Gallagher Re

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The Impact of Catastrophe on Engineering and Construction

eNGINEER Analytics

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With the growth of construction projects worldwide, the insurance industry is calling for risk assessment of buildings under construction against natural hazards such as flood, high wind speeds and earthquake shaking. The cyclic and costly nature of construction projects forces contractors and insurers to evaluate critically their potential losses at different phases of construction.

This report presents the estimation of relative vulnerabilities of civil and non-civil structures during different stages of construction for different natural hazards (earthquake, wind and flood) with respect to their final or serviceability vulnerability. After a short introduction, the document describes the stages of construction taken into consideration and discusses the type of damage caused by each peril. Based on this description, we present an assessment on the relative vulnerabilities of different structure types during the various construction phases.

I. Introduction

Gallagher Re's eNGINEER tool already considers changing values during the construction period and this document deals with changes in vulnerability. In contrast to the risk of existing structures, the risk of one under construction varies over time due to changes in the exposure value as the structure construction progresses and in the vulnerability of the system. As a result, relying on the final value of a completed project and its vulnerability for estimating the risk at different construction stages may lead to inaccurate estimations. Consequently, the vulnerability of each construction stage should be determined independently.

Figure 1: A building under construction following severe earthquake damage. (Source: NOAA/NGDC, M. Mehrain, Dames and Moore)

II. Methodology

The vulnerability function of existing structures is typically expressed as a ratio of the repair cost to the reconstruction cost of the structure or damage ratio. For an existing building, these two factors are independent of time, while for a building under construction, both will vary over the course of construction. In order to take into account this variation of vulnerability with time, the construction period is divided into a number of phases. This is a simplified approach that allows the consideration of the time component by grouping construction stages during which the vulnerability is similar in one phase. For this purpose, the construction period can be divided into the following distinct phases:

Phase I: Substructure and Foundation
This is the part of a building or structure which is constructed below ground level and transfers the weight of the structure to the ground. This stage includes site work, excavation and foundation execution.

Phase II: Superstructure
The portion of a building or structure that extends above ground level and includes the main beams and columns of the structure are executed during this stage.

Phase III: Walls, Roofing and Finishing
(Includes installation of doors, windows and mechanical/electrical facilities).

The stage during which the installation of the walls and roof take place, and the building is enhanced in terms of service and aesthetic qualities. These include painting, glazing, installation of doors and windows, floors, façade, etc. Furthermore, the installation of elevators, ventilation systems, electrical cabling and other non-structural facilities is part of this stage.

The length of each phase will vary depending on a number of parameters. The fundamental ones are summarised below in order of descending importance (Sagala, 2006; Elliott & Leggett, 2002). However, it should be noted that in some circumstances, and according to available data, the priority may change:

- Construction typology (e.g., steel and reinforced concrete)
- Building height (e.g., low, mid or high rise)
- Occupancy (e.g., residential, commercial, industrial, etc.) which indicates the space required and affects the amount of material needed
- Space occupied (e.g., area of each floor)
- The complexity of the design and execution process (comparing a simple one-storey house to a complex skyscraper)
- The geographical location (effects of labour, skills, weather, culture, funding, fluctuation of material prices, etc. should be considered)
- Location, logistics and access (including the elevation from sea level)

Each of the aforementioned parameters can be further distinguished based on more detailed characteristics. For instance, the shape of the building or structure has a considerable effect on its resistance to earthquakes. However, this would require more detailed data, which may not be available. Figure 2, illustrates a timeline for a mid-rise steel frame structure. It should be considered that a phase may start before the previous stage fully ends.

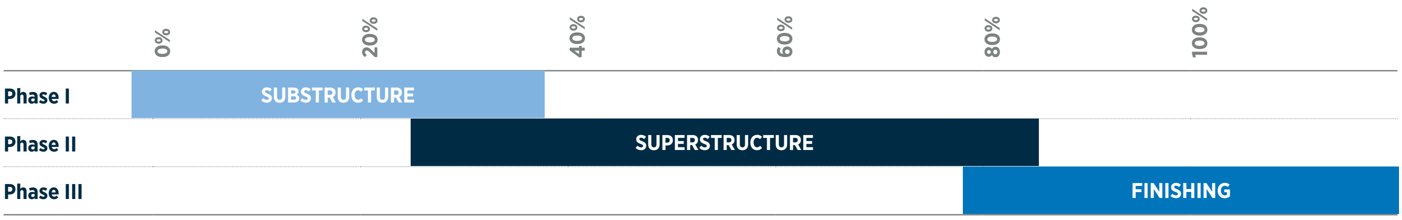

Figure 2: A case study of the construction timeline for a mid-rise steel frame high school. (Riley, 2011)

After defining the construction stages and their allocated period of completion, a replacement (reconstruction) cost should be estimated for each stage of construction. How much the replacement cost increases from phase to phase depends largely on the occupancy. For instance, the replacement cost of an apartment building is concentrated in the finishing stages, while for a wholesale trade centre, due to the extensive amount of wall and roofing, the superstructure phase is considered as the high-cost stage. Furthermore, the replacement cost of each phase also depends on the building height; as taller buildings require more elaborate foundations, the reconstruction cost increases at the first stage, while for low- and mid-rise buildings, the cost of the first phase is relatively small.

The final step is to evaluate the response and vulnerability of the building at each phase according to the specified natural hazard (e.g., earthquake, flood or wind). It should be noted that the cost of replacement is independent of the considered peril, while changes in vulnerability are peril specific. In the case of earthquakes, for example, upon completion of the foundation and the start of the superstructure phase, the vulnerability increases substantially and rises as the building height increases. Upon completion of the superstructure and the addition of the lateral-load resisting elements, the vulnerability levels off. The vulnerability of the finishing phase is similar to that of a completed building.

On the contrary, since flood damage decreases with building elevation, the most vulnerable stage of any construction will be the substructure and the execution of the first floors. Consequently, the vulnerability is expected to decrease significantly towards the finishing phase, when all openings have been covered.

III. Peril-Specific Damage

As the nature of each peril (e.g., wind, flood and earthquake) differs and the damage caused to each phase varies, the resultant effects of each one should be examined separately. In order to have a better understanding of the effects of each peril, an introduction is given before discussing the differences among the various construction stages. The assumptions or simplifications used for each stage are also discussed in the subsequent sections.

3.1 Damage to CAR Non-Civil Projects (Buildings)

3.1.1 Flood

Damage due to flooding depends on several factors, such as water depth (the most dominant), duration of flooding, flow velocity, sediment concentration and pollution.

Figure 3 illustrates the relationship between the building elevation and the resultant damage due to flood. It is clear that the top floors will have a lower flood risk in comparison to the basement or first floor.

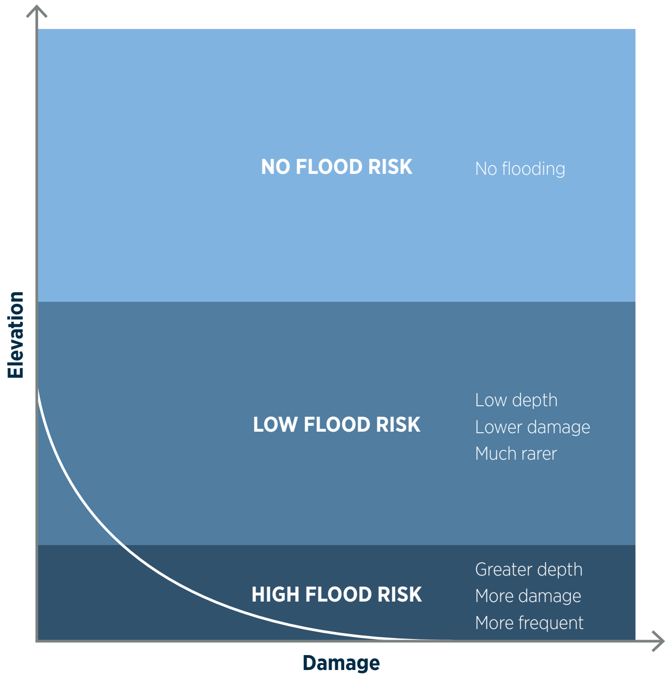

Figure 3: Building elevation and flood damage. (Low et al., 2006)

Generally, the damage to buildings due to flood can be categorised as follows (Low et al., 2006), and it should be noted that each of these may occur at any of the three phases of construction:

1. **Structures are washed away** due to the impact of the water under high stream velocity. The buildings are commonly destroyed or dislocated so severely that their reconstruction is not feasible. This is the most common structural damage caused by flood in low structures. For tall buildings in areas prone to flooding with high water speed, damage to doors, walls and contents in the ground floor and basement are expected (see Figure 4).
2. **Buildings constructed out of lightweight materials**, like wood, will float when they are not anchored properly, due to the uplift pressure of water. In the case of heavy multi-storey buildings made of steel or concrete, this is extremely rare.
3. **Damage caused by the inundation of the building:** The structure may remain intact on its foundation, but damage to construction materials or contents may be severe. Repair is often feasible but may require special procedures to dry out properly. Depending on the water height, the inundation can even reach higher floors than the basement or first floor. Similar damage is expected to the ground floor or basement of tall buildings. During the Queensland, Australia floods in 2011, the seven-level basement on the site of the Vision Tower, whose construction was at the time on hold, became completely inundated, as shown in Figure 5. Similarly, considerable flood damage was sustained to the foundation levels of the Freedom Tower in New York during Superstorm Sandy in 2012 (see Figure 6).

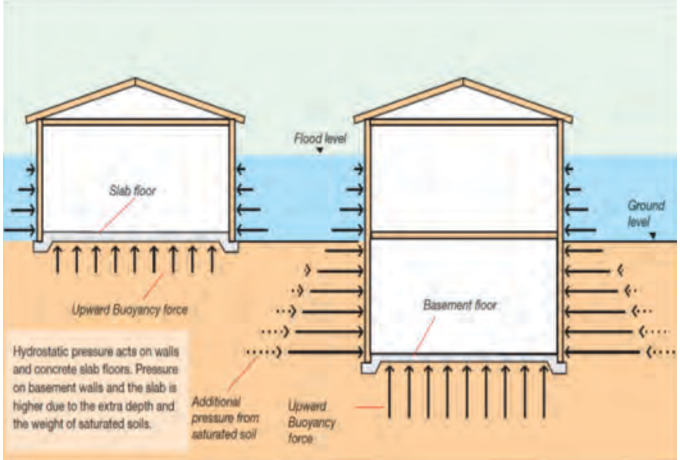

Figure 4: Hydrostatic forces. (Low et al., 2006)

Figure 5: Flooding of the Vision Tower Brisbane construction site in 2011. (Source: Brisbane Development)

4. **Undercutting of buildings:** The velocity of the water may scour and erode the foundation of the house or the earth under the foundation (see Figure 7). This may result in the collapse of the building or lead to the need for a complete replacement of the floor or in the worst case of the foundation. In tall buildings under construction this may lead to the failure of the foundation, though this is only likely to occur during the excavation process (i.e., during a short period of time). Considering the aforementioned causes of damage due to flooding, different degrees of damage are expected at each construction phase, which is discussed below.

Phase I—Substructure and Foundation

Depending on the height of the flood, the damage is more probable on the structural elements placed on the ground or lower ground level (e.g., storage rooms or parking). Therefore, the first stage of any construction, which includes the substructure and foundation, is the most critical phase. However, it should be considered that in comparison to the cost of the superstructure, the cost of the foundation is relatively low in most cases.

Phase II—Superstructure

When the construction progresses to the next phase (superstructure), the vulnerability decreases, especially if the first and second floors are covered by walls in a way that can withstand flood and prevent it from entering the building. However, as openings for doors and windows may not be covered yet, the flow of water may inundate and cause damage to the interior elements as well. Furthermore, various structural systems have different vulnerabilities against water. For instance, water may cause corrosion to steel elements, while concrete is more resilient.

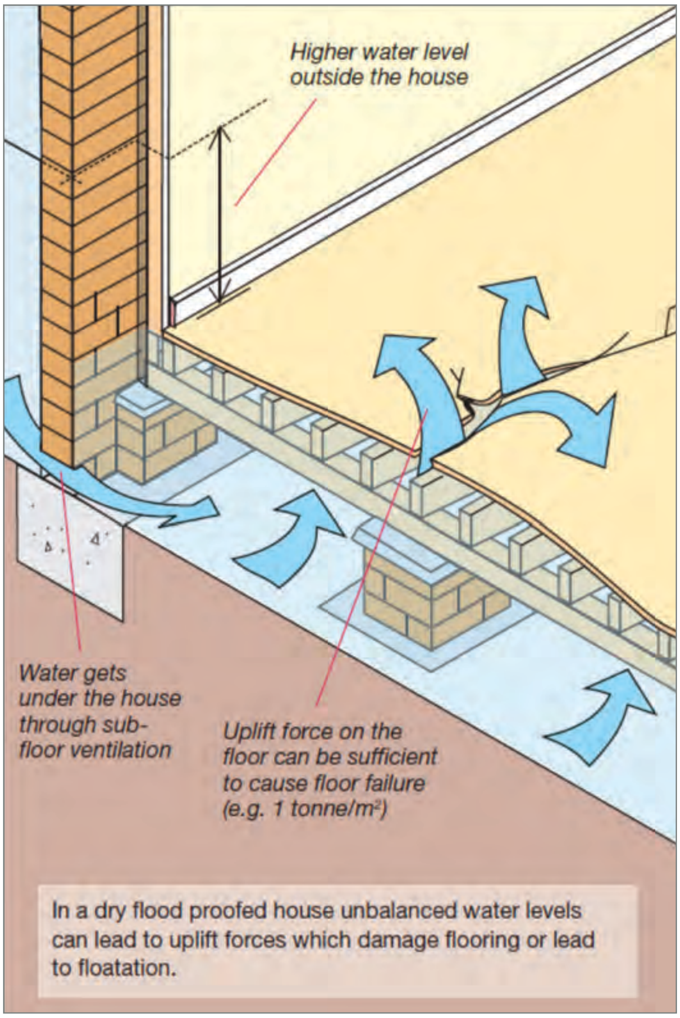

Figure 7: Uplift forces on suspended floors. (Low et al., 2006)

Figure 6: Flooding to Freedom Tower during Superstorm Sandy 2012. (Source: The Journal of the American Institute of Architects)

Phase III—Walls and Roofing, Finishing/Mechanical and Electrical Installation

In the finishing stage, the windows and doors, and non-structural elements are installed. As windows and doors are more vulnerable to flow impact than the exterior walls, the flood may still cause some damage (Figure 8). Most non-structural elements of a building, such as electrical cables, ventilation systems, elevators, etc. are highly vulnerable to inundation therefore any slight contact with water may result in a high cost of replacement, especially in the case of electrical equipment (FEMA P-348, 1999).

Additionally, landslides induced by flooding may cause significant damage and have the potential of causing total losses even in the case of tall buildings. However, this is a triggered peril and the discussion herein will only focus on flood as the primary peril. Finally, it is noted that regional differences would also play a role. If severe thunderstorms prevail, any project site is potentially vulnerable to flash flooding if the terrain is steep, surface runoff rates are high, and/or are located in narrow canyons or valleys (IMIA, 2012). For instance, due to the particular topography in England, flood waters tend not to have high speed and hence, damage from a given water level is expected to be less than in other places with high water speed.

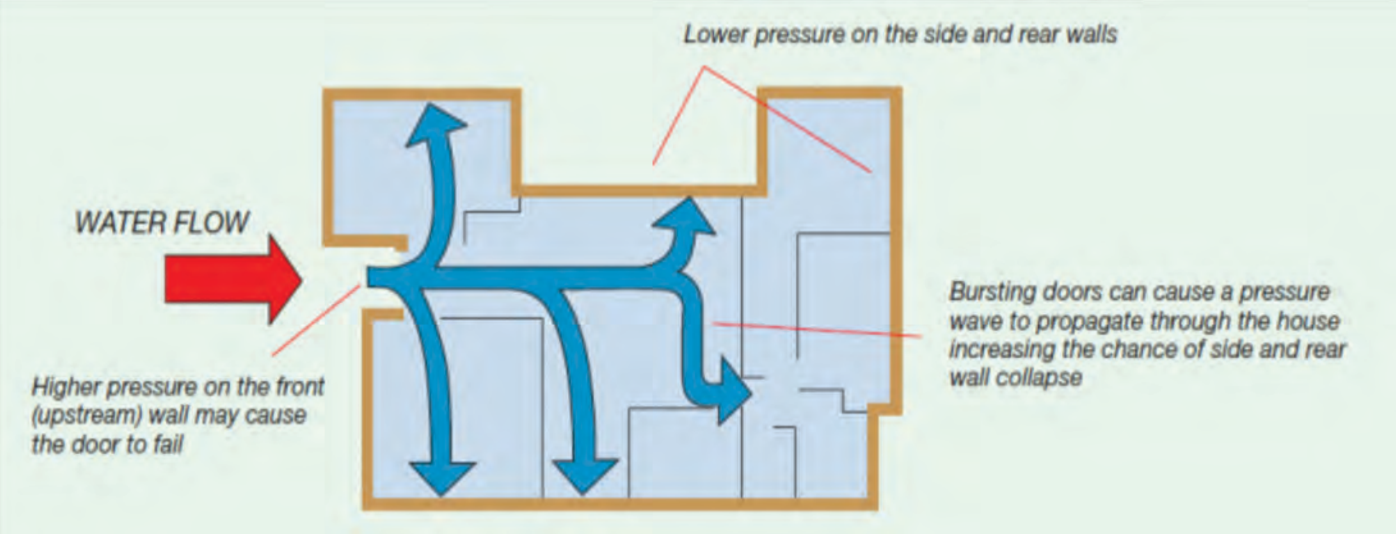

Figure 8: Collapse of walls due to pressure surges. (Low et al., 2006)

3.1.2 Wind

Under regular circumstances, a building is designed to resist expected wind loads. During a hurricane or a strong extra-tropical cyclone, a fully intact building envelope (enclosed exterior unit of the building) allows wind to flow at, over and past the structure without causing any damage (Figure 9). Preserving the envelope of the building is one of the most important steps in preserving the integrity of the structure and ensuring nondestructive wind flow during hurricane-force winds (Cope, 2004; Saflex, 2006).

During strong wind, intense pressure is created on a structure as the wind impacts the building (windward face). As the wind flows over or around a structure it can cause a "lift" on the roof or "suction" on the opposite side (leeward face). This "suction" is normally referred to as negative pressure. Negative pressure is always higher than the positive pressure acting upon a building during hurricane wind conditions. If the building envelope is breached, wind also enters inside, thereby causing a large increase in internal pressure (Figure 10). This internal pressure, summed with the external negative pressure, can effectively double the force acting to lift the roof and push the walls outward. Consequently, one of the most susceptible components of the building envelope is a glazed opening (Cope, 2004; Saflex, 2006).

During construction, as the building's envelope has not been completed and plenty of openings exist (especially in the superstructure phase), the structure has a low vulnerability against wind damage (see explanation below). However, this will vary at different phases. Furthermore, the resulting damage will clearly differ according to the wind speed (Gibbs, 2001; Tamura, 2009; Lia & Ellingwood, 2006; Ayscue, 1996).

Overall, the key causes of damage associated with strong winds during construction include (IMIA, 2012):

- Wind penetrating a building's envelope
- Uplift of the roof
- Flying debris
- Storm surge
- Irregularities in elevation and plan
- Siting problems

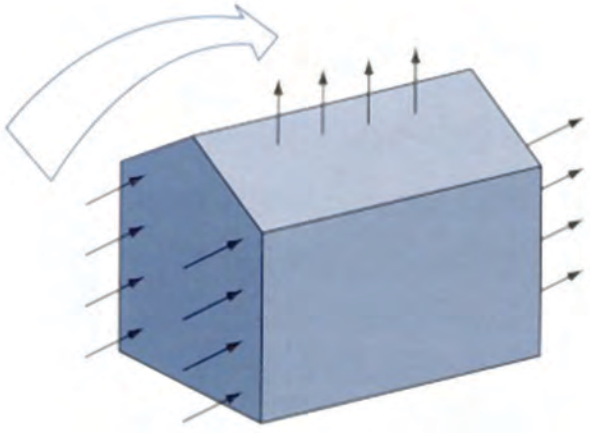

Figure 9: Fully enclosed building (preserving the envelope). (Saflex, 2006)

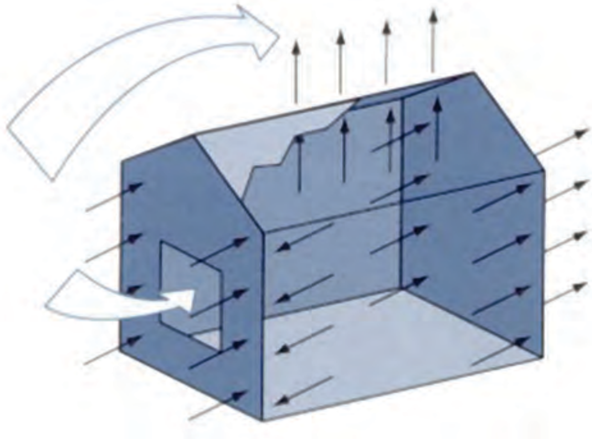

Figure 10: Fully enclosed building (preserving the envelope). (Saflex, 2006)

Phase I—Substructure and Foundation

The uplift forces from hurricane winds can sometimes pull small buildings completely out of the ground. In contrast to when designing for gravity loads, the lighter the building, the larger (or heavier) the foundations needs to be in wind-resistant design—particularly for those made of wood or light steel. Ignoring this precept has led to some dramatic failure of long-span, steel-framed warehouses. As a result, a light footing may be prone to be lifted by the hurricane during the construction.

Phase II—Superstructure

The suction and pushing of wind is the most common cause of wind damage. In the case of a building under construction, prior to any wall being installed, the wind can easily pass through the floors without any damage. However, on the other hand, this increases the risk of roof or floor uplift. Additionally, the debris carried may cause damage to the structural members.

The following discusses the effect of the hurricane on low constructions (e.g., houses and warehouses) for different structural systems (Gibbs, 2001);

- **Steel Frames:** A common misconception is that the loss of cladding relieves the loads from building frameworks. There are several circumstances where the opposite is the case and where the wind loads on the structural frame increases substantially with the loss of cladding. This is critical in the superstructure and roofing stage, as any damage to the roof may cause further damage to the superstructure. Usually, the weakness in steel frames is in the connections. Economising on minor items (bolts) has led to the overall failure during the construction of the major items forming the superstructure elements (columns, beams and rafters).
- **Masonry:** These are usually regarded as being safe in hurricanes. However, there are examples where the loss of wooden roofs has triggered the total destruction of unreinforced masonry walls. Therefore, if the roof installation has not been started, the superstructure phase of construction will be highly vulnerable to hurricanes.
- **Timber:** The key to the safe construction of timber houses is in the connection details. The inherent vulnerability of lightweight timber houses coupled with poor connections is a dangerous combination which has often led to disaster. Failure is also possible during the construction of the superstructure.
- **Reinforced Concrete Frames:** The design needs to ensure that the concrete frames can accommodate the wind forces. There have been a few isolated examples such as during the 1992 Hurricane Andrew in South Florida, where ignoring this, has led to structural failure. During the superstructure phase, as the concrete elements take time to reach their final strength (about 28 days), the wind force can cause damage or in some cases even remove the member.

Phase III—Walls and Roofing, Finishing/Mechanical and Electrical Installation

If the walls are installed in a way that allows wind to enter the building (i.e., the building envelope is breached) then again the suction and pressing forces may result in severe damage to exposed walls. At this stage, most window and door openings are not covered, therefore wind can pass through the external walls and enter the building, damaging the partitions.

Perhaps the common area of failure in hurricane-speed winds is roof sheeting and tiles. The causes are usually inadequate fastening devices, inadequate sheet thickness and insufficient frequencies of fasteners in the known areas of greater wind suction. Therefore, the roofing stage of construction has a high vulnerability, especially in cases where the roof is incomplete.

After roof sheeting, windows and doors are the components most frequently damaged in hurricanes. Of course, glass is vulnerable to flying objects and installation of hurricane shutters limits damage to windows, etc.

In the case of electrical and mechanical equipment, the wind speed and impact of flying debris may cause some disconnection in cables which are exposed and not covered. Additionally, tropical and extra-tropical cycles tend to be combined with rainfall, which may affect electrical installations if these are exposed. Also, the movement due to wind power can damage the mechanical equipment of the building, such as elevators and ventilation systems.

3.1.3 Earthquake

Due to the natural response period of vibration of a building, building height plays an important role in how different buildings respond to ground shaking. Generally, the natural period of building increases with building height (Figure 1) and as a result, small buildings are more affected, or shaken by high-frequency waves (short and frequent), while high-rise buildings are more affected by long-period shaking.

In the case of earthquake damage, the structural system plays a particularly important role. Structural and architectural detailing and construction quality control are very important to ensure ductility and natural damping so as to keep damages to a limited and repairable range. The expected seismic behaviour of some construction typologies is indicatively summarised below (Lorant, 2012):

- **Wood or timber frame:** Good energy absorption, lightweight; framing connections are critical.
- **Reinforced masonry walls:** Good energy absorption if walls and floors are well integrated; the proportion of spandrels and piers are critical to avoid cracking.
- **Reinforced concrete walls:** Good energy absorption if walls and floors are well integrated; the proportion of spandrels and piers are critical to avoid cracking.
- **Precast concrete frame:** Poor performer without special energy-absorbing connections.
- **Steel frame with masonry fill-in walls:** Good energy absorption if bay sizes are small and the building plan is uniform.
- **Steel frame, braced:** Extensive bracing, detailing and proportions are important.
- **Steel frame, moment-resisting:** Good energy absorption, connections are critical.
- **Steel frame, eccentrically braced:** Excellent energy absorption, connections are critical.

Irrespective of the typology of construction, the building's vulnerability to earthquake shaking will vary considerably at different construction phases, as described below:

Phase I—Substructure and Foundation

The earthquake may cause some cracks and discontinuity in the reinforced concrete foundations depending on its intensity. Also, severe ground shaking may cause destructive damage to the foundation in a way that complete replacement is required. Other earthquake side effects such as liquefaction may occur that will damage the footing. However, in general, the damage should not be very extensive due to the low height, continuity, considerable stiffness, strength and regularity that most foundations have.

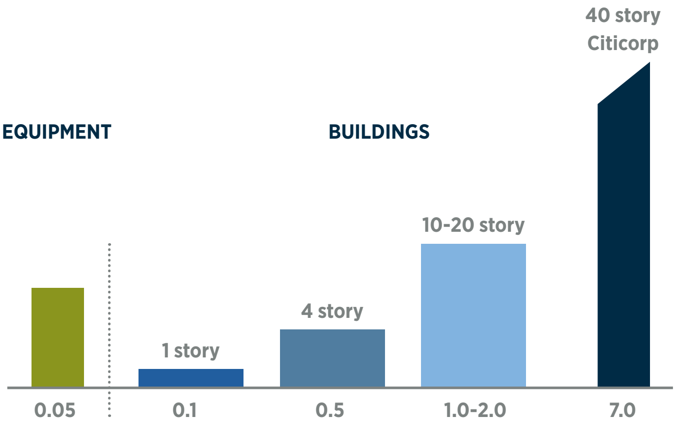

Figure 11: Height is the main determinant of fundamental period—each object has its own fundamental period at which it will vibrate. The period is proportionate to the height of the building. (Lorant, 2012)

Phase II—Superstructure

The most vulnerable phase in the case of earthquakes is the superstructure, with damage potential increasing as the building starts to rise in height. Differences in damage are expected for different typologies of construction (e.g., steel, reinforced concrete, etc.). In the case of reinforced concrete structures, as it takes considerable time for the concrete to reach its final strength (around 28 days), the fresh elements cannot act as load-bearing members and the vulnerability of the building is originally higher. However, in the case of steel structures, as the members are connected to each other, the load is distributed and the building gains its full resistance. One of the most important elements affecting the vulnerability of any building against earthquakes is the way members are connected to each other.

Phase III—Walls and Roofing, Finishing/Mechanical and Electrical Installation

By this stage, the building has reached its necessary design strength to withstand earthquake shaking. Therefore, the fragility at this stage is similar to a complete building and any added element will not have a significant effect. The fact that not all vertical loading is completely installed (e.g., furniture, machinery, etc.) would help with the building's behaviour; this is that the building would not be stressed to its design level due to its occupancy not being at 100%.

3.2 Damage to EAR and Bridges

Special structures such as bridges, dams, petrochemical or power plant facilities, can in some cases show a different vulnerability than ordinary buildings when exposed to natural catastrophes during their construction. An important difference, for example, between residential and specialist industrial facilities is that in the latter case, a significant amount of machinery and equipment will be transferred to the site prior to the completion of the work. It is often the case that this machinery and equipment account for the largest proportion of the insured value. It is expected, therefore, that the main differentiator between regular and special projects is the faster increase in the insured value as the construction progresses in the latter case. However, on average, the damage potential at different stages is not expected to be considerably different to that of regular buildings.

One particularly interesting case would be that of bridges.

During the construction of the bridge abutments and deck, the bridge is expected to be more vulnerable to earthquake loading than a completed structure. In addition, it is expected that due to the stability and stiffness provided to the structure upon completion of the deck and/or supporting cables, the vulnerability of a bridge during construction will be higher than that of a building.

3.3 Damage to CAR Civil Projects

Civil projects, such as tunnels, highways and pipelines usually span a large geographic area and can therefore be exposed to a wide range of hazards. Due to the large area covered by such projects, the value, as well as modelling of the project must be treated in segments. This is also due to the fact that construction usually takes place in phases, with only a limited number of sections of the project under construction at any given time.

The vulnerability of civil projects to the different perils examined will also vary depending on whether the project is constructed at the ground surface (e.g., highways) or at depth/buried (e.g., tunnels).

Of particular importance for civil projects, and specifically buried structures, is flooding; substantial damage to tunnels has occurred due to flooding, and/or wind-induced flooding that occurred while the construction shafts were still open. Even in the case of surface works though, flooding has led to unpaved roads being eroded due to current water moving over them (IMIA, 2012).

In the case of civil projects, construction phases are slightly altered from those used and discussed earlier. Due to the variety of projects under this category and the variable construction techniques, the phases considered are simplified. Herein, relative vulnerabilities will be estimated in two phases:

- **Phase I: Foundation and Superstructure Construction**
- **Phase II: Finishing**

IV. Vulnerability During Construction

Following the qualitative description of the expected damage during construction as a result of different perils, vulnerability adjustment factors are derived for each of the distinct phases detailed in Section 2. The use of the adjustment factors allows the determination of the relative vulnerability at different construction stages as a percentage of the final vulnerability (i.e., that of the complete structure). A factor of 0.5 thus means that the vulnerability of the structure at that particular stage is 50% lower than that of the final building, while a factor of 1.2 implies 20% higher vulnerability than that of the structure finalised. However, it is important to bear in mind that the replacement cost at a particular stage is likely to be lower than that of the final structure.

4.1 CAR Non-Civil Projects (Buildings) and EAR

The derived adjustment factors are peril specific and are summarised in Table 1 for CAR non-civil projects (buildings) and EAR. Further details regarding the suggested values are presented below.

Flood

As highlighted in Section 3.1, damage to a building due to flooding can occur through a number of different mechanisms. The substructure and foundation (Phase I), is considered to be the most critical phase, however, due to its relatively low cost compared to that of the superstructure, it is expected that the mean damage ratio will not exceed 80% of that corresponding to a completed structure. As the construction of the superstructure progresses (Phase II), the risk of flooding to higher storeys is very low and thus a further reduction in vulnerability is expected. On the other hand, during Phase III, the vulnerability of the building increases to levels beyond those of a complete structure due to the fact that some openings (i.e., doors and windows) may still not be covered, which could allow the ingress of water. Most non-structural elements of a building, such as electrical cables, ventilation systems, elevators, etc. are highly vulnerable to inundation therefore any slight contact with water may result in a high cost of replacement, especially in the case of electrical equipment (FEMA P-348, 1999).

Wind

The information presented in Section 3.2 regarding the expected wind damage to buildings under construction indicates that the vulnerability of the substructure is generally expected to be very low. The damage is expected to increase as the superstructure is constructed (Phase II), though this will still be lower than that of a complete building, since prior to the walls and roof construction wind can flow past the building causing fairly limited damage. During the construction of the walls and roof (Phase III), the vulnerability increases considerably as the structure is now exposed to large negative and positive pressures. However, as the building "envelope" has not been completed yet, the vulnerability of the structure at this stage is expected to be higher than that of the completed building.

	Flood	Wind	Earthquake
Phase I	0.8	0.1	0.05
Phase II	0.5	0.6	1.1
Phase III	1.1	1.2	0.95

Table 1: Adjustment factors for the estimation of the vulnerability during construction for various perils. Values are given as a proportion of the final vulnerability.

Earthquake

In the case of earthquake shaking the foundation and substructure (Phase I) would typically experience fairly limited damage. An exception to the above would be the case of pile foundations in liquefiable deposits, a very specialist case which, however, is not considered herein. The vulnerability of the building increases as the construction of the superstructure progresses (Phase II), where the building height and loads are increasing, but all load-carrying members might not have yet been completed. At this stage, the vulnerability of the building is expected to exceed that of the completed structure. In Phase III, the vulnerability is expected to be slightly lower than the final vulnerability due to the fact that load-carrying members have now been constructed, but not all live loads (i.e., E&M equipment, fixtures and fittings, etc.) have been installed yet.

4.2 CAR Civil Projects—Bridges

A separate set of vulnerability factors are presented in Table 2 for the case of bridges.

	Flood	Wind	Earthquake
Phase I	0.8	0.1	0.5
Phase II	1.0	1.0	1.2
Phase III	1.0	1.0	1.0

Table 2: Adjustment factors for the estimation of the vulnerability during construction for bridges. Values are given as a proportion of the final vulnerability.

Flood and Wind

The main differentiator from the values presented in Table 1 is the fact that during the construction of the bridge structure (Phases II and III), the vulnerability to flood and wind is expected to be the same as that of a completed structure. Due to the nature of the structure, there are no components during the superstructure construction (Phase II) that are expected to increase or decrease the bridge's vulnerability compared to what it will be upon completion of the construction. For example, the wind is expected to flow past the structure (no "envelope" concept is involved) and its impact is not expected to vary through Phases II and III and completion.

Earthquake

The vulnerability of a bridge under construction to earthquake shaking is expected to be different than that of a building, throughout all three construction phases considered. Bridge foundations, and in particular bridge abutments, are expected to be more vulnerable to earthquake shaking than building foundations during construction. Bridge foundations are often deeper; in addition, since in many cases bridges are constructed in proximity to water, soil conditions are often softer, of poorer quality, and thus more prone to failure.

During construction of the main bridge structure (Phase II), but prior to the completion of the deck and all supporting cables (if applicable), it is expected that the vulnerability of the structure will be higher than that of the final. This is due to concrete not reaching its final resistance or steel elements not being fully joined together. However, as soon as these are completed and prior to the deck surfacing and finishing of the bridge (Phase III), it is expected that the vulnerability will be the same as that of the completed structure.

4.3 CAR Civil Projects—Surface Works and Buried Structures

As mentioned earlier, different behaviour is expected depending on whether the structure is constructed at the ground surface (surface works) or at depth, and different vulnerability factors are derived for each case.

Surface Works

A set of vulnerability factors are presented in Table 3 for the case of shallow, linear projects. Shallow structures during construction are considered to be vulnerable mostly to flooding and wind-induced flooding. However, the vulnerability reduces as construction progresses and reaches the finishing stage, at which point any uncovered or open excavation has been completed. As far as earthquake loading is concerned it is believed that its impact on the structures will not vary during or after construction.

	Flood	Wind	Earthquake
Phase I	1.4	1.05	1.0
Phase II	1.0	1.0	1.0

Table 3: Adjustment factors for the estimation of the vulnerability during construction for surface works. Values are given as a proportion of the final vulnerability.

Buried Structures

During construction, buried structures, such as tunnels, are particularly vulnerable to flooding and wind-induced flooding. Shafts that are used for the construction of many large tunnel projects, which remain open throughout the construction phase, make the tunnel particularly vulnerable to flooding. On the other hand, buried structures have been seen to perform fairly well under earthquake shaking, with weak points being at the entrance/exit of the buried structures. The derived factors for buried projects are presented in Table 4.

	Flood	Wind	Earthquake
Phase I	1.6	1.1	1.0
Phase II	1.0	1.0	1.0

Table 4: Adjustment factors for the estimation of the vulnerability during construction for buried structures. Values are given as proportion of the final vulnerability.

V. Conclusions

This report has presented the estimation of relative vulnerability, given as a percentage of the final vulnerability (i.e., that of the complete structure), during different stages of building construction for three main perils: earthquake, wind and flood.

A factor of 0.5 thus means that the vulnerability of the structure at that particular stage is 50% lower than that at the final stage, while a factor of 1.2 implies 20% higher vulnerability than that of the structure finalised.

Due to the variability in the expected effects for various types of structures, different vulnerability adjustment factors have been presented for:

- CAR non-civil projects and EAR (Table 1)
- CAR civil projects—Bridges (Table 2)
- CAR civil projects—Surface works (Table 3)
- CAR civil projects—Buried structures (Table 4)

It is highlighted that the vulnerability of the structures will depend on a number of parameters, such as construction typology, occupancy or building/structure elevation. Nevertheless, due to the limited information available, the derivation of factors dependent on such characteristics was not deemed accurate.

Selected References

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