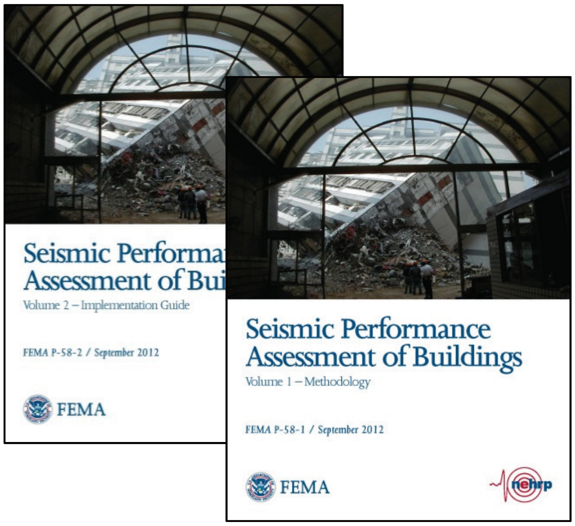

Background Document

FEMA P-58/BD-3.7.7

Risk Management Products Team Downtime Model

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Background Documentation

FEMA P-58 Background Documents are a series of reports documenting the technical background and source information for key aspects of the FEMA P-58 methodology and its implementation. These reports were developed over the course of the 10-year ATC-58/ATC-58-1 Projects funded under FEMA Contracts EMW-2001-RP-0056 and HSFEHQ-06-D-1105.

Background Documents were developed by consultants, serving at various levels within the project hierarchy, reporting the results of: (1) decisions on technical development protocols; (2) focused studies on the development of key aspects of the methodology; (3) documentation of recommended procedures; and (4) collection of available data for the development of structural and nonstructural fragilities. They were initially intended to serve as a record of the technical state-of-knowledge at the time they were produced, and as resources for the development of the eventual project reports. As such, they represent a snapshot in time, and may, or may not, match the technical content, recommended procedures, or data incorporated into the final methodology and its implementation.

This Background Document is intended for the purpose of providing supplemental knowledge to users of the FEMA P-58 methodology. Information contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Users of information in this document assume all liability arising from such use.

Notice

Cover illustration – Primary resource documents for the FEMA P-58 *Seismic Performance Assessment of Buildings, Methodology and Implementation* series of products: FEMA P-58-1, *Volume 1 – Methodology*, and FEMA P-58-2, *Volume 2 – Implementation Guide*.

Risk Management Products Team
Downtime Model

Phase 3-Year 1 Progress Report
October 10, 2008

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Downtime Team: Craig Comartin, Mary Comerio, Gee Heckscher, Judith Mitrani-Reiser, and Scott Shell

Assess Building Downtime

Building downtime may be caused by a number of factors: building closure due to red-tagging; building closure and/or business interruption due to repair efforts; business interruption due to excessive nonstructural damage; building inspection; damage assessment; finance planning; architect/engineering consultations; and a possible competitive bidding process. The portion of downtime that is attributed to the time needed to repair building damages is referred to, by Comerio, as the *rational* component of building downtime (2006), but will be referred to herein simply as *repair time*. The second component of downtime referred to, by Comerio, as the *irrational* component of building downtime (2006), includes time for inspection, mobilization, financing, relocation, and other economic and regulatory factors. These *Guidelines* focus on the factors contributing to building downtime that are directly influenced by the design of the building.

Repair time, as defined in these *Guidelines*, is related directly to the pace of construction in the field. It is assumed that a ("virtual") contractor has complete control of the building and thus that repairs will be performed efficiently (and realistically) to complete the work. The building damage state, described in Section 3.3.5, is assembled from the component-level fragility functions, the vector of demands from the simulation, and the building collapse consequence matrix. The building damage state a detailed description of the building's condition for a given ground motion or, realization in terms of repairs required to return the building to pre-earthquake condition. This description could be given to a contractor to form the basis for an estimate of the repair strategy needed to repair the building damage and replace its contents as needed. The contractor applies a *direct downtime consequence function* to the damage to calculate the building downtime needed to repair the building to pre-earthquake condition.

Consequence functions for building downtime (as for direct economic loss) should account for the effect of quantities on unit repair time. These are of the general form illustrated in Figure 1. For small quantities the unit repair time is constant at a maximum value. Beyond a certain quantity the repair time is reduced due to a flattening of the crew's learning curve, until a minimum unit repair time for large quantity repairs is reached. Since repair times are dependent on the owners, repair crew, the degree of damage on the region impacted by the seismic event, and other variables, unit repair times are treated as uncertain. These repair times are assigned a median value (solid line in Figure 1) and dispersion, β_t.

The amount of time that a damaged structure will be unoccupied will depend not only on the repair effort but also on the efficiency of the owner in retaining a contractor to make repairs, the availability of materials and labor, and other factors that are impossible to predict with certainty. The model presented here will address factors, in addition to repairs of damaged performance groups, that contribute to total downtime by capturing the time needed for damage assessment, consultations with professional engineers, the contractor bidding process, and the debris clean-up that is completed before repairs can begin. This time delay caused before construction begins is termed *mobilization time*. This component of downtime is highly situation dependent and more uncertain than the *repair time*. The functions for mobilization time depend on the building damage state and the collapse consequence matrix to determine building partial/complete closure and to estimate delays prior to repairs. The estimation of building closure and safety tagging is a function of the probability of collapse determined from the structural analysis. The mobilization time is assigned a median value and dispersion, β_m. There is also an ongoing effort to develop a “virtual” inspector for PACT that will mimic current building inspection practice.

Monte Carlo type procedures are used to develop mean estimates of total building downtime as well as information on the possible variation in these estimates. Total building downtime will be calculated by summing the delay prior to construction and the time needed to repair the building damage back to a pre-earthquake state. Similar to the Monte Carlo loss computation in Section 3.3.6, the factors affecting performance (earthquake intensity, structural response, damage, and consequences) are assumed to be random variables, each with a specific probability distribution defined by a median value and dispersion. Later sections of these *Guidelines* and Appendix F give an overview of acceptable procedures for generating a large number of simulations through statistical manipulation of a relatively small number of structural analyses.

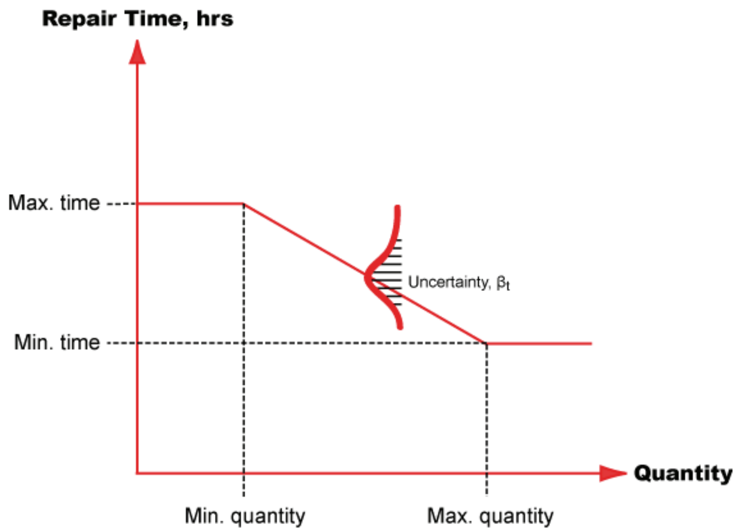

Figure 1. Sample consequence function for repair time.

Repair Time

As described in Section 4.1.1 of these *Guidelines*, fragility functions express the probability of realizing or exceeding a damage state given an appropriate EDP for each damageable building performance group. Each of these damage states is associated with a particular repair effort that is described by a consequence function comprising cost (dollar amount needed to cover the labor, material, equipment and overhead costs to repair the damaged component) and time (crew hours needed to complete this repair effort). The repair effort for one performance group may require more than one type of construction trade, so for ease of repair-time estimation, repairs will be aggregated per floor and by trade[1].

[1] The following construction trades are considered in these Guidelines (BLS 2008): (1) boilermakers; (2) brick-, block-, and stone-masons; (3) carpenters; (4) carpet, floor, and tile installers and finishers; (5) cement masons, concrete finishers, segmental pavers, and terrazzo workers; (6) construction and building inspectors; (7) construction equipment operators; (8) construction laborers; (9) drywall installers, ceiling tile installers, and tapers; (10) electricians; (11) elevator installers and repairers; (12) glaziers; (13) hazardous materials removal workers; (14) insulation workers; (15) painters and paperhangers; (16) pipelayers, plumbers, pipefitters, and steamfitters; (17) plasterers and stucco masons; (18) roofers; (19) sheet metal workers; and (20) structural and reinforcing iron and metal workers.

Sidebar: Consider, for example, the effort needed to repair low-cycle fatigue fracture of the beam flanges in the hinge region. This effort involves replacing a large portion of the beam in the disturbed area, taking the following steps: shoring and scaffolding as needed; demolishing finishes as needed; temporary relocation or removal of MEP; heat straightening and cut-out portion of steel beam; weld in replacement steel; test and inspect, and fireproof the repaired frame member; rough-in the MEP; install/repair the drywall; repair ceiling framing and MEP; finish ceiling and floors, and paint. Thus, this example of the repairs needed for a single performance group type, may involve more than five different construction trades to complete. The repair strategies associated with each damage state for all performance groups, are therefore organized by construction trade, which will facilitate the total repair time estimation for a damaged building.

The total repair time estimate is also dependent on the repair scheme preferred by the building owner. A slow-track repair scheme (components are repaired serially) and a fast-track repair scheme (components are repaired in parallel) were proposed by Beck et al. (1999) as bounding cases for possible repair schemes. However, the fast-track repair method shown in Figure 2, was deemed more realistic for current practice by a professional cost estimator in Mitrani-Reiser (2007). The parallel attributes of the fast-track repair method are employed in the *Most Typical* repair scheme used in these Guidelines and as the default repair scheme the Performance Assessment Calculation Tool (PACT). This repair scheme allows for some trades to overlap within floors, and assumes that the building is unoccupied during construction. This repair scheme also assumes that the repair effort will begin with the structural components in the first-story of the building, after initial demolition and scaffolding are completed. The repair of structural components is assumed to progress up the height of the building until completed. The repairs of nonstructural components (walls, ceilings, etc.) will begin on each floor once a significant portion of the structural-component repairs are complete. The nonstructural repairs progress, as needed given the building damage state, in the following order: repair wall frames; rough-in tenant walls and ceiling; install drywalls, install glazing and doors, and paint. Note that roof, elevator, and MEP repairs will overlap with the nonstructural repairs and will progress in parallel the other repair work. The *Most Typical* repair scheme also makes assumptions about crew size by trade, number of crews in day and night shifts, length of these shifts, and the extent to which construction trades overlap. However, users will be queried on their repair-strategy preferences in future versions of the PACT software, to speed up or slow down the default repair strategy.

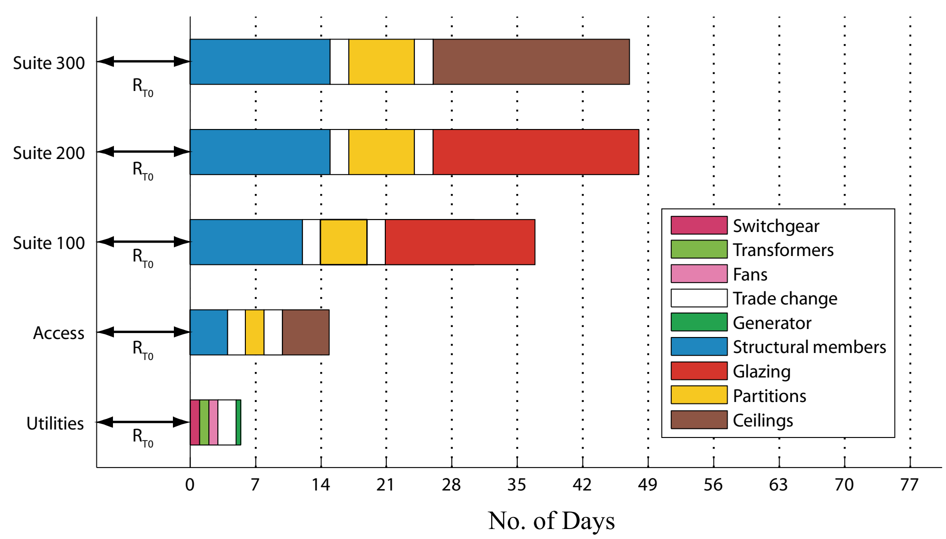

Figure 2. Gantt chart for fast-track repair scheme applied to an example 3-story steel frame building (reproduced from Beck at al. 1999).

The time to repair building damage is dependent on the building damage state. As described in Yang et al (2006), a random number generator is used to select the damage state for each performance group given the results of the structural analysis (i.e., EDP values). The repair quantities of each performance group are given in a look-up table in PACT for every damage state. The repair time for each performance group is calculated by multiplying the repair quantity by the unit repair time given by the consequence functions described above. Since the unit repair times are uncertain, a random number generator is used to adjust the unit repair time up or down before multiplying by the quantities. The repair times for each performance group are depicted by the colored bars in Figure 2, and they are ordered in this Gantt chart according to the defined fast-track repair scheme. The total repair time for the building is represented by the widest bar in this figure.

Loss results for an intensity-based assessment (S_a = 0.86g) of Example Building #1, described in Chapter 7 of these guidelines, are given in Figure 3. The bottom two curves show the total losses associated with the repair effort for the specified ground shaking intensity level. The losses are plotted on the horizontal axis, while the vertical axis gives the probability of the loss being equal to or less than any specified value. The dashed lines show the median loss value for repair cost and repair time. The plot shown in the upper left hand portion of the figure shows the contribution of repair costs for each performance group considered in the loss analysis. This whisker plot, generated using MATLAB, shows the minimum, maximum, lower and upper quartile and median values for the loss results generated using the Monte Carlo simulation method described above. The plot shown in the upper right hand portion of Figure 3 is a Gantt chart describing the repair effort needed to return the building back to an undamaged state for the specified scenario, which is calculated using the downtime scheme described above.

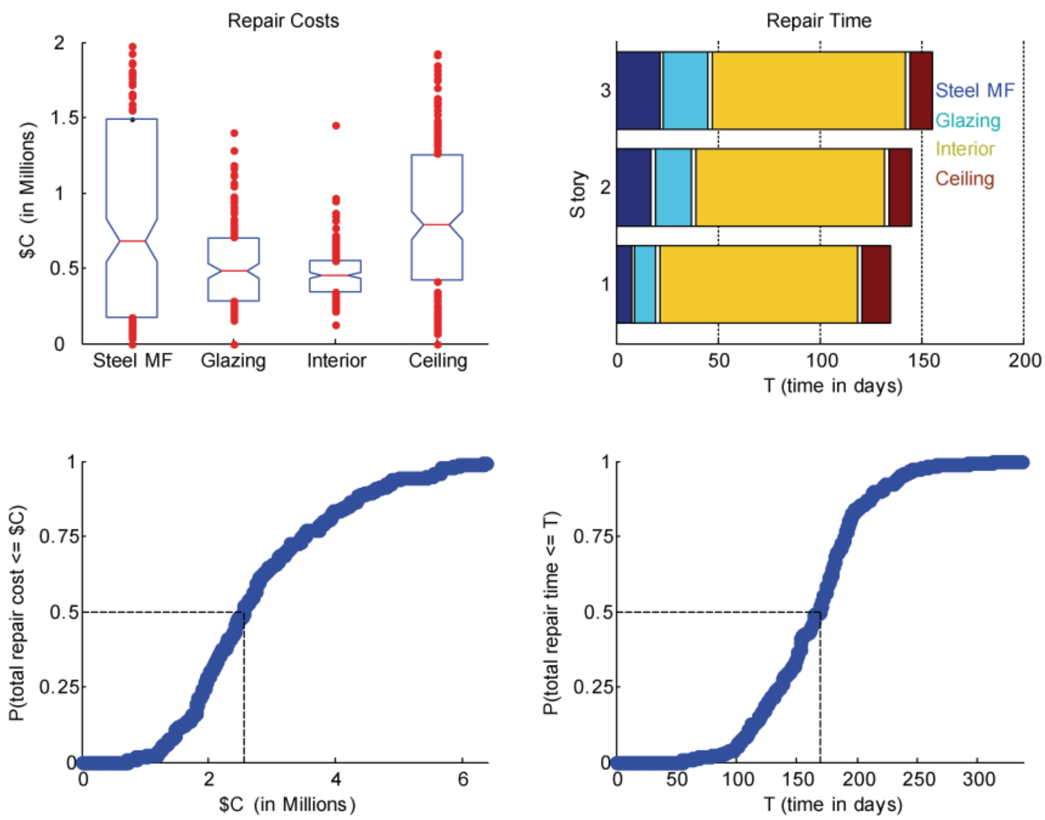

Figure 3. Example results from an intensity-based scenario using the repair cost and repair time algorithms implemented in PACT.

Mobilization Time

A "virtual" inspector developed by Mitrani-Reiser and Beck (2007) was used to estimate mobilization delays caused by forcible complete or partial building closure. This procedure matches up damage descriptions from fragility functions with safety inspection guidelines (ATC 1989; ATC 1995) to recreate typical rapid and detailed evaluation procedures, and follows the logic of the event tree shown in Figure 4. The first branch of the event tree determines the probability of a building's red-tagging due to severe leaning and/or collapse (global or local) of the structure. The complement of this branch is for the event where the building does not collapse nor is seriously out of plumb; this branch breaks off into three others that classify the overall damage to the exterior structural members as "severe," "moderate," and "none or light." If the first block of the event tree, representing a rapid evaluation, does not result in a green or red tag, a subsequent detailed evaluation of the interior structural and nonstructural damage is completed to determine appropriate safety tagging assignments and building operability.

A similar "virtual" inspector module, based on the above-mentioned model is underway as a joint effort between the RMP, NPP, and SPP groups of the ATC-58 Project. Flags for damage states that could result in the red-tagging structures and/or building inoperability (see Appendix for examples) are already integrated into the specifications of fragility functions in these Guidelines. However, the current procedure for estimating building safety tagging is coupled with the probability of collapse resulting from the structural analysis, similar to what is shown in **Figure 5**. Conditioned on the probability of collapse, a Monte Carlo simulation approach will again be used to determine the probabilities of a building requiring a red-, yellow-, and green-tag for a given ground-motion intensity level or for a given scenario event. The mobilization time will thus be estimated using probability distributions of these times conditioned on safety tagging and determined from empirical data, literature review of past case studies, and from expert opinion. A random number generator is then used to determine downtime due to mobilization delays and is added to the repair time to calculate total building downtime.

Sidebar: Excessive nonstructural damage can lead to building inoperability, even if the building is structurally safe. Current inspection guidelines address some of the nonstructural damage leading to partial or complete building closure. In general, damage to any nonstructural components (e.g., roof tiles, parapets, chimneys, ceilings, etc.) that creates a potential falling hazard during an aftershock will lead to partial or complete building closure. Additionally, blocking or damage to means of egress can also lead to building closure (e.g., jamming of doors and damage to stairways). Failure or damage of critical utility services may lead to secondary effects that may result in building closure. For example, power loss could affect HVAC systems, elevators and critical equipment in a building, interrupting daily functions of the structure. Additionally, some buildings house critical equipment, materials, chemicals, or other **occupancy-specific** contents that if damaged, could lead to inoperability or closure (see Tables 1-8 in Appendix for a list of these). These *Guidelines* address building downtime caused by damage of all nonstructural components and building contents included in Appendix E.

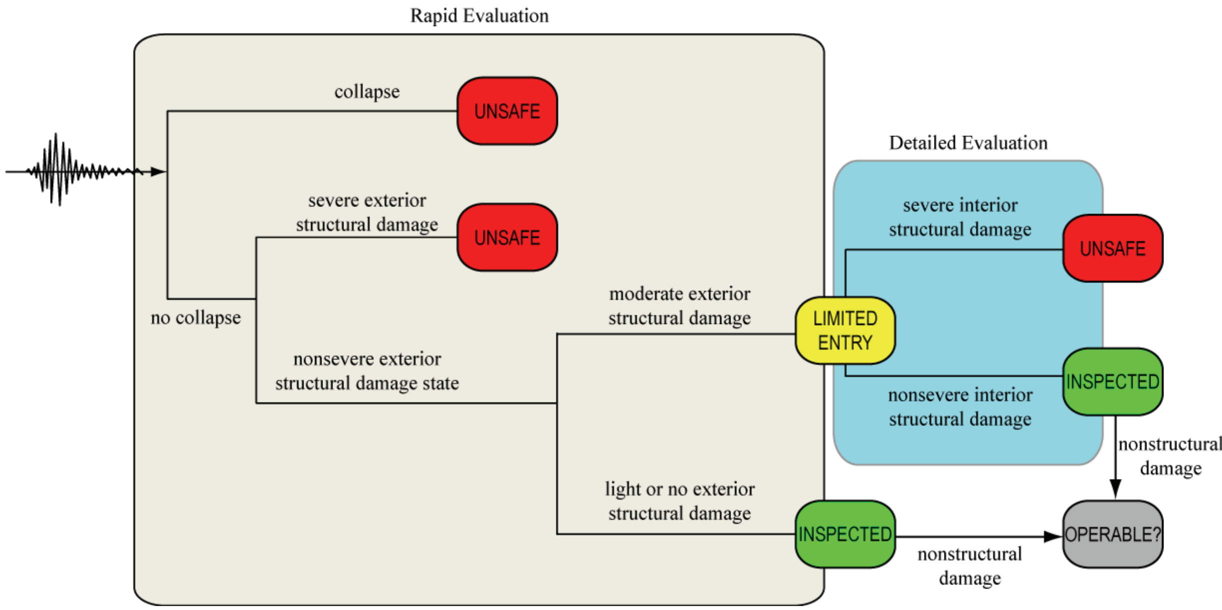

Figure 4. Event tree model for building safety evaluation based on ATC-20's (1989, 1995, 1996a) (a) rapid evaluation, and (b) detailed evaluation procedures.

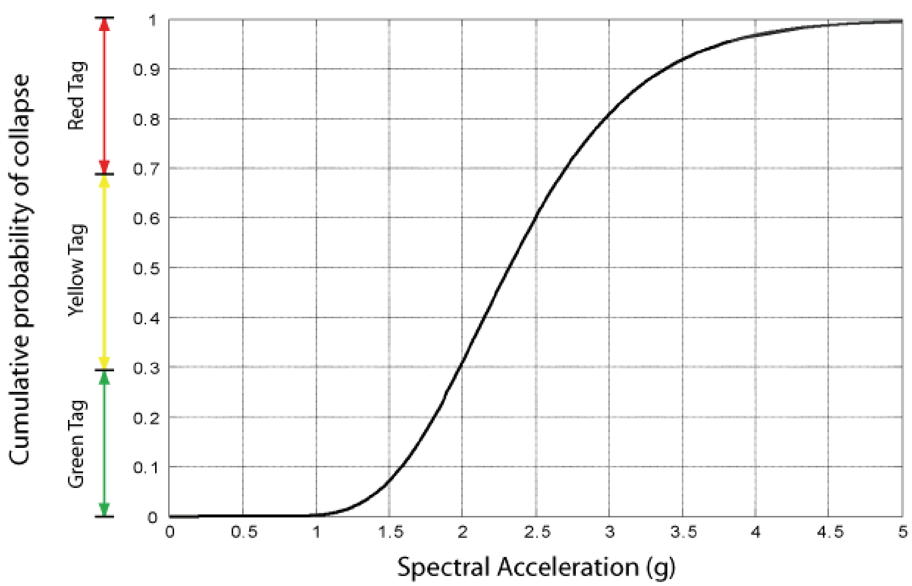

Figure 5. Cumulative probability distribution of building collapse and corresponding tagging scheme.

APPENDIX

Table 1. List of nonstructural items typically found in schools, which may lead to building closure and business interruption, and are **not** currently included in the NPP List of Fragility Items.

Architectural Elements	Furnishings and Equipment	Hazardous Materials
■ Canopies and walkways ■ Water towers ■ Covered play areas	■ Computers ■ File cabinets ■ Shelving ■ Display cabinets ■ Shop equipment ■ Lab equipment ■ Kitchen appliances ■ Vending machines ■ Lockers ■ Bleachers	■ Chemicals ■ Asbestos, lead

Table 2. List of nonstructural items typically found in research campuses and laboratories, which may lead to building closure and business interruption, and are **not** currently included in the NPP List of Fragility Items.

Architectural Elements	Furnishings and Equipment	Hazardous Materials
■ Canopies and walkways	■ Computers ■ File cabinets ■ Shelving ■ Display cabinets ■ Shop equipment ■ Lab equipment (fume hoods, incubators, refrigerators, etc.)	■ Chemicals ■ Asbestos, lead

Table 3. List of nonstructural items typically found in retail buildings, which may lead to building closure and business interruption, and are **not** currently included in the NPP List of Fragility Items.

Furnishings and Equipment
■ Computers/Cash registers; File cabinets; Shelving; Display cabinets

Table 4. List of nonstructural items typically found in commercial office space, which may lead to building closure and business interruption, and are **not** currently included in the NPP List of Fragility Items.

Furnishings and Equipment
■ Computers/Servers; File cabinets; Shelving.

Table 5. List of nonstructural items typically found in healthcare facilities, which may lead to building closure and business interruption, and are **not** currently included in the NPP List of Fragility Items.

Architectural Elements	Furnishings and Equipment	Hazardous Materials
■ Canopies and walkways	■ Computers ■ File cabinets ■ Shelving ■ Biomedical equipment (ICU monitoring, anesthesia equipment, manual/electrical ventilators, defiblerators) ■ Medical Physics Equipment (Imaging X-ray units) ■ Clinical Lab Equipment (blood/gas analyzers) ■ Refrigerators, incubators, etc.	■ Chemicals

Table 6. List of nonstructural items typically found in hospitality facilities, which may lead to building closure and business interruption, and are **not** currently included in the NPP List of Fragility Items.

Architectural Elements	Furnishings and Equipment
■ Canopies and walkways	■ Computers ■ File cabinets ■ Refrigerators, vending machines, etc.

Table 7. List of nonstructural items typically found in warehouses, which may lead to building closure and business interruption, and are **not** currently included in the NPP List of Fragility Items.

Furnishings and Equipment
■ Storage racks (e.g., pallet-type steel storage racks)

Table 8. List of nonstructural items typically found in multi-unit residential buildings, which may lead to building closure and business interruption, and are **not** currently included in the NPP List of Fragility Items.

Architectural Elements
■ Canopies and walkways

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