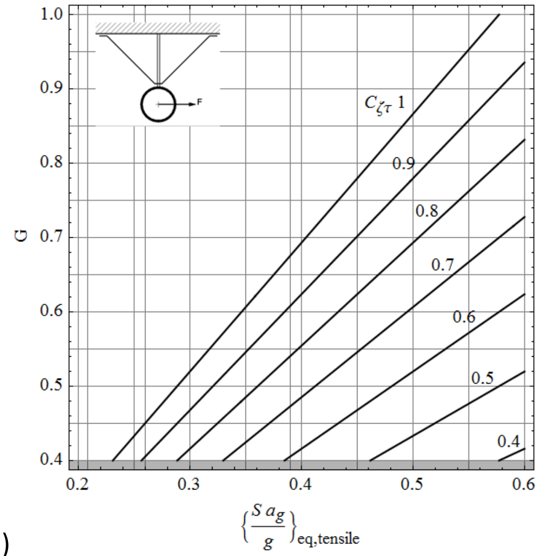


Figure 4: (a) equivalent $S{\cdot}a_g/g$ (NTC 2008) parameter for rigid sway-brace with λ=200 and instability curve “a” (b) equivalent $S{\cdot}a_g/g$ (NTC 2008) parameter for tension only sway-brace. The grey filled area represents the value of G lower than 0.4, not recommended by FM Global.

5. Example of comparison

In order to illustrate the proposed methodology, the $\{S{\cdot}a_g/g\}_{eq}$ parameter is evaluated for some cities in Italy, and for a rigid sway-brace originally designed according to FM standard. The results are compared with the $S{\cdot}a_g/g$ values esteemed on the basis of NTC 2008 requirements considering different soil classes (A, B, C and D, as defined by NTC 2008) (Table 1). 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, therefore $C_{\zeta T}$=1 is adopted. The values of the expected horizontal acceleration (*G*) for FM come from the FM 1-2 (Figure 1). By using the two abacus in Figure 4, it is possible to obtain the maximum $S{\cdot}a_g/g$ values ensuring that the FM seismic design is compliant with NTC 2008. In Table 1 the values of the $S{\cdot}a_g/g$ demand for rigid sway-braces are calculated for 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 FM standard is not compliant with NTC 2008.

Table 1. Design compliance FM Global – NTC 2008 for rigid sway-braces (λ=200, curve of instability “a”). Values of G, the equivalent $\{S{\cdot}a_g/g\}_{eq}$, and $S{\cdot}a_g/g$ parameter for A, B, C and D soil Italian classification (NTC 2008). The filled cells with bold values are the cases in which the FM Global is not compliant with NTC 2008.

City	importance V_R (y)	*G*	$\{S{\cdot}a_g/g\}_{eq}$	$S{\cdot}a_g/g$ (soil A)	$S{\cdot}a_g/g$ (soil B)	$S{\cdot}a_g/g$ (soil C)	$S{\cdot}a_g/g$ (soil D)
L'Aquila	50	0.75	0.44	0.26	0.30	0.35	0.39
L'Aquila	75	0.75	0.44	0.30	0.33	0.38	0.40
Bologna	50	0.5	0.29	0.17	0.20	0.24	**0.30**
Bologna	75	0.5	0.29	0.19	0.23	0.27	**0.33**
Udine	50	0.5	0.29	0.21	0.25	0.29	**0.34**
Udine	75	0.5	0.29	0.24	0.28	**0.33**	**0.37**
Udine	100	0.5	0.29	0.27	**0.31**	**0.35**	**0.38**
Udine	150	0.5	0.29	**0.32**	**0.35**	**0.39**	**0.39**
Tolmezzo	50	0.5	0.29	0.24	0.28	**0.32**	**0.36**
Tolmezzo	75	0.5	0.29	0.28	**0.32**	**0.36**	**0.39**
Taranto	50	0.75	0.44	0.07	0.09	0.11	0.13
Taranto	75	0.75	0.44	0.08	0.10	0.12	0.14

For example, a sprinkler system designed in L'Aquila according to FM Global has *G*=0.75, and consequently $S{\cdot}a_g/g$ of 0.44 for rigid sway-braces; this sprinkler system is always compliant with the NTC 2008 code for the considered soil classes. However, a sprinkler system with rigid sway-braces designed in Udine according to FM Global (*G=0.50*) has a correspondent $S{\cdot}a_g/g$ value of 0.29 and then it is compliant with NTC 2008 in case of soil A, B and C for small factories (V_R = 50 years), soil A and B for schools (V_R = 75 years), only soil A for civil protection offices (V_R = 100 years), and it is never compliant with NTC 2008 in case of hospitals (V_R = 150 years) (Table 1).

6. Conclusions

Safety managers of premises located in seismic regions need to evaluate the increase of a fire risk as a consequence of an earthquake. Indeed, relevant earthquakes could cause damage on structures and content, but also out-of-services and potential losses. For this reason, insurance companies require the design of fire protection systems according to specific standards such as FM Global. In Italy, the compliance with these standards is not mandatory; on the other hand, the design of new fire protection systems must follow the rules of NTC 2008. In order to identify the cases in which FM Global satisfies Italian NTC 2008 and the cases in which it is not possible to apply FM standards in the Italian territory, the Authors illustrate the comparison of the two approaches for the seismic design of sprinkler system sway-braces. The Authors prove that in several cases in Italy the FM standard is not compliant with NTC 2008 and they introduce simple abacuses which can be used by designers and Authorities to make easier the compliance verification process.

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