Factors Affecting Vulnerability of Ready-Made Garment Factory Buildings in Bangladesh: An Assessment Under Vertical and Earthquake Loads

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Abstract The importance of workplace safety in the ready-made garment (RMG) industry in Bangladesh came to the forefront after a series of disastrous events in recent years. In order to reduce the loss of lives and to ensure sustainable development, an in-depth understanding of the determining factors governing structural vulnerability in the RMG industry is needed. This research explores the key factors influencing the vulnerability of factory buildings under both vertical and earthquake loads. For this purpose, an ordered probit model was applied to 3746 RMG factory buildings to determine the key factors that influenced their vertical load vulnerability. A smaller subset of the original sample, 478 buildings, was examined by the same modeling method in greater detail to assess the key factors that influenced their earthquake load vulnerability. This research reveals that column capacity, structural system, and construction materials are the most influential factors for both types of vulnerabilities. Among other factors, soil liquefaction and irregular internal frame affect earthquake load vulnerability significantly. These findings are expected to enable factory owners and designers to better weigh the appropriate vulnerability factors in order to make informed decision that increase workplace safety. The

research findings will also help the designated authorities to conduct successful inspections of factory buildings and take actions that reduce vulnerability to both vertical and earthquake loads.

Keywords Bangladesh · Building vulnerability factors · Earthquake load vulnerability · Ordered probit model · Ready-made garment industry · Vertical load vulnerability

1 Introduction

Over the last three decades, the ready-made garment (RMG) industry has enjoyed significant growth in Bangladesh (Wadud et al. 2014). It has become the single most important sector contributing to the country's export earnings (Ansary and Barua 2015). The RMG industry emerged as an important contributor in employment generation, poverty alleviation, and women's empowerment (Rahman and Hossain 2010). But occupational safety issues remain a matter of great concern for this industry. Despite many efforts made to address safety issues, assuring the safety of workers remains a challenge. This in turn adversely affects worker livelihood, dependent families, and those living in the vicinity of the RMG industry

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(Hofmann et al. 2017). Among different occupational safety issues, building collapse is of prime importance in the Bangladesh RMG industry, a catastrophic failure that is strongly related to poor structural safety conditions. The cost-saving mentality of the factory owners, frequent violation of Bangladesh National Building Code (BNBC),¹ and lack of proper monitoring by relevant authorities has resulted in the construction of structurally unsafe RMG factory buildings. Such violations and the reluctant attitudes of other stakeholders towards structural and workplace safety compliance issues have contributed to many occupational disasters in Bangladesh's RMG industry (Ahmed and Hossain 2009).

The Rana Plaza collapse is the largest industrial accident in terms of fatalities in the history of Bangladesh, and one of the deadliest in the world. Rana Plaza collapsed on 24 April 2013, and result in 1134 deaths and more than 2500 injuries. Ansary and Barua (2015) found that the accident occurred because of the plaza's structural weakness to vertical loads, which was due to violation of the provisions of the BNBC. Bangladesh is also vulnerable to potential earthquakes. An earthquake of only medium magnitude on the Richter scale can produce a mass graveyard in the country (CDMP 2009). Structural weakness combined with the earthquake threat represents an enhanced risk for RMG factory buildings. Realizing the necessity to understand the scope of this risk, initial structural vulnerability assessments of RMG factories have already been carried out (DIFE 2016).

Completion of structural vulnerability assessments of all factory buildings revealed that Bangladesh has progressed a lot in terms of achieving workplace safety compliance. Nevertheless, assessment alone is not enough to ensure a safe working environment for all factories in the RMG sector (Barua and Ansary 2017). Weak factory buildings must be strengthened to withstand both vertical and earthquake loads and to prevent them from collapse. For this purpose, it is necessary to understand the factors that are responsible for causing such vulnerability.

Different researchers have made vulnerability assessments of buildings worldwide, particularly for such hazards as earthquakes (Hassan and Sozen 1997; Porter et al. 2001; Lagomarsino and Giovinazzi 2006; Chian 2016), tsunamis

(Dall'Osso et al. 2010; Suppasri et al. 2013), windstorms (Khanduri and Morrow 2003), and hurricanes (Pinelli et al. 2004), among others. Some studies have focused on vulnerability assessment of particular building structure type, for example: masonry buildings (Cardoso et al. 2005; Calio et al. 2012; Lagomarsino et al. 2013), unreinforced masonry buildings (Betti et al. 2014), stone masonry structures (DeJong and Vibert 2012), reinforced concrete buildings (Hassan and Sozen 1997), and so on. In Bangladesh, some studies have concentrated on the structural assessment of RMG factory buildings (Ansary and Barua 2015; Hodgson et al. 2016). None of these studies have focused on modeling those factors responsible for the vulnerability of buildings to vertical and earthquake loads, particularly by considering a building's specific use, and especially by concentrating on structures used for industry. This study addresses this gap in our understanding of building vulnerability and develops two separate models to explore and determine the key factors that influence the vulnerability of RMG factory buildings to vertical as well as earthquake loads.

2 Structural Vulnerability Assessment Initiatives in Bangladesh RMG Industry

After the Rana Plaza accident, several diverse national and international commitments and initiatives were begun to reduce the risks of structural failure and to improve workplace safety by ensuring structural safety. These initiatives were taken as part of the effort to reform and restructure the RMG sector in Bangladesh. Among the different initiatives, structural safety assessments of all active export-oriented RMG factories for vertical load vulnerability were included in all the action plans. As part of the National Tripartite Plan of Action (NTPA), the National Tripartite Committee (NTC)² agreed on an initial

¹ The Bangladesh National Building Code (BNBC) provides minimum standards and guidelines that address different aspects of building construction, which include building layout, construction materials, foundations, and safety. The BNBC follows the recommendations of other internationally used codes, which include the American Concrete Institute, the German Institute for Standardization (Deutsches Institut für Normung or DIN), the British Standards Institution (BSI), and the Eurocode: Basis for structural design (EN 1990) all of which are discussed briefly by Hodgson et al. (2016). Drafted in 1993, the BNBC was revised in 2006 to provide minimum standards for new construction.

² To safeguard the lives of over four million RMG workers and to retain the confidence of global buyers following the Rana Plaza accident, a variety of national and international commitments and initiatives were undertaken to reform and restructure the Bangladesh RMG sector. These initiatives included, but were not limited to, the National Tripartite Plan of Action (NTPA); the European Union Sustainability Compact; and the United States Trade Representative (USTR) Plan of Action. Tripartite partners, that is the Government of Bangladesh (GoB) and employers' and workers' organizations, also signed a Joint Statement built upon NTPA on May 2013 (CPD 2014). The NTC was established in 2013 under a NTPA commitment to ensure and monitor implementation of the NTPA (CPD 2014; ILO 2014). The committee chaired by the Labor Secretary, includes government agencies, employers organizations—the Bangladesh Employer's Federation (BEF), the Bangladesh Garment Manufacturers and Exporters Association (BGMEA), and Bangladesh Knitwear Manufacturers and Exporters Association (BKMEA)—and trade unions.

structural vulnerability assessment of all buildings housing RMG factories. Additionally, two different factory inspection programs were established: (1) the Accord on Fire and Building Safety in Bangladesh (the Accord),³ and (2) the Alliance for Bangladesh Worker Safety (the Alliance)⁴ (Bangladesh Accord 2013; Alliance for Bangladesh 2013). Bangladesh University of Engineering and Technology (BUET), acting on behalf of the NTC, the Accord, and the Alliance, was responsible for conducting the assessments of the structural integrity of factory buildings under NTPA. To carry out these assessments with a common approach, *Guidelines for Building Assessments (Structural and Fire) for Existing RMG Buildings in Bangladesh*⁵ was developed including harmonized standards and an inspection checklist for vertical load vulnerability (NTPA 2017).

By March 2016, a total of 3746 RMG factory buildings were assessed under NTPA for vertical load vulnerability. Among those buildings, 2.3% were identified as highly vulnerable, 42.7% as moderately vulnerable, 24.4% as slightly vulnerable, and 30.6% as not vulnerable (Ansary and Barua 2015). Ansary and Barua (2015) and Barua and Ansary (2017) presented detailed description of the procedures and the outcomes of assessment for vertical load vulnerability of RMG factory buildings. The majority of these buildings are located in Dhaka Division (comprising Dhaka, Gazipur, Magura, Munshiganj, Mymensingh, Narayanganj, Narsingdi, Nawabganj, and Tangail Districts) followed by Chittagong Division (comprising Chandpur, Chittagong, Comilla, Feni, Noakhali, and Rangamati Districts). Figure 1 shows the distribution of the assessed factory buildings in different districts of Bangladesh.

Given the extreme spatial concentration of the RMG industry in two divisions (Fig. 1), factory buildings located

in Dhaka City (from Dhaka Division) and Chittagong City (from Chittagong Division) were selected for earthquake load vulnerability assessment by the Department of Civil Engineering, BUET. Though Gazipur has much more factories compared to Chittagong, it was not selected for this assessment because Gazipur falls under Dhaka region. To ensure variation in dataset considering locational context, two distinct but significant areas from two divisions were selected. In Dhaka City the assessed factories are mainly located in three areas: Mirpur, Banani, and Tejgaon, whereas in Chittagong City they are located in two export processing zones: Chittagong Export Processing Zone and Karnaphuli Export Processing Zone. A total of 478 buildings out of the 3746 were assessed for earthquake load vulnerability. The earthquake load assessment was conducted on the basis of the standards mentioned for TIER-1 analysis in ASCE31-03 (ASCE 2003). As a result of the assessment, 20.8% buildings were found to be vulnerable to earthquake loads.

These national and international structural vulnerability assessment initiatives are internationally recognized to ensure workplace safety in Bangladesh RMG industry. In the research presented in this article, we used the assessment results of these initiatives to determine the factors affecting vertical and earthquake load vulnerability of RMG factory buildings in Bangladesh.

3 Factors Considered in the Structural Vulnerability Assessment Initiatives

The assessment to determine the vertical load vulnerability of RMG buildings under NTPA considered four factors on the basis of the *Guidelines for Building Assessments (Structural & Fire) for Existing RMG Buildings in Bangladesh* (NTPA 2017). These included: column capacity, structural system, construction materials, and the bearing capacity of soil (NTPA 2017). On the other hand, twelve factors were considered for earthquake load vulnerability assessment by BUET on the basis of the standards required for TIER-1 analysis in ASCE31-03 (ASCE 2003). These included: column capacity, structural system, construction materials, bearing capacity of soil, column slenderness, column shear stress, irregular internal frame, soft story, building shape, building adjacency, site amplification, and soil liquefaction. Detailed discussion on these factors considered in the structural vulnerability assessment initiatives for the Bangladesh RMG industry is provided in the following.

(1) Column Capacity: Eq. 1 was used by the assessment teams to calculate the column factor of safety (*FOS*), where greater column *FOS* represents greater column capacity.

³ The Accord was signed by more than 190 apparel companies from over 20 countries in Europe, North America, Asia, and Australia; two global trade unions, Industry ALL and UNI Global; and eight Bangladeshi trade unions on 15 May 2013. It is a 5 year, independent, and legally binding agreement designed to build a safe and healthy Bangladeshi RMG Industry (Bangladesh Accord 2013; Alliance for Bangladesh 2013).

⁴ The Alliance officially launched its local operation in Dhaka on 9 December 2013. This compact also is a five year, independent, and legally binding agreement founded by a group of North American apparel companies, retailers, and brands (26 North American retailers and brands) to develop and launch the Bangladesh Worker Safety Initiative (Bangladesh Accord 2013; Alliance for Bangladesh 2013).

⁵ The guidelines developed by technical experts (structural engineers, fire safety experts, and so on) from BUET on behalf of the NTC, the United Kingdom based consultancy firm Arup on behalf of the Accord, and the U.S. based consultancy firm Walter P. Moore on behalf of the Alliance. These organizations also have been responsible for conducting structural vulnerability assessments of the RMG factory buildings. The guideline document has been prepared in relation to the BNBC (1993), since the code had been in force at the time of construction of most of the factories (Hodgson et al. 2016).

Fig. 1 Distribution of factory buildings assessed for vertical load vulnerability in different districts of Bangladesh under NTPA (DIFE 2016)

$$\text{Column Factor of Safety (FOS)} = \frac{\text{Column Ultimate Strength}}{\text{Column Working Stress}} \quad (1)$$

The ultimate strength of the columns was calculated by the assessment teams using Eq. 2 according to BNBC (1993) standards.

$$P_n = 0.8\phi[0.85f'_c(A_g - A_{st}) + f_y A_{st}] \quad (2)$$

where P_n = Ultimate strength of a column, ϕ = Strength reduction factor (= 0.7), f'_c = Compressive (cylinder) concrete strength, A_g = Gross area of concrete section, A_{st} = Area of reinforcement, and f_y = Steel strength.

For the calculation of working stress, three columns (one corner, one middle, and one edge) from each story were selected. Necessary documents related to factory design and layout was collected from the Bangladesh Garment Manufacturers and Exporters Association (BGMEA) and Bangladesh Knitwear Manufacturers and Exporters Association (BKMEA).

Based on the column *FOS* values, the factory buildings were classified into four categories by BUET experts. The categories are:

- $FOS \geq 1.86$ = Safe structure;
- $1.50 \leq FOS < 1.86$ = Moderately safe structure;
- $1.25 \leq FOS < 1.50$ = Moderately unsafe structure;
- $FOS < 1.25$ = Unsafe structure

According to the BNBC (1993), Eq. 3 was used for calculating *FOS* from vertical loads.

$$FOS = \frac{LF}{VL \times \phi} \quad (3)$$

where LF = Load factor = $1.2 \times \text{Dead load factor (DL)} + 1.6 \times \text{Live load factor (LL)}$, VL = Vertical load factor = $DL + LL$, ϕ = Reduction factor for column = 0.7.

From the assessment of factory buildings, it was found that typical values of vertical loads were: dead load = 120 psf (including slab, beam, and floor finish) and live load = 40 psf. Thus, the ratio of dead load to live load is 3:1. For this context,

$$FOS = \frac{1.2 \times 3 + 1.6 \times 1}{4 \times 0.7} = 1.86$$

Therefore, structures with column *FOS* values greater or equal to 1.86 were considered to be safe structures, with the structural strength necessary to withstand both vertical and earthquake loads. Many of the factory buildings were constructed violating the BNBC rules, which resulted in lower column *FOS* values. Hence, other categories of *FOS* values were decided on the basis of the findings.

(2) Structural System: From the structural assessment results, it was observed that three types of structural systems generally were used in the factory buildings: the beam-column frame system; the flat plate system; and the mixed system. The beam-column frame system involves floor slabs designed with beams that support the edges of each slab, which stiffens the slab and adds considerable robustness and lateral stability to the structure by greatly strengthening the connections between columns and floors (Hodgson et al. 2016). In contrast, the flat plate system is normally designed with slabs without beams, which results in the lack of an alternate load path and makes the resulting structure weaker than the beam-column frame system (Durrani and Du 1992). Such structures do not have lateral force resisting elements in both directions to provide bracing, which may result in punching shear failure without warning (FEMA 1998). Structures with a flat plate system are considered vulnerable to both vertical and earthquake loads. A third type of structural system was followed by some factory buildings, which is referred to as the mixed structural system. In the mixed structural system, the first two or three stories were constructed using the beam-column frame system and the remaining top stories employ the flat plate system. We used 3D structural computer software (ETABS)⁶ to simulate building response to different vertical and earthquake loads. Our simulations demonstrated that buildings with a mixed system are less able to withstand vertical loads than are beam-column frame systems, but are stronger than flat plate systems.

⁶ ETABS is software for linear, nonlinear, static and dynamic analysis, and the design of building systems.

(3) **Construction Materials:** The structural capacity of a building to withstand vertical and earthquake loads is greatly affected by the ultimate strength of the materials used. This ultimate strength largely depends on the properties of construction materials involved, that is, aggregates mixed with concrete (Kwon and Elnashai 2006). In Bangladesh, generally three types of concrete are used—concrete with brick aggregate, concrete with stone aggregate, and concrete with both brick and stone aggregate. To understand the comparative strength of different concretes with these aggregates, cylinder tests were conducted (Ansary and Barua 2015). For this purpose, at least four three-inch diameter core samples were collected from each of the factory buildings and tested at the BUET Concrete Laboratory between 2003 and 2009 (Ansary and Barua 2015). The code requirements of the American Concrete Institute (ACI) were used by the assessment teams to estimate equivalent concrete strength from the core data as shown in Eq. 4 (ACI 2013).

$$\begin{aligned} &\text{Compressive (cylinder) concrete strength } f'_c \\ &= \text{Mean of concrete strengths} - 1.34 \\ &\quad \times \text{Standard deviation of concrete strengths} \end{aligned} \quad (4)$$

The result of core tests of concrete with different types of aggregates indicates that the average strength of concrete with crushed stone (3312 psi) is higher than the average strength of both concrete with mixed aggregate (3009 psi) and crushed brick chips (2805 psi) (Ansary and Barua 2015).

(4) **Bearing Capacity of Soil:** To understand the bearing capacity of soil beneath factory buildings, a factor of safety against the bearing capacity of the soil was considered. It was calculated using Eq. 5.

$$\text{Factor of Safety (FOS) against bearing capacity} = \frac{q_u}{q_{all}} \quad (5)$$

where q_u = Ultimate bearing capacity of soil under a shallow strip footing, and q_{all} = Allowable bearing capacity of soil.

To calculate the ultimate bearing capacity of soil under a shallow strip footing for existing factory buildings, undisturbed soil samples were collected. To estimate shear strength parameters, a Triaxial Consolidated Drained test was performed for clay samples and a Standard Penetration Test N value was obtained for sandy soil. Based on the estimated shear strength parameters, the ultimate bearing capacities of soil for the samples were calculated using Eq. 6 (Peck et al. 1974).

$$q_u = cN_c + \gamma DN_q + 0.5B\gamma N_\gamma \quad (6)$$

where N_c , N_q , and N_γ are shear strength parameters bearing their usual meanings.

The allowable bearing capacity of soil (q_{all}) was estimated based on the imposed vertical load. For greater safety against soil bearing failure, a factor of safety against the bearing capacity equal to three or above was considered the best (Peck et al. 1974). Factory buildings with bearing capacity less than three were considered to be vulnerable to both vertical and earthquake loads.

(5) **Column Slenderness:** Column slenderness of a building is decided on the basis of the ratio of effective column height to least radius of gyration, that is, l/r where “ l ” represents effective column height and “ r ” represents the least radius of gyration. This relationship reduces the capacity of columns to withstand earthquake loads by a factor $1.18 - 0.009 \times (l/r)$ (Nilson and Darwin 1997). According to Winter et al. (1964), a column is identified as slender when the l/r ratio is greater than 35. Buildings with columns having a l/r ratio greater than 35 were identified to exhibit column slenderness and consequently were considered to be vulnerable.

(6) **Column Shear Stress:** The shear stress in the concrete columns should be less than the greater of 100 psi (6.85 MPa) or $2\sqrt{f'_c}$ psi (f'_c = equivalent cylinder concrete strength) for life safety and immediate occupancy in the context of Bangladesh (Ansary and Barua 2015). The buildings with shear stress in the concrete columns greater than the maximum value were considered vulnerable.

(7) **Irregular Internal Frame:** If the beam-column systems of a structure are not placed in a regular grid, then the structure is considered to have an irregular internal frame structure. Buildings with an irregular internal frame are subjected to torsion, instability, and localized damage (FEMA 2006). They also behave poorly under earthquake load (Yee et al. 2011).

(8) **Soft Story:** The stiffness of the lateral-force-resisting system in any story must not be less than 70% of the lateral-force-resisting system's stiffness in an adjacent story above or below. Also any of the story's stiffness must not be less than 80% of the average lateral-force-resisting system's stiffness of the three stories above or below. If less than 80%, then the story in question is designated as a soft story (FEMA 2015). The presence of a soft story suggests that the building is vulnerable to any earthquake load (Arlekar et al. 1997; Dolšek and Fajfar 2001; Setia and Sharma 2012).

(9) **Building Shape:** Buildings with equal or close to equal proportional width, length, and height dimensions are considered regular shaped buildings. For regular shaped buildings, the effect of lateral loads will be minimal. In the case of buildings with a variation in the proportion of their dimensions (for example, L-shaped or T-shaped), the effect

Fig. 2 Location of selected sites in amplification maps of Dhaka and Chittagong, Bangladesh, **a** Dhaka city, **b** Chittagong city. *Source:* Rahman (2004) and Masud (2007)

of lateral loads will be very high, which may cause building damage (FEMA 2015).

(10) Building Adjacency (pounding): There should be a minimum distance between adjacent buildings to ensure life safety and permit immediate occupancy. The clear distance between the buildings being evaluated and any adjacent building should be greater than 4% of the height of the shorter building (FEMA 1998). If the actual clear distance is less than this minimum distance, then damage can be caused due to buildings pounding against one another.

(11) Site Amplification: Ground shaking is the primary cause of earthquake damage to structures. During earthquake events, however, some places in the same area may experience stronger seismic shaking than others. The effect of local soil conditions on the amplitude and frequency content of earthquake motions define the characteristics of the seismic motions that can be expected at the free surface (or at any depth) of a soil stratum, which is called the soil amplification effect (USGS 2016). The RMG factories assessed for earthquake load are located in Dhaka City (Mirpur, Banani, and Tejgaon), and Chittagong City (Chittagong Export Processing Zone and Karnaphuli

Export Processing Zone). So, in our research we have considered the site amplification test results of these two cities conducted by Rahman (2004) and Masud (2007). Figure 2 shows the site amplification maps of Dhaka and Chittagong cities where the location of the selected sites in this research are identified. Factory buildings with site amplification characteristics were categorized based on their locations accordingly.

(12) Soil Liquefaction: Saturated, loose granular soil, loose sandy soil, and soil with a shallow water table are considered to be susceptible to liquefaction during an earthquake. Liquefiable soil does not have any stiffness in the case of lateral loads such as earthquake loads (Bird et al. 2006). Liquefaction-susceptible soil should not exist in the foundation soils at depths within 50 feet under the building for life safety and immediate occupancy (ASCE 2003). In this research we have considered soil liquefaction test results of Dhaka and Chittagong Cities conducted by Rahman (2004) and Masud (2007). They classified soil liquefaction susceptibility into three categories based on a liquefaction potential index—10 represents high liquefaction potential, where ground improvement is indispensable; 5 represents moderate liquefaction potential, where ground

Fig. 3 Location of selected sites in soil liquefaction maps of Dhaka and Chittagong, Bangladesh, **a** Dhaka city, **b** Chittagong city. *Source:* Rahman (2004) and Masud (2007)

improvement is required and investigation of important structures is indispensable; and 0 represents negligible liquefaction potential, where no remedial measure is required. Figure 3 shows the soil liquefaction maps of Dhaka and Chittagong cities where the location of the selected sites in this research are identified. Factory buildings with soil liquefaction were categorized based on their locations accordingly.

4 Methodology

In this section, methodology of this research is described, which includes data collection, selection of factors, and specification of the models that were developed in this research based on collected data considering selected factors.

4.1 Data Collection

We used the assessment results of national and international structural vulnerability assessment initiatives in Bangladesh RMG industry, which have been discussed in Sect. 2 of this article. Two datasets were collected: individual vertical load vulnerability assessment reports of all the 3746 factory buildings assessed by DIFE (2016) and individual earthquake load vulnerability assessment reports of all the 478 factory buildings assessed by BUET. Thus, individual assessment reports of each of these buildings were collected. After collection of individual reports, we prepared two compiled datasets separately for vertical load vulnerability and earthquake load vulnerability based on factors selected for this research, which are discussed in the following section.

Table 1 Factors affecting vertical and earthquake load vulnerability in ready-made garment industry factory buildings in Dhaka and Chittagong, Bangladesh

Name of factors	Scale (Greater value represents greater vulnerability)		
	1	2	3
Column capacity ^{a,b}	High ($FOS \geq 1.86$)	Moderate ($1.25 \leq FOS < 1.86$)	Low ($FOS < 1.25$)
Structural system ^{a,b}	Beam-column	Flat plate	Mixed
Construction materials ^{a,b}	Concrete of crushed stone	Concrete of mixed aggregate	Concrete of crushed brick
Bearing capacity of soil ^{a,b}	Good ($FOS \geq 3.00$)	Fair ($2.00 \leq FOS < 3.00$)	Poor ($FOS < 2.00$)
Column slenderness ^b	No ($l/r \leq 35$)	Yes ($l/r > 35$)	N/A
Column shear stress ^b	Within limit	Beyond limit	N/A
Irregular internal frame ^b	No	Yes	N/A
Soft story ^b	No	Yes	N/A
Building shape ^b	Regular	Irregular	N/A
Building adjacency (pounding) ^b	No (Clear distance $> 4\%$)	Yes (Clear distance $\leq 4\%$)	N/A
Site amplification ^b	Low	Moderate	High
Soil liquefaction ^b	Negligible	Moderate	High

^aFactors affecting vertical load vulnerability^bFactors affecting earthquake load vulnerability

4.2 Factor Selection

Our research considered the 12 factors used for structural vulnerability assessment in the Bangladesh RMG industry under the national and international initiatives discussed in Sect. 3. These factors were chosen for two reasons: first, these factors contribute to structural vulnerability; and second, data on these factors for individual factory buildings were available. These factors were ordered into Likert scales of measurement accordingly. Table 1 shows the factors considered to affect the earthquake and vertical load vulnerability of factory buildings and associated Likert scales of measurement where lower value (1) represents lower vulnerability and higher value (3) represents greater vulnerability. Based on the assessment results (discussed in Sect. 4.1), the buildings were categorized into different scales corresponding to the factors.

4.3 Model Specification

We built two separate ordered probit models to determine the factors associated with vulnerability of RMG factory buildings to vertical and earthquake loads, respectively. For this purpose, the factors described in Table 1 were considered as independent factors. The assessment teams classified the factory buildings into four categories based on vertical load vulnerability (highly, moderately, slightly, and not vulnerable), and into two categories based on earthquake load vulnerability (vulnerable and not vulnerable). For the model building developed in this research, these assessment results were considered as dependent factors. All dependent and independent factors (for both

vertical and earthquake load vulnerability) were arranged in a discrete and ordered fashion. Again, the ordered probit model is most suitable when the specification of the choice factors are defined on a discrete and ordered scale (Greene and Hensher 2008; Garrido et al. 2014; Russo et al. 2014; Ye and Lord 2014).

The ordered probit model assumes that there is a latent continuous factor y_i^* underlying the vulnerability of i number of factory buildings. The latent continuous factor, y_i^* is a linear combination of independent factors, x_i , plus an error term ε_i that has a standard normal distribution. In this research, factors discussed in Table 1 have been considered as independent factors. Specifically:

$$y_i^* = \beta x_i + \varepsilon_i \quad (7)$$

Here, i = index for each factory building assessed, x_i = vector of observed independent factors (column capacity, structural system, and so on), β = vector of coefficients to be estimated by the model, ε_i = error term (assumed to be normally distributed in the ordered probit model, with mean zero and unit variance), and y_i is the dependent observed ordinal factor (factory buildings' vulnerability index). y_i can be determined as follows:

$$y_{i,vv} = \begin{cases} 1, & \text{if } -\infty \leq y_{i,vv}^* \leq \mu_{1,vv} \quad (\text{Not Vulnerable}) \\ 2, & \text{if } \mu_{1,vv} \leq y_{i,vv}^* \leq \mu_{2,vv} \quad (\text{Slightly Vulnerable}) \\ 3, & \text{if } \mu_{2,vv} \leq y_{i,vv}^* \leq \mu_{3,vv} \quad (\text{Moderately Vulnerable}) \\ 4, & \text{if } \mu_{3,vv} \leq y_{i,vv}^* \leq \infty \quad (\text{Vulnerable}) \end{cases}$$

Here, $y_{i,vv}$ = Dependent observed ordinal factor representing vertical load vulnerability of i number of factory buildings, $\mu_{k,vv}$ = Threshold values for the model

Fig. 4 Year of construction and number of stories of factory buildings in Dhaka and Chittagong, Bangladesh

factors affecting factory buildings' vertical load vulnerability. For this model $k = 1, 2, 3, 4$;

$$y_{i,ev} = \begin{cases} 1, & \text{if } -\infty \leq y_{i,ev}^* \leq \mu_{1,ev} \text{ (Not Vulnerable)} \\ 2, & \text{if } \mu_{1,ev} \leq y_{i,ev}^* \leq \infty \text{ (Vulnerable)} \end{cases}$$

Here, $y_{i,ev}$ = Dependent observed ordinal factor representing earthquake load vulnerability of i number of factory buildings, $\mu_{k,ev}$ = Threshold values for the model factors affecting factory buildings' earthquake load vulnerability. For this model $k = 1, 2$.

We assumed that neither coefficients β nor thresholds μ_k vary over each factory building assessed. The probability that factory building^{*i*} will take on category k is given by the probability (p_{ik}) expressed in Eq. 8.

$$p_{ik} = P(y_i = k) = P(\mu_{k-1} \leq y_i^* \leq \mu_k) = \Phi(\mu_k - \beta x_i) - \Phi(\mu_{k-1} - \beta x_i) \quad (8)$$

To estimate this model we used maximum likelihood estimation (MLE) and for that first we required a log-likelihood function. The requirement was fulfilled by defining an indicator factor z_{ik} . The log-likelihood is given by Eq. 9.

$$\ln(\xi) = \sum_i^N \sum_l^k z_{ik} \ln(\Phi_{ik} - \Phi_{i,k-1}) \quad (9)$$

Here, Φ = cumulative normal distribution function

$$\Phi_{ik} = \Phi(\mu_k - \beta x_i)$$

$$\Phi_{i,k-1} = \Phi(\mu_{k-1} - \beta x_i)$$

Computation of these probabilities allows the understanding of the effect of individual estimated parameters. Indeed, a positive value of β implies that an increase in x_i will clearly generate an increase of the probabilities of building vulnerability levels and vice versa. However, it is not obvious what effects a positive or negative β will generate on the probabilities of the intermediate levels. For this reason, the computation of marginal effects for each level is suggested. According to

Washington et al. (2010) these marginal effects provide the direction of the probability for each level shown by Eq. 10.

$$\frac{P(y = k)}{\partial x} = [\Phi(\mu_k - \beta x_i) - \Phi(\mu_{k-1} - \beta x_i)]\beta \quad (10)$$

In this research, factors having a t-stat greater than 1.64 at the 90% confidence level were considered significant. For all computations we used software STATA,⁷ version 13. Detail specification of the model is provided in (Greene 2000).

5 Results and Discussion

The findings of this research are discussed in this section, including description of the dataset, two models representing factors affecting vulnerability of the factory buildings, and validation of the developed models.

5.1 Description of the Dataset

Figure 4 indicates the percentage of factory buildings with respect to their year of construction and number of stories. The figure shows that 65% of the factory buildings were 6 stories or less, and 83% of the buildings were constructed between 1991 and 2010.

Figure 5 shows the distribution of the factory buildings corresponding to the scale of factors affecting their vertical and earthquake load vulnerability in percentage for our two datasets. The buildings were categorized according to the Likert scale, which represents their vulnerability in terms of different factors. This was done based on the categorization shown in Table 1.

⁷ STATA is software used for statistical analysis. For more information please visit <https://www.stata.com>.

Fig. 5 Distribution of factory buildings in Dhaka and Chittagong, Bangladesh, corresponding to the scale of factors affecting their vulnerability, **a** dataset of vertical load vulnerability, **b** Dataset of earthquake load vulnerability

5.2 Study Findings

Table 2 shows parameter estimates and the marginal effect analysis of the factors that contribute to the vulnerability of RMG factory buildings to vertical and earthquake loads. Tables 3 and 4 show the correlation matrix between factors considered and vertical and earthquake load vulnerability, respectively.

Model results make it evident that the vulnerability of factory buildings to vertical loads is significantly affected by all four factors considered in this study. Among those variables column capacity has the highest parameter value (4.147; Table 2) and t-statistics (10.71; Table 2). The high correlation value of column capacity with vertical load vulnerability (correlation value: 0.724; Table 3) indicates that a decrease in column capacity increases vulnerability significantly. During the analysis, we observed that the factory buildings with low column capacity had critical visible defects that may result in immediate structural collapse. This result is supported by Ansary and Barua (2015), where the authors suggest that column capacity is the most important structural quality of factory buildings. It is obvious that if the columns do not have the capacity to withstand imposed vertical load (live load and dead load), the structure will certainly not have the capacity to

withstand lateral loads like earthquake loads. Thus, this is a very significant factor when considering earthquake load vulnerability. This determination is also supported by the model results (estimated parameter: 3.143; Table 2 and correlation value: 0.62; Table 4).

In addition to column capacity, the structural system affects vertical load vulnerability (estimated parameter: 2.673; Table 2) as well as earthquake load (estimated parameter: 2.321; Table 2) substantially. This interaction indicates that factory buildings become more vulnerable as disintegration of the structural system increases. Although flat plate structures (as part of lateral load carrying system) are not permitted by the BNBC (1993), about 19% of all factory buildings (Fig. 5b) were built using flat plate structures for greater floor height. This is a matter of grave concern because with flat plates, the region around the column is always the critical location as it transfers combined gravity and lateral loads in a relatively small, shallow section. Unbalanced moments generated due to seismic action need to be transferred to columns from the flat plate. Brittle punching failures of flat plates were observed during several earthquakes as documented by Mitchell et al. (1995) and Mitchell et al. (1990). Despite the significant effect, structural system shows positive (Table 3) but weak correlation (Table 4) with both vulnerabilities.

Table 2 Parameter estimates and marginal effect analysis results of the ordered probit models

Factor name	Total sample								Sample 1		Sample 2	
	Estimated parameter	t-statistics	Marginal effect analysis						Estimated parameter	t-statistics	Estimated parameter	t-statistics
			Factors affecting vertical load vulnerability				Factors affecting earthquake load vulnerability					
			1	2	3	4	1	2				
Column capacity	4.147 ^a 3.143 ^b	10.71 ^c 7.72 ^d	− 0.126	− 0.238	0.263	0.100	− 0.252	0.252	4.148 ^a 3.13 ^b	10.77 ^c 7.75 ^d	4.172 ^a 3.171 ^b	10.74 ^c 7.74 ^d
Structural system	2.673 ^a 2.321 ^b	5.57 ^c 4.67 ^d	− 0.004	− 0.008	0.009	0.003	− 0.552	0.552	2.379 ^a 2.479 ^b	5.60 ^c 4.69 ^d	2.485 ^a 2.385 ^b	5.48 ^c 4.42 ^d
Construction materials	0.924 ^a 0.824 ^b	6.72 ^c 5.61 ^d	− 0.081	− 0.152	0.168	0.064	− 0.054	0.054	0.906 ^a 0.806 ^b	6.47 ^c 5.47 ^d	0.981 ^a 0.871 ^b	6.74 ^c 5.74 ^d
Bearing capacity of soil	2.672 ^a 0.316 ^b	5.57 ^c 1.89 ^d	− 0.148	− 0.279	0.309	0.118	− 0.447	0.447	2.379 ^a 0.315 ^b	5.60 ^c 1.84 ^d	2.485 ^a 0.311 ^b	5.48 ^c 1.81 ^d
Column slenderness	0.449 ^b	1.97 ^d	−	−	−	−	− 0.078	0.078	0.441 ^b	1.89 ^d	0.467 ^b	2.01 ^d
Column shear stress	0.109 ^b	1.09 ^d	−	−	−	−	− 0.024	0.024	0.103 ^b	1.08 ^d	1.102 ^b	1.17 ^d
Irregular internal frame	0.604 ^b	3.21 ^d	−	−	−	−	− 0.047	0.047	0.587 ^b	3.25 ^d	0.612 ^b	3.49 ^d
Soft story	0.291 ^b	1.89 ^d	−	−	−	−	− 0.187	0.187	0.290 ^b	1.85 ^d	0.287 ^b	1.82 ^d
Building shape	0.349 ^b	1.87 ^d	−	−	−	−	− 0.009	0.009	0.316 ^b	1.78 ^d	0.317 ^b	1.81 ^d
Pounding	0.273 ^b	1.76 ^d	−	−	−	−	− 0.551	0.551	0.267 ^b	1.66 ^d	0.279 ^b	1.80 ^d
Site amplification	0.122 ^b	1.25 ^d	−	−	−	−	− 0.458	0.458	0.121 ^b	1.19 ^d	0.137 ^b	1.34 ^d
Soil liquefaction	0.703 ^b	3.41 ^d	−	−	−	−	− 0.041	0.041	0.701 ^b	3.20 ^d	0.712 ^b	3.48 ^d
Threshold values												
Factors affecting vertical load vulnerability					Factors affecting earthquake load vulnerability							
$\mu_{1,w}$		4.710			$\mu_{1,ev}$			11.116				
$\mu_{2,w}$		6.455			−			−				
$\mu_{3,w}$		7.817			−			−				

Italic numbers indicate t-stat < 1.64

Factors with t-stat > 1.64 are considered significant

^aParameter estimates of the model: factors affecting vertical load vulnerability

^bParameter estimates of the model: factors affecting earthquake load vulnerability

^ct-stat of the model: factors affecting vertical load vulnerability

^dt-stat of the model: factors affecting earthquake load vulnerability

Model results also show that construction materials influence vertical and earthquake load vulnerability significantly with a parameter value of 0.924 and 0.824, respectively (Table 2). Construction materials have a correlation value of 0.383 (Table 3) and 0.317 (Table 4) for vertical and earthquake load vulnerability, respectively. Vulnerability to vertical and earthquake loads largely

depend on the type and characteristics of the construction materials used. The building assessment analysis identifies many cases where both quality of construction materials and construction practices were very poor. Yépez and Yépez (2017) found that substandard construction materials and poor construction practice were some of the main reasons behind the collapse of thousands of buildings after

Table 3 Correlation matrix of the factors contributing to vertical load vulnerability

Factor	Factor				
	Column capacity	Structural system	Construction materials	Bearing capacity of soil	Vertical load vulnerability
Column capacity	1				
Structural system	0.381	1			
Construction materials	0.125	0.293	1		
Bearing capacity of soil	0.120	0.188	0.118	1	
Vertical load vulnerability	0.724	0.424	0.383	0.314	1

Positive value (+): positive correlation; Zero (0): no correlation; Negative value (−): negative correlation

(0 to ± 0.25): No association

(± 0.25 to ± 0.50): Weak association

(± 0.50 to ± 0.75): Moderate association

(± 0.75 to ± 1): Strong association

(± 1): Perfect association

the Ecuador earthquake in 2016. Bangladesh has not experienced a major earthquake since Great Indian Earthquake 1897 (Roy 2014; Chakravorti et al. 2015). But the country should be careful to maintain its construction quality in order to reduce vertical as well as earthquake load vulnerability to avoid a potential future disastrous situation.

If a building is robust, and it has a good structural system with quality construction materials and columns with sufficient capacity, the building generally will not fail. If the soil beneath a building is liquefiable, however, then an earthquake event will cause severe damage to structures. Soil liquefaction considerably affects the vulnerability of factory buildings to earthquake load (estimated parameter: 0.703; Table 2). This result is consistent with the findings of Bird et al. (2006) and O'Rourke et al. (1991), who concluded that soil liquefaction from earthquake loads causes serious damage to structures. The model results show that the vulnerability of buildings to vertical load is significantly affected by the bearing capacity of soil (estimated parameter: 2.672; Table 2).

The presence of an irregular internal frame substantially increases building vulnerability to earthquake loads (estimated parameter: 0.604; Table 2). Our marginal effect analysis demonstrates that a one-unit increase in internal frame irregularity increases the earthquake load vulnerability of factory buildings by 0.047 (Table 2). This result is consistent with the findings of Yee et al. (2011) where the authors mentioned that a regular column grid is a prerequisite for seismic resistance. An irregular internal frame has moderate correlation with earthquake load vulnerability (correlation value: 0.409; Table 4).

Building shape (estimated parameter: 0.349; Table 2) and the presence of a soft story (estimated parameter 0.291;

Table 2) increase earthquake load vulnerability moderately. Raj and Shashikala (2011) concluded that buildings with abrupt changes in story stiffness due to building shape irregularities cause uneven lateral force distribution as the height of the building increases, which is likely to locally induce stress concentration. This has adverse effect on the performance of buildings to seismic resistance. Similar results were found by Arlekar et al. (1997), Dolšek and Fajfar (2001), and Setia and Sharma (2012). The researchers showed that the seismic response of reinforced concrete frames is worst where a soft story is created by infilling only the upper part of the structure, whereas the bottom story remains bare (open except for columns).

Model results show that vulnerability to earthquake loads is positively affected by column slenderness (estimated parameter: 0.449; Table 2). Column slenderness has weak positive correlation with both column capacity (0.120; Table 4) and vulnerability to earthquake loads (0.127; Table 4). Similarly, pounding positively affects building vulnerability to earthquake loads (estimated parameter: 0.273; Table 2). A majority of the factory buildings (about 61%) do not have an adequate gap with adjacent buildings, which leads to an enhanced impact of the pounding effect (Fig. 5b) on closely clustered factory buildings. In the event of a major earthquake, this inadequate gap can cause serious damage to the structures. Hao (2015) stated that the pounding usually causes local damage around the collision-impacted area. Collapse of the building structures may also happen in extreme cases. Thus any increase in the pounding effect will obviously increase earthquake load vulnerability.

Surprisingly, model results found site amplification and column shear stress were insignificant factors. This result is inconsistent with that of Hough et al. (2010), who found

Table 4 Correlation matrix of the factors contributing to earthquake load vulnerability

Factor	Factor												
	Column capacity	Structural system	Construction materials	Bearing capacity of soil	Column slenderness	Column shear stress	Irregular internal frame	Soft story	Building shape	Pounding	Site amplification	Soil liquefaction	Earthquake load vulnerability
Column capacity	1												
Structural system	0.281	1											
Construction materials	0.078	0.083	1										
Bearing capacity of soil	0.008	0.081	0.141	1									
Column slenderness	0.120	0.188	0.002	0.011	1								
Column shear stress	0.055	0.123	0.008	0.008	0.054	1							
Irregular internal frame	0.210	0.230	0.083	0.261	0.119	0.035	1						
Soft story	0.089	0.078	0.007	0.004	0.084	0.008	0.201	1					
Building shape	0.035	− 0.289	0.009	0.002	0.089	0.021	0.121	0.058	1				
Pounding	0.040	0.313	− 0.019	0.012	0.216	0.008	− 0.045	0.045	0.130	1			
Site amplification	0.025	0.121	0.022	0.010	0.011	0.001	0.102	0.078	0.022	0.018	1		
Soil liquefaction	0.024	− 0.024	0.290	0.014	− 0.114	− 0.001	0.017	0.002	0.014	− 0.012	− 0.005	1	
Earthquake load vulnerability	0.62	0.127	0.328	0.247	0.127	0.006	0.409	0.105	0.247	0.014	0.002	0.304	1

Positive value (+): positive correlation; Zero (0): no correlation; Negative value (−): negative correlation

(0 to ± 0.25): No association

(± 0.25 to ± 0.50): Weak association

(± 0.50 to ± 0.75): Moderate association

(± 0.75 to ± 1): Strong association

(± 1): Perfect association

Fig. 6 The effect of individual factors on the vulnerability of factory buildings in Dhaka and Chittagong, Bangladesh, **a** vertical load vulnerability, **b** earthquake load vulnerability

site amplification to be one of the most important factors to assess when determining the earthquake load vulnerability of structures. The main reason behind this anomaly is that the sites of the factory buildings surveyed were located on well-compacted soil with a very low site amplification potential. We did not omit this variable from our model because in a different locational context this factor might significantly affect earthquake load vulnerability.

Figure 6 displays the effect of individual factors on the vulnerability of factory buildings to vertical load and earthquake load, respectively, assuming the vulnerability function is linear. From Fig. 6a, it can be observed that the percent increase in vertical load vulnerability due to column capacity is 50% when the individual factor scale changed from 1 to 3, and in the case of structural system it is 32%. Figure 6b shows that the percent increase in earthquake load vulnerability is also most significant due to column capacity (35.5%) and structural system (27%). Additionally, construction materials (9.3%), soil liquefaction (7.9%), and irregular internal frame (6.8%) are other significant factors that increase the earthquake load vulnerability of RMG factory buildings.

5.3 Model Validation

The validity of the models was investigated by McFadden's pseudo R-squared (ρ^2) estimates using software STATA version 13. Here the value ranging from 0.2 to 0.4 indicates very good model fit (McFadden 1977). To check the stability of the models, a hypothesis testing was carried out. For this purpose, first both the datasets (assessment data of 3746 buildings for vertical loads and a subset of 478 buildings (drawn from the larger vertical load data set) were analyzed for earthquake load vulnerability. The smaller subset was split into two equal halves—Sample 1 and Sample 2. Using these two samples, two separate models were developed with the same specification.

Here the hypothesis was, H_1 : Model parameters are equal for the models estimated on the basis of the full dataset and two samples. If we fail to reject the hypothesis, then the validity of our specification is established. To test the hypothesis, likelihood ratios (LR) were estimated for the two datasets using Eq. 11 (Hasan et al. 2013).

$$LR = -2 \left[LL(\beta_{full-data}) - LL(\beta_{sample1}) - LL(\beta_{sample2}) \right] \quad (11)$$

Table 5 Validation of models representing factors affecting vertical and earthquake load vulnerability

Model validation parameters	Building's earthquake load vulnerability	Buildings' vertical load vulnerability
McFadden's pseudo R-squared (ρ^2)	0.198	0.217
$LR = -2[LL(\beta_{(full-data)}) - LL(\beta_{(sample1)}) - LL(\beta_{(sample2)})]$	$35.25 < \chi^2_{12,0.10} = 37.566$	$11.78 < \chi^2_{4,0.10} = 13.277$

Here, $LL(\beta_{(full-data)})$ = log-likelihood at convergence of the model estimated using the full data, $LL(\beta_{(sample1)})$ = log-likelihood at convergence of the model estimated using Sample 1, and $LL(\beta_{(sample2)})$ = log-likelihood at convergence of the model estimated using Sample 2.

Table 5 shows validation of models representing factors affecting the vertical and earthquake load vulnerability of RMG factory buildings. From the table it is evident that the proposed models have a good fit. For the model representing factors that affect the vulnerability of buildings to vertical and earthquake loads, the *LRs* were obtained as 11.78 with degrees of freedom four and 35.25 with degrees of freedom 12 respectively (Table 5). Since, $\chi^2_{4,0.10} = 13.277$ and $\chi^2_{12,0.10} = 37.566$ we accept the hypothesis that the parameters across different samples are equal. The tests validate the fitness as well as the stability of models developed and presented in this article.

6 Conclusion

In this research, we endeavored to determine the key factors affecting the vulnerability of RMG factory buildings to vertical and earthquake loads by use of ordered probit modeling. A number of factors were found to influence the vulnerability of buildings to vertical and earthquake loads. It is important to realize that if a structure is vulnerable to vertical loads, then that structure is sure to be vulnerable to earthquake loads. This statement is very much evident from the model results. To be more specific, we demonstrated that column capacity is the most influential factor governing both earthquake and vertical load vulnerabilities. To ensure the required design strength of the structural members of a building, and thereby to get proper resistance against vertical and earthquake loads, the best quality of construction materials should be chosen. Structural system was found to be another significant factor that influences vertical as well as earthquake load vulnerability. To reduce earthquake load vulnerability, structures must have enough lateral force resistance. In that case, structural system and irregular internal frame play vital roles. Superstructures having adequate resistance to lateral loads may collapse due to soil liquefaction in the case of an earthquake. Thus,

soil liquefaction and irregular internal frame are the other significant factors that influence earthquake load vulnerability.

The developed models give useful insights about the factors affecting the vulnerability of Bangladesh's RMG factory buildings to vertical and earthquake loads. Model parameters also show the nature of the effect that the factors have on both vulnerabilities. Thus, the models are not only statically reliable, but also they are very effective in representing the exact phenomenon. The correlation matrixes also show the influence of different factors. The methodology developed can be readily applied by factory owners to better weigh the factors that increase their building's vulnerability. The study findings would also help the relevant authorities to conduct successful inspections of factory buildings and to reduce both vertical and earthquake load vulnerability. Planners and stakeholders of RMG sector should be more careful about these factors when formulating measures for promoting safety and sustainability. In this research, only material vulnerability (inherent weakness of the built environment) was considered. Attitudinal vulnerability (fatalism, ignorance, and a low level of awareness) can cause serious loss to human life in the event of a disaster. In future, research needs to be carried out to incorporate both material vulnerability and attitudinal vulnerability in order to assess the vulnerability of RMG factories in the event of a disaster.

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