Designing Earthquake Protection for Fire Sprinkler Systems

Using the Model Building Codes

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In the September 2003 issue of *Sprinkler Age* we presented the steps to determine whether or not earthquake protection is required for a particular project. We pointed out that protection is no longer based solely upon the zone number from the NFPA 13 seismic map and that a sprinkler system in one building might require earthquake protection while a system in a nearby building may not. Then, in the November 2003 issue, we discussed developments in the relationship between using the *Building Construction and Safety Code (NFPA 5000)*, the *International Building Code (IBC)*, and NFPA 13. We also gave justification for only using NFPA 13 when designing for earthquake protection, although it may not be permitted by the explicit wording of the model building codes. In this third and final article, we will present an example of how to calculate force factors used to design earthquake protection based on building code criteria and identify the major problem with those criteria. As you read this article, keep in mind that NFPA 5000 and the IBC both essentially point to American Society of Civil Engineers (ASCE) 7 for criteria on earthquake protection.

The working example for this article is a five-story, 60 ft high hospital in Jonesboro, AR, 72404. Using the step-by-step process outlined in the first article, we must determine whether or not earthquake protection is required for the fire sprinkler system. The hospital is in seismic use group III (ASCE 7:9.1.3, IBC:1616.2). Using the Seismic Design Parameters (SDP) software, we determine the mapped maximum considered earthquake spectral response acceleration at short periods S_s to be 1.9756g and at 1-second periods S_1 to be 0.597g. There are at least two opportunities for exemption from earthquake protection in this process. The first is found in exception #5 to IBC:1614.1. According to the given parameters, the building in our scenario is not exempt. If the S_s was less than or equal to 0.15g and if the S_1 was less than or equal to 0.04g, the building would be exempt. Next, based on information obtained from the civil engineer for the project, the site is determined to be in Site Class C. It is important to note that the A/E building design team is expected to have this information on-hand since it is required for other seismic aspects of the building itself. However, if this information cannot be obtained, the default is Site Class D, which is more demanding than most scenarios. Using the SDP software, which includes the site class factors (F_a = 1.0, F_v = 1.3), the maximum considered earthquake spectral response acceleration for short periods S_{MS} is 1.9756g and at 1-second periods S_{M1} is 0.777g. Then the design spectral response accelerations are determined at short periods S_{DS} to be 1.3171g and at 1-second periods S_{D1} to be 0.518g (ASCE 7:9.4.1.2.5, IBC:1615.1.3). Here is the second opportunity for exemption. Exception #6 to IBC:1614.1 allows that where S_{DS} is less than or equal to 0.167g and where S_{D1} is less than or equal to 0.067g, the building is exempt. The building is still not exempt. Finally, the building is placed in Seismic Design Category F based on both the short and 1-second period response accelerations (ASCE 7:9.4.2, IBC:1616.3). To this point in the process there are no exemptions for this building that would allow omission of earthquake protection, so protection must be provided.

NFPA 5000:35.10 and IBC:1621 both refer to ASCE 7, Section 9 for design and construction to resist the effects of earthquakes. ASCE 7:9.6.23.11.2 allows the use of NFPA 13 for the design and construction of the earthquake bracing system provided force and displacement requirements of ASCE 7:9.6.1.3 and ASCE 7:9.6.1.4 are satisfied. This means we can use NFPA 13, but with a caveat. We have to verify that the NFPA 13 design will meet or exceed the force and displacement design from ASCE 7.

First we will calculate the design forces for sizing braces to be installed on portions of the fire sprinkler system in our hospital. Despite the entire system being protected, we intentionally said "portions" since the design force differs throughout the building for the same size piping. NFPA 13 uses the same design force throughout regardless of height. For this example, the F_p calculated from NFPA 13 is 560 lbs. This is based on a calculated weight of water filled pipe in the zone of influence of 973.9 lbs, a force factor W_p of 0.50, and a miscellaneous fittings and components factor of 1.15. The F_p calculated from NFPA 13 must be compared to the F_p calculated from ASCE 7 and the larger value used to size the brace. This value is calculated from ASCE 7 using a base formula and two bounding formulas (ASCE 7:9.6.1.3) as follows.

$$F_p = \frac{0.4 a_p S_{DS} W_p}{R_p / I_p}\left(1 + 2\left(\frac{z}{h}\right)\right)$$

F_p is not required to be greater than
$F_p = 1.6 S_{DS} I_p W_p$
and F_p shall not be less than
$F_p = 0.3 S_{DS} I_p W_p$
where:
F_p = seismic design force
S_{DS} = design short period spectral acceleration (1.3171g calculated above)
a_p = component amplification factor (1.0 for sprinkler systems)
I_p = component importance factor (1.5 for sprinkler systems)
W_p = component operating weight (973.9 lb in our example)
R_p = component response modification factor (3.5 for sprinkler systems)
z = height of attachment point with respect to the base (55 ft in our example)
h = average roof height with respect to the base (60 ft in our example)

The above formulas set limits on the force used to size the earthquake protection components. For example, if you calculate F_p to be 3000 lbs but the first upper bounding formula results in F_p = 2745 lbs, then you are only required to design the component to withstand a force of 2745 lbs. You are free to design it using an F_p of 3000 lbs, but it is not required. Conversely, you may calculate an F_p to be 200 lbs, but the lower bounding formula results in F_p = 273 lbs. You must design the component to withstand a force of at least 273 lbs, but not less.

Back to the base formula and substituting all the values:

$$F_p = \frac{0.4(1.0)(1.3171)(973.9)}{3.5/1.5}\left(1 + 2\left(\frac{55}{60}\right)\right)$$

and solving we have:
$F_p = 623$ *lbs*

Also be aware of the minimum and allowed maximum loads discussed earlier.

Substituting and solving we have:
$F_p = 1.6(1.3171)(1.5)(973.9) = 3078.5$ *lbs*
and
$F_p = 0.3(1.3171)(1.5)(973.9) = 577.2$ *lbs*

This means that the design load for any brace in our example is not required to exceed 3078.5 lbs and is not permitted to be less than 577.2 lbs regardless of location. Also, notice that the value calculated using ASCE 7 is greater than the value calculated using NFPA 13. The higher value must be used to size the brace components.

Now, let's take the same scenario and move it to the first floor of the hospital at approximately 8 ft above finished floor. This will show the impact of where the brace is located within the building. The only variable changing in the equation would be z, which would now be 8.

Substituting and solving we have:

$F_p = 278.5\ lbs$

Note that the design load from the fifth floor is 623 lbs, but on the first floor it is 278.5 lbs for the same size zone of influence. This difference reflects the expectation that more loading will be induced on components located higher in the building than components located lower in the building, due to the building's movement in an earthquake.

The calculated design force for our first floor brace was less than the minimum allowed, so it must be designed to the minimum 577.2 lbs. Also note that the NFPA 13 calculated design load was 560 lbs, which is also less than the minimum. Once the design load F_p is established, using either building code or NFPA 13 criteria, select and size the brace components using NFPA 13.

Now, let's look at displacement and deflection. This is where the problem starts. If you are accustomed to using NFPA 13 in designing earthquake protection, you probably aren't familiar with these terms. These aspects are not brought out in the text and formulas of NFPA 13. This may be because they are already addressed in the NFPA 13 design criteria by the very nature of the materials used in fire sprinkler systems and the maximum allowed spacing of certain components.

Since these terms are not adequately defined, here is an analogy to help us understand their meaning. Let's say you get out your favorite fishing rod, set the reel end on the ground, and stand the rod upright. Secure it about half way up with your left hand. Now with your right hand move the tip of the rod in any direction bending the rod. Notice how the rod bends? This is deflection. Now, take note of the rod tip's new location relative to its original location. This is displacement. Notice that some parts of the rod are displaced farther from their original locations than others. In an earthquake, a building will deflect similarly. When it deflects, portions of the building are displaced from their original location. Some parts are displaced farther than others.

Again, ASCE 7:9.6.3.11.2 allows NFPA 13 designed earthquake protection provided the force and displacement requirements of ASCE 7:9.6.1.3 and ASCE 7:9.6.1.4 are satisfied. But, how do you verify that displacement from NFPA 13 satisfies ASCE 7, when NFPA 13 does not directly address displacement? This can cause a major problem, especially if an AHJ is very literal in interpreting codes and standards. ASCE 7 prescribes a method for determining displacement and, in doing so, presents another problem. Although it may not be absolutely necessary to understand this method, as much as possible is presented here for your benefit. The seismic relative displacement required by ASCE 7:9.6.3.11.2 and 7:9.6.1.4, can be calculated using the formula:

$D_p = \delta_{xA} - \delta_{yA}$

where:

δ_{xA} = the deflection in the building at Level x, as determined by an elastic analysis as defined in ASCE 7:9.5.5.7.1

δ_{yA} = the deflection in the building at Level y, as determined by an elastic analysis as defined in ASCE 7:9.5.5.7.1.

Then ASCE 7:9.5.5.7.1 discusses story drift (displacement) as being the difference of the deflections at the top and bottom of the story under consideration and gives the following formula for calculating deflections at each story level.

$$\delta_x = \frac{C_d \delta_{xe}}{I}.$$

where:

C_d = the deflection amplification factor in ASCE 7:Table 9.5.2.2

δ_{xe}= the deflections determined by an elastic analysis

I = the importance factor determined in accordance with ASCE 7:9.1.4

The seismic protection for both the building and its systems must accommodate the displacements and deflections discussed here. It appears that these displacements and deflections are only of significance in systems and buildings that have a significant change in elevation. That is, a system entirely located at a single elevation in a building such as the piping down-stream from a floor control valve will not experience these types of displacements and deflections. It appears that these are only experienced by pipes with multiple elevation attachment points in the building, such as a standpipe/sprinkler system riser in a high-rise building.

We must point out that the deflections (δ_{xe}) can only be determined by an elastic analysis. At this point you should kneel down and pray that your contract has not put this totally in your lap or bow your head in tears, if you already know it has. Because, unless you have one in-house, you'll have to go out and hire a consulting structural engineer to perform an elastic analysis. Really, someone on the A/E building design team should have already performed an elastic analysis and calculated the building deflections and displacements for each level. These numbers can then be compared to the amount of deflection accommodated by vertical fire sprinkler or standpipe riser piping using listed flexible couplings.

Looking at this article's example and NFPA 13:9.3.2, we see that at least 10 listed flexible couplings will be installed (two on each floor) in each vertical riser. By definition (NFPA 13:3.5.4), listed flexible couplings are required to allow axial displacement, rotation, and at least 1 degree of angular movement of the pipe without inducing harm on the pipe. Considering 10 flexible couplings each allowing one degree of movement, installed at the NFPA 13 required locations, the cumulative minimum available displacement at the top of the riser would be approximately $5^1/_2$ ft. That's quite a bit of movement for the fifth story of a building. It can be expected that if the fifth story of a building moves this much, the sprinkler system piping probably won't be needed any more.

With regard to deflection and displacement, we conclude that vertical piping in all buildings of significant height will inherently be protected by listed flexible couplings, when installed in accordance with NFPA 13. This more than adequately satisfies the requirement of ASCE 7:9.6.1.4 (thus the building codes) regarding displacement.

This article has covered, as much as possible, how to design a seismic protection system in accordance with the model building codes referencing ASCE 7. A tentative interim amendment (TIA 02-1) was issued that changed the NFPA 13 criteria for earthquake protection. This measure brings the NFPA 13 criteria into alignment with ASCE 7. Additionally, changes are expected in ASCE 7 in the forthcoming 2005 edition. Word has it that the paragraph (9.6.3.11.2) in ASCE 7 referencing NFPA 13 will be changed. Instead of saying that you can use NFPA 13, provided force and displacement requirements are satisfied, it will simply say that NFPA 13 can be used. This will allow designers to use NFPA 13 alone to design the earthquake protection for fire sprinkler systems. Let's all cross our fingers and hope this comes to fruition.

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