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Grasping the Nonconformities in Building Construction Supply Chains

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Abstract

Identifying and understanding potential nonconformities in different construction phases is a key to ensuring the anticipated quality and performance of a building in its service period. Previous studies mostly focus on studying nonconformities in the handover or post-handover phases of building projects. There has been relatively less attention paid to the issue in the pre-construction and construction phases of building projects in densely populated South Asian countries in particular. This study aims to identify the potential and critical nonconformity problems from the initiation to construction phases of building projects, with a particular focus on Bangladesh, where the quality and integrity of building construction works and practices is generally lacking. The study is informed by a comprehensive literature review of the topic followed by a series of discussions and workshops with highly qualified and experienced experts to identify the potential nonconformities frequently encountered in building construction projects. Additionally, three building projects are studied to identify the instances of nonconformities and their root causes. The major nonconformities identified from this study are improper soil investigation, the poor quality of materials, poor quality of concrete, improper alignment of structural members, insufficient concrete cover, lack of or no curing of concrete, defective formwork, and early removal of formwork. Subsequently, specific remedial actions are recommended for the individuals/organizations involved throughout the building construction phases in developing countries such as Bangladesh towards improving the quality and performance of buildings in their service lives.

Keywords: nonconformity, building construction, construction quality, concrete curing, construction project.

Introduction

Durability, safety, structural integrity, and sustainability are critical factors for sustainable building construction work. However, serious concerns have been raised in recent years over the risks involved from 'nonconforming' building construction, where 'nonconformance' is defined as "the failure to fulfill an intended or specified requirement" (Gashi 2018), and typically refers to defective work, defective products, or deviation from the specified quality of work or a product (Sommerville 2007). Nonconformity frequently occurs in the construction industries of many countries, including Australia and the UK (Abdelsalam and Gad 2009; Heravi and Jafari 2014; Love and Edwards 2005; Sommerville 2007; Zhang et al. 2012).

The potential risks of nonconforming building work to the community, the building occupants, and the construction industry are widespread – ranging from simply not satisfying the intended purposes of the dwellers, to the substantial loss of lives because of building collapse. The recent era has witnessed some of the most severe accidents, including Bangladesh's Rana Plaza (2013), Nepal's Dharahara (2015), New Zealand's Canterbury Television Building (2011), Taiwan's Weiguan Jinlong (2016), and China's Fengcheng Power Station (2106) (Omondi 2019). Apart from natural disasters (e.g., earthquakes, strong winds, and landslides) (Lili and Zhe 2018), such nonconformities as improper soil investigations, weak building foundations, defective formwork, the poor quality of materials, and violation of construction codes are the primary reasons for structural collapses (Almarwae 2017; Dietz 2013; Wardhana and Hadipriono 2003). Moreover, construction nonconformities often lead to rework and eventually increase project costs (Chiel 2014), Love et al.'s (2018) study finding substantial extra costs of up to $10,689 per non-conformance. However, identifying the several types and causes of nonconformities and taking appropriate actions to control them throughout the building construction supply chain (BCSC) can help reduce defects in built projects (Kazaz et al. 2005).

To ensure the expected quality, structural safety, and durability of buildings, construction industry professionals and associated stakeholders need to understand the potential and critical nonconformities encountered in the BCSC (i.e., from initiation to commissioning). In recent years, most studies of nonconformities or defects are of the handover, post-handover, or operation phases of buildings (Jonsson and Gunnelin 2019; Bortolini and Forcada 2018; Forcada et al. 2012, 2013, 2016). With the exception of a detailed study conducted in the Gaza Strip (Tayeh et al. 2020), nonconformities in the pre-construction (i.e., initiation and planning) and construction phases have been partially studied in some developed countries (Chiel 2014; MacArulla et al. 2013; Silvestre and De Brito 2011; Forcada et al. 2016; Forcada et al. 2014; Sommerville 2007) and a few developing countries (Ahzahar et al. 2011; Wasfy 2010). However, researchers in this field have paid less attention to studying *the types and causes of nonconformities and their actors (liable parties)* in the BCSC, especially during the construction phases. Moreover, nonconformities in the BCSC have not been studied in the more densely populated South Asian developing countries. There is thus an urgent need to seek answers to the questions of why, how, where, and by whom the non-conformance occurs in the BCSC throughout the various stages of the construction process. This is particularly the case in South Asian developing countries, where the skills and knowledge of construction workers can often be severely lacking.

In response, therefore, this study aims to identify the potential and critical nonconformities and their key actors in the BCSC. Accordingly, a literature review was conducted to pinpoint the research gap and identify potential nonconformities in the BCSC. Following this, an experts' panel was formed, and a series of focus group discussions arranged to identify the critical nonconformities frequently encountered in the building construction industry in the northeastern region of Bangladesh. Finally, three case studies were carried out for a comprehensive investigation of the nonconformity types, causes, and their actors in building construction in the same region. The specific contributions of the study are as follows:

- This study identifies the potential and critical nonconformities and their actors in separate phases of a building construction project. Thus, it provides a platform for building construction **practitioners and researchers** to understand the potential and critical nonconformities involved and their possible actors in the BCSC.
- This study contributes to the existing **body of knowledge by** presenting comprehensive case studies to provide a realistic insight of nonconformities in the step-by-step construction phases of building projects.

- **Policymakers** are informed about the reality of construction quality and understand the pathway of nonconformities in the BCSC. These findings will assist them in evaluating the capability of existing construction quality assurance policies and guide them to revise the policies if needed for assuring the expected level of construction quality.
- Overall, the outcomes of this study facilitate the achievement of the intended performance of a delivered building in its service period for the owner(s)/occupants by reducing rework and maintenance costs and saving lives from a possible building collapse.

The remainder of this paper details the building construction nonconformities in the literature, research methodology, focus group and case study findings, discussion of the critical causes of nonconformities in the BCSC, and specific recommendations for reducing the identified nonconformities. The concluding section summarizes the work, identifies its limitations, and provides recommendations for further study.

Building Construction Nonconformities in the Literature

The term 'nonconformity' covers a variety of terms such as defect, rework, and deviation from design and specification (Forcada et al. 2014). So far, there are many studies of rework or defect types, causations and costs, and their effects on overall project performances. Three terms – nonconformity, rework, and defects – are commonly used. Rework is carried out when the original work fails a conformity test (Love and Edwards 2004), while defective work is also nonconforming work for which rework is the only solution (Forcada et al. 2016). Hence, the relevant papers for this review are considered to be those most closely concerned with defects, nonconformities, rework, and associated areas in the BCSC. Table 1 lists the nonconformities and associated studies conducted in various parts of the world and available in the literature. These are labeled sequentially from 'substantial' to 'none' based on their level of nonconformity in the initiation to construction phases. The collected studies are also clustered according to their broader aims of research as the development of standard inspection and testing systems for construction nonconformities, understanding building defects and their relationship with various factors, effects of the implementation of a standard quality management system on building nonconformities, and causes of construction nonconformities. These studies are briefly discussed with these clustered as follows:

While researching construction nonconformities, some studies (Silvestre and De Brito 2011, Bortolini and Forcada 2018, MacArulla et al. 2013, Chiel 2014) were aimed at systematizing the classification system and inspection system for defects. In doing so for building façades in Portuguese building construction projects, Silvestre and De Brito (2011) found the causes of anomalies of ceramic tiling to be design and detailing, execution error, environmental actions, and changes in initial conditions. MacArulla et al. (2013) used a mixture of literature search, panel discussions and workshops, expert interviews, and case studies in identifying potential and critical defects in the Spanish construction industry to include affected functionality, inappropriate installation of materials/elements, broken/deteriorated materials or constructed building components, corrosion of used mild steel, levelness, flatness, and misalignment of building items. In a further study of the Spanish construction industry, Bortolini and Forcada's (2018) questionnaire survey identified the performance of aged buildings to be predominantly influenced by such structural defects as settlement/deformation, cracking, and water storage in concrete, with flooring and roofing also encountering cracking, water problems, detachment/breaking, and surface problems. Chiel (2014) identified 24 nonconformities influencing the performance of Dutch construction projects that could assist quality management during the initial stages of projects.

Table 1 History of studying building construction nonconformities in the literature

Citation	Study type	Clustering based on the broader aim	Methodology	Studied nonconformities in 'initiation to construction' phases	Location of the study	Economic status of the study location
Bortolini and Forcada (2018)	Development of technical inspection system for constructed buildings	Development of standard inspection and classification system for construction nonconformities	Questionnaire survey, case study	None	Spain	Developed
Chiel (2014)	Risk-based classification of nonconformities		Theoretical classification procedure development from literature review, testing the procedure with real projects of a construction company	To some extent	Netherlands	Developed
MacArulla et al. (2013)	Development of a defect classification system		Literature review, panel workshops, interviews, case study	To some extent	Spain	Developed
Silvestre and De Brito (2011)	Inspection system, classification, and causes of anomalies in ceramic tiling in building façades		Field observation, standardized inspection, statistical analysis	Very few	Portugal	Developed
Jonsson and Gunnelin (2019)	Defects (post-handover) reported by owners, and the relationship between building characteristics, developer's company size and defect type	Understanding building defects and their relationship with various factors	Questionnaire survey	None	Sweden	Developed
Forcada et al. (2016)	Analysing handover defects (mainly aesthetic and functional defects)		Data obtained from one of the largest Spanish construction company's database	Very few	Spain	Developed

Citation	Study type	Clustering based on the broader aim	Methodology	Studied nonconformities in 'initiation to construction' phases	Location of the study	Economic status of the study location
Forcada et al. (2014)	Analysing the defects by defected building element, defect location, and subcontractor		Data obtained from two large Spanish construction companies' databases	Very few	Spain	Developed
Forcada et al. (2012)	Relationship between building types and post-handover defects		Data obtained from post-handover client complaint forms	None	Spain	Developed
Sommerville (2007)	Understanding defects (mostly post-handover) and reworks		Literature review	Very few	UK	Developed
Liu (2003)	Public satisfaction, performance of public housing projects after ISO 9000 adaptation, and awareness/behavior of the contractors	Effects of implementation of standard quality management system on building nonconformities	Questionnaire, contractors' defect lists, interviews, progress measurement matrix	few	Hong Kong	Developed
Pheng and Wee's (2001)	Effect of ISO 9000 on the amount of defects		Case study (document analysis, interviews, and observations), conducted over two months of full-time attachment in a local construction company	few	Singapore	Developed
Tayeh et al. (2020)	Factors causing defects in the construction phase	Causes of construction nonconformities	Literature review, pilot study, questionnaire survey	Substantial	Gaza Strip	Developing
Ahzahar et al. (2011)	Contribution factors to building defect and failures		Questionnaire survey	To some extent	Malaysia	Developing

Citation	Study type	Clustering based on the broader aim	Methodology	Studied nonconformities in 'initiation to construction' phases	Location of the study	Economic status of the study location
Wasfy (2010)	Causes and impacts of reworks		Interviews, case study	Few	Saudi Arabia	Developing
Love and Edwards (2004)	Rework determinants (mostly organizational and managerial issues)		Questionnaire survey	Very few	Australia	Developed

Some studies are aimed at understanding and defining the phenomenon of defects and reworks (Sommerville 2007), and investigating their relationships with different characteristics of buildings and contractors, defect elements, defect location, etc. (Forcada et al. 2012, Forcada et al. 2014, Forcada et al. 2016, Jonsson and Gunnelin 2019). But these solely concentrate on defects normally identified in the *post-construction phases* (handover, post-handover, and maintenance) of buildings. For instance, Forcada et al. (2012) found building types, clients' involvement in construction, and capability of understanding defects to be closely associated with post-handover defects for Spanish flats and detached houses, with more defects occurring in flats. Using defects listed by MacArulla et al. (2013), Forcada et al. (2014) identified 3647 defects for 68 Spanish residential building projects, with those relating to structural stability and the installation of roofs and façades prevailing; most were associated with inappropriately installed materials/elements, surface appearance, affected functionality (for example, door scraping on the floor), missing work, tolerance error, and misalignment of building elements. Forcada et al.'s (2016) comparison of construction, handover, and post-handover housing defects found that structural (functional) defects mostly occurred during the construction phase and were resolved through inspection and rework, while non-structural (aesthetic) defects were usually rectified only at the occupants' request. Sommerville's (2007) literature review of newly constructed UK private house-buildings finds that 50% of defects originate in the design phase, 40% in on-site construction, and 10% are related to building materials – the most common design-related defects being poor technical detailing and specifications, and noncompliance with construction legislation. Based on the owners' judgments, Jonsson and Gunnelin (2019) find that newly constructed Swedish buildings have significant shortcomings in the functioning of windows and balconies, cracks in the façade and rainwater leakage, with defective construction directly influencing the buildings' performance and periodic maintenance.

The outcomes of construction companies' adopting the international standardized quality management system ISO 9000 were scrutinized by Pheng and Wee (2001) and Liu (2003). Pheng and Wee's (2001) study of building defects in Singapore found that they originate from technical causes (defective materials, design complexity, poor site management, overemphasizing cost over quality, and disregarding site conditions), human resource issues (lack of knowledge, training, skill, motivation, and care), and management subsystems (improper documentation, lack of communication, and poor change management). Considering these causes, they then developed a quality assurance framework following ISO 9001 for identifying and reducing design and construction-related building defects. Liu (2003) found the causes of defects in Hong Kong public housing projects to include design faults, poor workmanship, product failures, plumbing/drainage failures, and damage – these being assessed by the occupants' post-occupancy evaluation, housing managers' judgments of the performance of building products, and the contractors' acknowledgment and awareness of total quality management in response to the implementation of ISO 9000.

Finally, some studies (Ahzahar et al. 2011, Love and Edwards 2004, Tayeh et al. 2020, Wasfy 2010) focus mainly on finding the reasons that produce nonconformities in building construction phases. Moreover, unlike Love and Edwards (2004) who predominantly discuss organizational and managerial issues, the other three studies have a considerable amount of description of the nonconformities encountered in the construction phases. Ahzahar et al. (2011) found the major defects/failures in Malaysian building projects to be honeycombed concrete surfaces, rusting mild steel, damaged exterior surfaces, cracks in beams and floors, and defective roofs, with their causes including poor material quality, faulty construction, poor construction supervision, and design faults. Wasfy's (2010) study of Saudi Arabian building projects found that wrong materials supplied for façade and cladding, glassworks, electrical wiring, and plumbing fittings directly influenced rework frequency and cost, with deviations from the working drawings during civil work and improper work sequence (e.g., floor tiling before celling plastering and painting) also frequent causes of defective/nonconforming works. Tayeh et al.'s (2020) study of Gaza Strip residential building projects, on the other hand, found potential and critical defects to include poor quality materials, poor soil compaction or backfilling, insufficient reinforcement clear cover, corroded mild steel used for construction, damaged formwork, inadequate curing, and early removal of formwork, with the leading causes being the owner's negligence in arranging work inspections (absence of site engineer), lack of material testing, neglecting recommended corrective actions during job execution, and unqualified inspectors.

From the above, it is apparent that only a few studies are concerned with BCSC nonconformities (i.e., initiation to construction), while most studies focus on post-construction (handover, post-handover, or maintenance) defects. Further, the majority of studies were conducted in the context of European and other developed countries. To date, little attention has been paid the construction nonconformities in such a densely populated and high-growth South Asian countries as

Bangladesh (Ahmad 2015). Although there are some studies of the construction practices of developing territories (Malaysia, Saudi Arabia, Gaza Strip), they do not represent the characteristics of South Asian construction industries. Thus, there is a clear research gap for the in-depth study of nonconformities originating in the BCSC in South Asian countries. Such a study would not only have a direct influence on improving the performance of the buildings there in the post-handover and maintenance phases but is also likely to benefit other parts of the world as well.

Research Methodology

In this section, the types and causes of nonconformities are organized according to different construction phases following previous studies. These include initiation and planning, procurement (materials), construction of substructure (foundations) and super-structure (reinforced concrete construction (RCC) and masonry works), and finishing (plastering and painting works, plumbing fittings and fixtures, and electrical wearing) (Ahzahar et al. 2011; Forcada et al. 2016; Liu 2003; MacArulla et al. 2013; Pheng and Abeyegoonasekera 2001; Tayeh et al. 2020). The key actors (i.e., stakeholders) responsible for creating nonconformities in the BCSC are also determined. The nonconformities encountered in the commissioning/handover, post-handover, and operation and maintenance phases of a building are not considered. The qualitative modeling of the types, causes, associated project phases, and actors of nonconformities follows the approach of MacArulla et al. (2013) in comprising a **literature review, focus group discussion and workshop, and few case studies**. The literature review helps in organizing the potential causes of nonconformities and finding their actors (people or organizations). Several project documents were also collected from academia and professional construction and consultancy firms; these were studied to find the potential causes and types of nonconformities.

Some ongoing construction projects were visited to gather more information and collect necessary data concerning nonconformities in the BCSC. Once the list of the causes and types of nonconformities was developed, a panel of six domain experts was formed following Liu (2003) and Gutierrez and Hussein (2015) by randomly selecting academic and industry professionals. The experts' panel participated in a series of discussions and workshops to modify the listed BCSC nonconformities to suit the local construction context. This was followed by 180 days of fieldwork to observe a building construction project from layout to first-floor slab casting, with time-phased findings with project progress recorded in a notebook. Two other building projects were also studied to find nonconformities in the construction phases by physical observation of the constructed buildings and interviews with the building owners and their consultants.

Findings from the Focus Group Discussion

The list of nonconformities in separate phases of construction projects, their causes, and actors identified in the focus group discussion are presented in Table 2. These are explained in detail below.

Table 2: Types, causes, and actors of potential nonconformities in BCSC

Phase	Nonconformity	Cause	Actor					
			Owner/ Representative	Design Consultant	Supplier	Contractor/ Representative	Supervisor/ Manager	Subcontractor
Initiation and planning	Improper site survey/assessment	Low-cost priority, ignorance	x	x				
	Improper sub-soil investigation	Poor workmanship, ignorance, low-cost priority						x
	Drafting error	Unwillingness, carelessness, policy, time constraint, lack of supervision		x				
	Architectural design error	Knowledge gap, unwillingness, carelessness, lack of supervision		x				
	Structural design error	Knowledge gap, unwillingness, carelessness, lack of supervision		x			x	
	Plumbing design error	Knowledge gap, unwillingness, carelessness, lack of design supervision, policy		x			x	
	Electrical design error	Unwillingness, carelessness, time constraint		x			x	
	Lack of detailing	Unwillingness, carelessness, policy		x			x	
Materials procurement	Poor quality stones	Lack of knowledge or unwillingness of the owner, supply of poor quality materials	x		x			
	Poor quality of sand	Lack of knowledge of the owner, supply of poor quality materials	x		x			
	Poor quality of water (mud-mixed)	Water pollution by the workers' habits	x			x		
	Poor quality of cement	Storing, supplying, date expiration	x		x			
	Poor quality (corroded/failed to tensile test) of mild steel bar	Poor storage facility, poor quality of products	x		x			
	Poor quality of paint	Low-cost priority, poor quality of the product	x		x			
	Poor quality of frame and shutter of doors and windows	Low-cost priority, poor quality of the product	x		x			
Cons tructi	Inadequate soil compaction/consolidation	Poor workmanship, bad intention, low-cost priority						x

Phase	Nonconformity	Cause	Actor: Owner/ Representative	Design Consultant	Supplier	Contractor/ Representative	Supervisor/ Manager	Subcontractor
	Insufficient clear cover	Poor workmanship, lack of technical knowledge				x		
	Improper reinforcement (deviation from the provided design)	Poor workmanship, lack of technical knowledge, inability to read the design/drawing, poor supervision/ inspection				x	x	
	Insufficient lapping					x	x	
	Improper stirrup-spacing & alignment					x	x	
	Insufficient bond, hook, and development length					x	x	
	Improper mixing ratio	Poor workmanship, hurrying up to finish				x		
	Inadequate curing	Lack of technical knowledge, unattended/unwillingness to curing for prescribed days				x		
	Premature stressing on concrete	Lack of technical knowledge, pressure to start succeeding tasks				x		
	Insufficient compaction	Lack of technical knowledge, unattended/unwillingness to proper compaction				x		
	Incorrect shuttering alignment	Lack of technical knowledge and skills				x	x	
	Defective formwork	Intentional use of poor quality materials, lack of technical skills				x	x	
	Premature de-shuttering	Lack of technical knowledge, pressure to start succeeding tasks				x	x	
Construction (Superstructure)	Insufficient clear cover	Poor workmanship, lack of technical knowledge				x		
	Insufficient lapping	Poor workmanship, lack of technical knowledge, inability to read the design/drawing, poor supervision/ inspection				x	x	
	Improper stirrup-spacing & alignment					x	x	
	Insufficient bond, hook, and development length					x	x	
	Incorrect vertical alignment					x	x	
	Improper mixing ratio	Poor workmanship, hurrying up to finish				x		
	Inadequate curing	Lack of technical knowledge, unattended/unwillingn				x		

Phase	Nonconformity	Cause	Actor: Owner/ Representative	Design Consultant	Supplier	Contractor/ Representative	Supervisor/ Manager	Subcontractor
Construction (Finishing)		ess to curing for prescribed days						
	Premature stressing on concrete	Lack of technical knowledge, pressure to start succeeding tasks				x		
	Insufficient concrete compaction	Lack of technical knowledge, unattended/unwillingness to proper compaction				x		
	Incorrect shuttering alignment	Lack of technical knowledge and skills				x	x	
	Defective formwork	Intentional use of poor quality materials, lack of technical skills				x	x	
	Premature de-shuttering	Lack of technical knowledge, pressure to start succeeding tasks				x	x	
	Improper mortar ratio for masonry work	Poor workmanship						
	Excessive time spent on using cement mortar	Poor workmanship				x		
	Inadequate curing of brick walls	Unwillingness to water, lack of knowledge				x		
	Inadequate water soaking of bricks	Unwillingness to water, lack of knowledge				x		
	Incorrect vertical and horizontal alignment of the brick walls	Poor workmanship				x		
	Improper space provision for doors and windows	Poor workmanship				x		
	Improper alignment of doors and windows	Poor workmanship				x		x
	Damage of column during doors/windows fitting	Improper construction technique		x		x		
	Cracks in plaster	Lack of curing, improper mixing ratio of mortar, poor workmanship				x		
	Efflorescence of plaster/paint	Not removing the salinity from sand/bricks				x		
Total			8	8	6	35	18	3

Initiation and Planning

Nonconformities in any construction start from the initiation and planning phase. The panel identified some critical issues in this phase: for instance, inadequate site surveys; improper sub-soil investigation; lack of detailed drawings (shop drawings); and imperfect drawings/design for electrical, plumbing, and HVAC (heating, ventilation, and air-conditioning). Inadequate *site surveys* occur frequently and have a direct impact on the project objectives – making layout setting in the field particularly difficult. Even the entire architectural and structural design may need to be changed, which may increase project cost. *Inadequate sub-soil investigations* are a critical issue, but experienced engineers are not involved in their supervision in most cases, with soil-testing companies regarded as distrustful, unskilled, and unconscious of the need to obtain an appropriate standard penetration test value for every 1500 mm stage of a borehole. This has a serious consequence for foundation design, which very much relies on the soil report. The panel stated that this issue alone is a major cause of building failure. They recommended appointing a full-time, experienced engineer for supervising the sub-soil investigation.

The *lack of detailed working drawings* of a building project is also a frequent problem, as it delays construction, reduces construction productivity and quality, and misleads the construction of different building elements/members (Islam and Suhariadi 2018). Such other designs as electrical, plumbing, sanitary, and HVAC are frequently ignored, or incomplete drawings are provided, which has a direct impact on quality assurance. In particular, incorrect electrical work is currently responsible for severe life-threatening fires in buildings (Rahman Tishi and Islam 2019).

Procurement of Materials

There are particular nonconformities identified at this phase. For example, poor quality materials (i.e., stone, sand, cement, mild steel) are procured because of financial constraints, the owners' lack of knowledge about material quality, the unavailability of quality materials, transportation difficulties, and unreliable suppliers. In recent times in Bangladesh, the quality of available stone aggregate (20 mm downsize) is unsatisfactory in terms of size, shape, crushing strength, and gradation. Most local stone quarries in the northeastern region of Bangladesh are closed, forcing suppliers to depend mostly on imported stones with less strength according to the laboratory reports shared by the academic expert. Moreover, locally available cement varies in quality – randomly selected cement samples frequently fail to ensure design strength – while local sand is also of variable in quality, which can easily misguide first-time builders in particular.

Construction

The construction phase is the most challenging and critical, which needs to ensure the structure is constructed according to the drawings, design, and specifications. As Table 2 indicates, the worst 18 nonconformities are identified in this phase. The critical nonconformities associated with structural members are the uneven horizontal leveling and vertical alignment of structural members (footings, beams, columns, slabs, brick-walls, etc.); steel fabrication deviations from the provided design; insufficient concrete cover to protect steel; improper stirrup hook sizes, shapes, spacing, and alignment; and insufficiently lapped main bars. Some of the important issues related to formwork are defective formwork, misalignment and improper leveling, insufficient strength to take the design load, holes that allow cement mortar to leak out, uneven surfaces, early removal of formwork, and overloading on immature concrete members. The quality of concrete is also degraded due to such reasons as an improper mixing ratio, water-cement ratio, poor quality materials, insufficient mixing, and mud-mixed water used for concrete mixing. Concrete placement and consolidation techniques in reinforced concrete members are other sources of nonconformity. The unskilled laborers usually tasked with placing concrete may release concrete from an elevated height, which segregates the concrete. Although a vibrator machine is used, the correct method of vibrating is not used, which further accelerates concrete segregation and provides insufficient consolidation.

Of these nonconformities, early removal of formwork from reinforced concrete members is a severe problem: in many cases, the formwork is released from the column, beam, or slab-bottom earlier than the specified curing period. For example, after casting a column, at least 72 hours needs to be allowed to release the formwork. However, most Bangladeshi contractors allow a maximum of 36 hours instead; this creates self-weight loading on an immature concrete member, which accelerates cracks in the concrete, and in some cases causes structural failure even during the construction period. Overloading an immature construction member is also sometimes observed. For example, a floor slab heavily loaded with cement bags, sands, and stones or some construction equipment after 2 to 3 days of concrete curing. The experts also identified insufficient curing of concrete to be a critical nonconformity, producing sub-standard compressive strength. Such poor-quality concrete is frequently used with high-strength steel (500W MS bar), creating an imbalance between the stress-strain ratio of steel and concrete that can subsequently result in the failure of a RCC member.

The experts furthermore mentioned some nonconformities of masonry work and finishing tasks, with incorrect mortar ratios (cement-sand-water) and excessive time lapses for using mortar, for example. Although the initial setting time of locally available Portland composite cement is usually 45 minutes, many masons are accustomed to working with the mortar even throughout an entire day. Also, in most cases, little or no curing is allowed for a brick wall, with the plastering carried out immediately after its completion, which makes the wall too weak to carry its design load. The salinity of the bricks is not removed, as the bricks are not soaked in water before being used. Architectural detailing is not followed to provide the spaces specified for door and window fittings, and doors and windows are commonly misaligned. Cracks in plaster occur frequently, because the design guide for maintaining the correct cement-sand mix ratio for mortar preparation is not followed, and the curing time of plaster on any masonry work or surface is often too short. An extremely severe outcome in plaster or painting work is efflorescence, particularly where there is a chance of water absorption.

Actors of BCSC Nonconformities

Fig. 1 shows the percentage contribution of nonconformities produced by each of the key actors in different construction phases, indicating that contractors produce the most nonconformities, followed by the supervisory group. However, supervisory issues do not always mean that project managers/supervisors are incapable of managing the quality of a project. Instead, owners often simply do not appoint a site supervisor or project manager. During the focus group discussion, the experts mentioned that, due to their unawareness or lack of knowledge (or merely a cost saving device), owners often did not appoint a site supervisor or project manager to oversee the construction quality of contractors at job-sites, trusting their appointed contractors' supervision instead. The absence of a site supervisor for a project's quality control was also found critical in the case study projects (discussed in the following case studies). This issue is also identified as a major cause of construction defects or nonconformities in other parts of the world (e.g., Ahzahar et al. 2011; Pheng and Wee 2001; Tayeh et al. 2020).

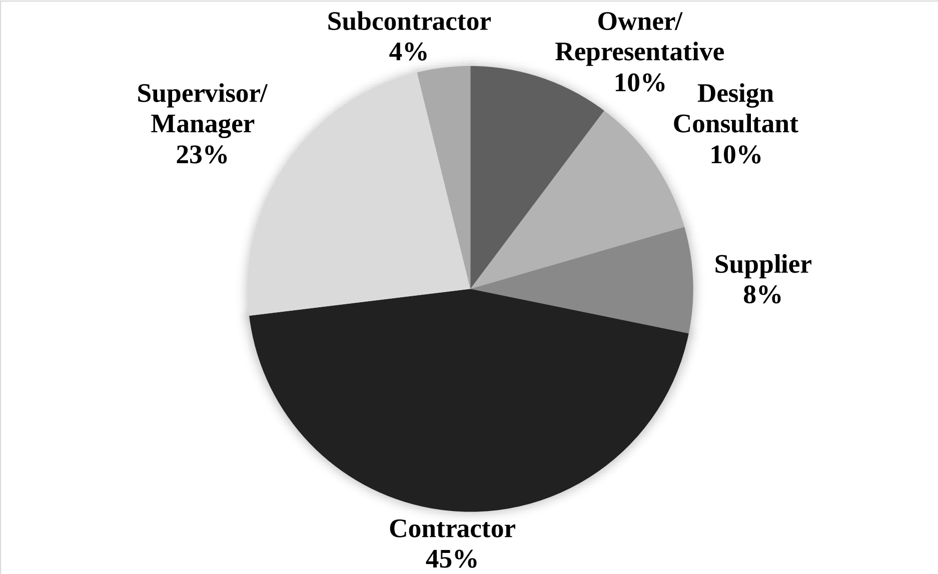

Fig. 1. Contribution (%) of nonconformities produced by the actors

Nonconformities from Case Study-1

The case study concerns a building construction project located in a peri-urban area in the northeastern region of Bangladesh. The floor area of the building is 121.89 m^2. It is a six-story residential building having a ground floor garage, with other stories typically consisting of a single apartment per floor. The project owner selected the Design-Bid-Build (DBB) method for the project's procurement. The project's consulting firm is well-reputed and well-recognized in the northeastern region of Bangladesh. The firm is also enlisted by the Sylhet (a major city in the northeastern region of Bangladesh) Corporation. Most consultants associated with the project hold a Ph.D. or at least a B.Sc. (Engineering) degree in their respective fields. They also have full membership of the IEB (Institute of Engineers, Bangladesh), and with 10 to 20 years of experience in professional fields. The contractor was selected based on the limited tendering method. The owner first invited tenders from some contractors selected based on their experience and performance with locally constructed buildings. All the contractors are also enlisted and certified by the Sylhet city corporation. The tender evaluation team, consisted of the owner and the consultants, evaluated the tenders. The contractors were also invited for an interview. Once the contractor was selected, a well-written contract document was signed by both parties (i.e., owner and contractor) with the consultants' as witnesses. As there were some socio-political issues associated with the jobsite, a local leader also signed the contract document as a witness.

The site is free from such site-related constraints as limited space, traffic load, adjacent structures, and time zone restrictions (e.g., no work can be done between 7pm to 7am) for construction work. The construction works were supervised continuously by a site engineer with the top-level supervision of consultants during the period from October 2019 to March 2020. The nonconformities encountered in this period were recorded, dividing the project work into such major milestones as initiation and planning, materials procurement, and construction. The construction nonconformities were recorded by subdividing the structure into the major components of foundation, columns, grade beams and floor beams, ground floor slab, masonry works, and finishing tasks. The following subsections briefly describe the nonconformities found and their causes and actors involved.

Initiation and Planning

One of the researchers observed the soil testing process. This involved a manual in-situ standard penetration test (SPT) technique. During that process, the laborers were often careless in dropping the donut hammer from the specified height (750 mm), which had a direct impact on the field-SPT values. They also tended not to drive the full 450 mm of the sample collection tube (i.e., Shelby tube): rather, after driving 150 to 300 mm, they measured the field-SPT for the next 150 mm penetration by guesswork, particularly in hard soils. Moreover, they tended to collect a sample at 3000 mm intervals instead of prescribed 1500 mm. The on-site engineer discussed this issue with the foreman and advised him to use the correct approach. However, in the case of a hard layer, they still did not drive the tube the full 450 mm and continued to be careless of the height when dropping the donut hammer. Furthermore, when pulling the hammer, it sometimes crossed the reference height or fell down below that height. Thus, the correct SPT values for each borehole were not provided to the geotechnical engineer for testing and reporting. The on-site engineer was aware of the problem and informed the owner. However, the owner was not convinced enough to change the soil testing contractor. The owner thought this is a normal issue that simply changing the contractor would not necessarily provide a solution, which we had to accept. The on-site engineer must know the sources of non-conformities during soil testing and try to minimize them accordingly by managing the contractor and its field workers.

During this phase, the design consultant failed to provide the detailed working drawings needed, while the site engineer also failed to read the drawings and specifications to correctly guide the foreman. This had a direct effect on the next phases, which are discussed in the following subsections.

Procurement of Materials

In this phase, the owner's unplanned act of purchasing and storing materials (and dealing with the suppliers) was a critical issue. As the owner was a first time builder and no professional project manager was hired, he contacted the suppliers directly for purchasing construction materials (sand, stone, and cement) immediately before they were needed, leaving no time for justifying or testing their quality. The owner also frequently changed suppliers to find better quality suppliers, which sometimes impelled him to receive inadequate quality materials with a no-return policy.

Sometimes, suppliers showed the owner good quality samples but delivered inadequate quality materials. They also supplied some materials of less weight than contracted. Thus, the suppliers were identified as distrustful in both quality and measurement.

After pile-driving, the construction work was paused for a month. During this period, the owner established the suppliers' quality by visiting stone crushing facilities. He found this not to be a discrete matter, but it is the norm for suppliers to supply less stones than the ordered quantity, and to provide a good quality sample but poor quality supply. In this market environment, finding a trustful stone supplier is critical. The on-site engineer suggested that the owner should buy stone directly from the stone crushing plant and arrange trustful transport for supplying the stones to the site without contacting the professional suppliers. However, this was not possible for this busy owner. Later, the owner contacted multiple suppliers and bought stones from them subject to an on-site measurement and quality check. This policy significantly improved the quality of stones supplied, but slight improvement was noticed in contracted weight, as all those contracted for stone supply provided less than agreed. In such cases, the owner could have cancelled the purchase order, imposed a financial penalty on the suppliers, or taken legal action (Engebø et al. 2017; Minchin et al. 2017; Naderpajouh et al. 2015). In the event, he did not take any of these actions but instead frequently changed the suppliers because that they usually provide good quality materials in their first few orders.

Construction

The site layout was set at the beginning of the construction work, during which time the foreman identified a column displaced by about 150 mm in the grade beam setting; this resulted in the corresponding grade beam deviating from the drawing by passing just outside the column –

creating an eccentric load on the column. According to the foreman, this was not correctly checked at the time.

Numerous problems arose during the steel fabrication for preparing pile cases. For instance, there were insufficient and defective welds around the pile case, the 16 mm diameter mild-steel main pile case bars were not straight, and the laps of the main bars and spiral stirrups were shorter than specified. Initially, the spacing between the main bars varied along the periphery of the pile case, and the spacing of the stirrups did not comply with the design specification. All these nonconformities occurred because of the lack of inspection by the site engineer, the foreman's lack of knowledge, poor workmanship, and the tendency of both skilled and unskilled workers to finish the work as quickly as possible providing the site engineer with a little opportunity to make appropriate inspections.

The concrete cover protecting the mild steel of the pile was to be provided by cylindrical concrete blocks. However, the blocks were 100 mm instead of 150 mm diameter, their thickness less than the specification, they were immature, could not carry enough load, and broke during pile cage driving. After driving some pile cages in the boreholes, the site engineer noticed the blocks were at 3000 mm centers instead of the specified 1500 mm – although the drafter was liable for this nonconformity by not providing a detailed working drawing showing the centers. Mostly, muddy water, sand, and stones mixed with mud were used for concrete mixing; the water-cement ratio was very high; the mixing ratio of cement, sand, and stones was frequently inaccurate; and the funnel, bucket, and tremie pipe for concrete casting were mud-mixed: all of which had a direct impact on reducing the concrete's compressive strength. Although the concrete workers took clean water from an underground water supply source, their habit of dropping muddy buckets, washing their muddy hands and bodies frequently in the water container, etc., made the water unclean. Although the site engineer instructed them to use clean water, clean sand and stones, and maintain the volumetric sand-stone-cement ratio, and water-cement ratio prescribed by the design engineer, they frequently transgressed his instructions, as they were prone to doing at other sites and not listening to the engineer's instructions. The owner raised this issue with the piling contractor who employed the concrete workers, but no significant change was made. Although the owner then had the opportunity to terminate the contract with the piling contractor, he did not do so as the owner considered that such a change would not produce a better outcome.

After piling, the as-built drawing showed that some piles were displaced from their centers, which created a substantial structural problem for positioning the corresponding pile caps and columns. Following advice from the structural engineer, the columns were shifted from their designated positions, while still maintaining a tolerable limit. As the pile cap and column were cast monolithically, it was important to check the reinforcement detailing of the column and the pile cap carefully. However, both the foreman and contractor had difficulty reading the reinforcement detailing in the drawing: they could not understand the size, hook length, and spacing of the stirrups in the design documents. The site engineer also did not correctly inspect the reinforcement fabrications of the pile caps and columns. At the very end of placing concrete into a pile cap, the site engineer found the stirrup spacing and positioning to be incorrect, and the concrete cover was insufficient for many pile caps. None of these were rectified due to rework difficulties.

The quality of concrete for the pile cap was better than the pile casting. However, the pile caps had particular problems with the stones supplied not being sufficiently well-graded or properly washed. The water-cement ratio in the concrete was high enough to fail in the slump test, the vibrator was frequently not used during concrete consolidation, and there was a high chance of insufficient concrete consolidation in the pile cap and column joint as the gaps between the mild steel bars were too small to pass the stones. The number of main bars in a particular column was more than the design guide, and the length (90-degree hook) of the main bars of the column was undersized.

Some of these structural nonconformities were rectified through rework, although many remained untouched.

Several frequent and severe issues were identified regarding the formwork for reinforced concrete members, such as vertical and horizontal misalignments, gaps in the formwork joints, and inaccuracies in the diagonal check of formwork boards. Due to a severe concrete leakage, one of the columns' kickers was broken and needed to be reworked afterward. Gaps in the contraction of the formwork board and kicker, a joint between two formwork boards, and even some cracks in the formwork boards were discovered during column casting, causing a significant amount of concrete leakage from the formwork. The site engineer advised the contractor to change the formwork boards and to take effective action to seal the holes, but no significant change was made. Some holes in the steel formwork board of the column were 12 mm or more diameter in size. Although they understood that the concrete would seep through these holes, the contractor and foreman did not consider the holes a problem during concrete placement and surprisingly did not seal them.

The ironworker repeatedly deviated from the design guidelines and building codes in the size and shape of the stirrups, hook size, stirrup bends, and distance between the stirrups along the vertical length of the column/beam. Therefore, the site engineer showed him a video of the stirrups for column and beam being made, which resulted in some improvements in stirrup making, yet some problems continued. For instance, the hook length of the stirrup was excessively more than the design guide. The lack of knowledge and skills of the ironworkers was identified as the main cause of these nonconformities.

After the plinth level, the researchers identified a reduction in minimum concrete cover for almost all the columns. Although design specification prescribes the clear cover of a column above the plinth level to be 37.5 mm, after the fitting of the formwork board, the columns had clear covers of only 25 mm to 31.75 mm. This problem occurred due to the slight displacements and misalignments of the columns at the foundation level. The foreman was instructed to reset the formwork board to ensure the minimum clear cover for the columns. The size of some columns was found to be insufficient from a constructability point of view. This was recognized during placement of the concrete into the columns, as the gaps between the steel bars were too small to insert the vibrator nozzle (37 mm dia.). Thus, there was concrete insufficient consolidation for the columns, with a great chance of voids in the concrete. Numerous honeycombs were later found in some concrete columns.

The extra top and bottom bars of the grade beam were undersized, as the foreman did not understand the drawing detail of the bar cut-off. The site engineer noticed this issue and ordered an accurate bar size cut-off for the extra top and bottom. The grade beams were cast on uncompacted soil instead of a formwork board, increasing the likelihood of soil settlement below the grade beam, which could subsequently create loading on the immature beam (i.e., immediately after concrete casting) due to self-weight. There were too many gaps in the joints of the formwork boards at the beam-column joints and concrete seeped out during the vibration process. At the very end of the casting, the casting depth of the beam was found to be 12 mm less than the design depth because the foreman mistook the depth calculation from the reference point used. Moreover, the concrete cover of the grade beam was 37.5 mm instead of the 75 mm prescribed in the design specification. The site engineer notified this to the contractor and foreman to ensure the correct minimum cover, but nothing was changed. Some grade beams were significantly horizontally and vertically misaligned and, after a thorough level check, the foreman was instructed to rectify the alignment issue. Some corrections were made but many others remained unchanged. The vertical misalignments of the grade beam directly influenced the variations in the casting depth of the grade beam. During the grade beam concrete placement, the mixture machine temporarily failed, and the concrete was placed after its initial setting time. The mixture machine driver was also unskilled and a first-time user. He did not understand the water-cement ratio of the concrete and added extra water – sharply reducing the strength of the concrete.

The foreman fabricated the steel and placed the floor beam and slab concrete monolithically. Some variations in the slab casting depth were found, and the foreman was instructed to rectify them. The position of some openings for electric and sanitary fittings created structural problems in the beam and slab. The structural engineer provided guidelines for changing or adjusting the opening positions, but the contractor ignored them. The slab thickness was found to be at least 12 mm less than the design depth at the four corners of the slab. The foreman was instructed to correct this, and he spent some hours fixing a corner, leaving the other corners unchanged. While the design guide prescribed corner reinforcement where both ends of the slab were discontinuous, the foreman could not properly fabricate the corner reinforcement, making a significant error. The slab's bars were positioned in the wrong layers in the beam-supported zone, which significantly reduced the spacing of the bars in the top layer of the slab. The crank depth of the main bars at the beam-supported zone was insufficient to ensure the correct slab-thickness at that zone. Finally, the mild steel bars were corroded as they were procured at the start of the project and stored in the open over the six-month period of continuous fabrication of different structural elements.

The researchers discovered some significant problems during the brick-working. The bricks were not soaked and washed properly for desalination and water absorption. Lacking knowledge of its setting time and impact on the strength of the wall, the contractor/foreman mixed mortar (cement-sand-water) for the masonry work and used it for almost the whole day – usually adding more sand and water to increase workability. There was a considerable variation in the size and shape of the purchased bricks compared to a standard brick. The walls were both vertically and horizontally misaligned in some cases. There was insufficient curing time for the mortar, the wall being plastered immediately after its construction. The plaster was also not watered enough for curing. Excessively thick cement mortar (37.5 mm or more instead of 12 mm as per the specification) was used for the bricks and the wall-column joints, increasing the shrinkage of the mortar and the likelihood of the wall separating from the column.

Finally, the sand bed was poorly compacted during backfilling under the garage area on the ground floor, which could eventually cause the floor slab to crack under load or settlement. No damp proof membrane was used in the ground floor slab, which could also be the eventual cause of dampness.

Overall, numerous nonconformities arose throughout the observed construction period. The more significant nonconformities in structural integrity including displacements of pile positions, failure to ensure minimum concrete cover, gaps in formwork joints, poor quality concrete, misalignment of structural members, incorrect hook sizes and stirrup spacing, and unauthorized opening positions in the slab for electric and sanitary fittings.

Nonconformities from Case Study-2

Case study-2 is a 5-story residential building project located in an urban area of the northeastern region in Bangladesh. The building area is 213.87 m^2 per floor. The project owner selected the Design-Bid-Build (DBB) method for the project’s procurement. The ground floor is occupied by the garage, with the other stories typically consisting of two separate apartments per floor. The contractor was selected using the same approach as the first case study project. The construction period of this project was November 2019 to May 2020. By the end of this period, the civil works of the first three floors of the project had been completed. The soil was investigated without the presence of an on-site engineer. Thus, the quality of the report was unknown. The consultant trusted the soil test report and designed the building’s foundation without any further soil testing.

The building's layout was checked by an engineer of the consulting firm, who found some serious errors, which were rectified accordingly before starting the foundation work. Although a pile foundation was selected for the building, the owner did not call or appoint any on-site engineer to control the building's construction quality. He did not even call or appoint an engineer to supervise the superstructure construction quality. The researchers interviewed the building owner about the basic specific requirements (see the Appendix) to justify the construction quality. The interview findings are briefly presented as follows:

The owner did not know about such technical issues as the concrete mix ratio (i.e., cement: sand: stone) or the water-cement ratio for preparing the concrete, nor asked the consultant to ensure the correct concrete mixing ratio. Referring to the experts' opinions discussed in the 'Focus Group Discussion' section, it can be stated that the contractor was reluctant to ensure the correct concrete mixing ratio and water-cement ratio during concrete preparation as no one was overseeing the work. The owner also said that the contractor released the column formwork after just 24 hours instead of the 72 hours provided in the construction specification. Our field observations found honeycombs in many places of the beams, columns, and slabs. Usually, honeycombs are produced due to the lack of vibration/consolidation, bleeding of the cement slurry, and a poor water-cement ratio. Moreover, the owner was not concerned about the proper curing of the concrete elements. Thus, insufficient curing was identified as another critical nonconformity of this project. Stirrups hooks and lapping lengths of the main bars of the beams and column were other critical issues that were not sufficiently considered during the steel fabrication for the major structural elements (i.e., columns, beams, slabs, etc.). Our site observations also identified an insufficient clear concrete cover for the columns in particular.

Nonconformities from Case Study-3

Case study-3 involves a five-story building located in a peri-urban area of a city in the northeastern region of Bangladesh. The building area is 361.2 m^2 per floor, where the ground floor is devoted to garaging, the 1st to 3rd floors consist of three apartments per floor, and the 4th floor is a residential hotel. The project had similar procurement methods and specific requirements as the other case study projects. Unlike case study 1, the owner personally selected the contractor. In this case, the contractor's previous experience with neighboring projects was the main criterion for awarding the project. The study is of the construction work from October 2019 to May 2020. By the end of this period, the civil works up to the 4th floor had been completed. Similar to case study 2, the owner did not appoint a supervising engineer to control the construction quality or soil testing throughout the construction period. No further soil testing was done to check the validity or accuracy of the tests performed. During the construction phase, the owner identified a major construction quality issue in recognizing that each pile construction involved over 30% fewer bags of cement than estimated. He immediately spoke to the estimator/consultant team, which sent an experienced engineer to investigate the problem. It was identified that the concrete workers did not understand the concrete mix ratio: they were providing more stone and sand than the designed ratio. As no field test or laboratory test of the concrete was performed, the design consultants advised that this nonconformity could have sharply reduced the concrete quality of the previously constructed piles. Surprisingly, the owner did not appoint an on-site supervision engineer even after this incident. From the consultation with the owner, the researchers identified that the prescribed concrete curing period, hooks, and development lengths of the main bars of the beams and columns, stirrups hooks were not followed correctly during construction, as well as the minimum clear concrete cover and allowable time for releasing formwork of any structural elements. The formwork for each column was released after just 24 hours instead of the prescribed

72 hours. The slab formwork was released after only 15 days instead of 28 days. Construction work began on the slab after just three days of concrete placement into the formwork, which created a large loading on the immature slab by its self-weight, material storage, and workers' movement on it.

Discussion and Recommendations

Some of the nonconformities identified by the present study, bold-Italic texts in Table 3, are reported for the first time. The most important of these are incorrect soil investigation, variations in individual footing depths, incorrect main bar and hook lengths in different structural elements, insufficient laps, improper spacing and alignment of stirrups, problems in footing/pile cap horizontal/vertical leveling, and placement/holes in the formwork.

Considering all the studies, the most common types of nonconformities are inferior quality materials, misalignment of brick walls, and deviations from the design/drawings. Previous studies in various parts of the world have identified numerous nonconformities that are similar to our findings. Both Pheng and Wee (2001) and Liu (2003), for example, state that the lack of shop drawings or design detailing are critical nonconformities in the design phase, also greatly emphasized by our experts as a problem at almost every site during building construction.

Previous work with the most similar results to the present study are MacArulla et al.'s (2013) defects classification system for the Spanish housing sector and Tayeh et al.'s (2020) factors affecting the occurrence of defects in residential buildings in Gaza Strip. In particular, the former's important nonconformities akin to our findings are the deviation of the foundation/column line from the setting layout, vertical and horizontal misalignments of different structural elements, improper installation of reinforcement in concrete slabs, location of joints in the slab with other fixtures (electrical and/or plumbing), and incorrect concrete mixing ratios. For the latter, the most significant matching issues are insufficient concrete cover of reinforcement, inaccurate concrete mixing ratios, and insufficient curing of RCC members.

Table 3 Comparison of the identified nonconformities with previous studies

No.	Nonconformity identified	Previous studies					
		Pheng and Wee (2001)	Liu (2003)	Wasfy (2010)	Ahzahar et al. (2011)	MacArulla et al. (2013)	Tayeh et al. (2020)
1	Improper site survey/assessment	x					x
2	***Improper soil investigation***						
3	Drafting errors			x			
4	Architectural design errors				x		
5	Structural design errors				x		
6	Lack of detailing for any drawing/design	x	x				
7	Lack of soil compaction/consolidation						
8	Deviation of pile/footing centers from the layout position					x	
9	***Variation in individual footing depths***						
10	Insufficient concrete cover protecting mild-steel reinforcement						x
11	Insufficient/absence of damp proofing (dampness)				x		
12	Displacement of the column center from footing/pile cap due to errors in layout setting					x	
13	Improper reinforcement (incorrect size) due deviation from the design			x		x	
14	***Improper hook and development length of reinforcing bars in fabrication***						
15	***Problems in horizontal/vertical leveling of footing/pile caps***						
16	***Insufficient lapping of reinforcement bars during fabrication***						
17	***Incorrect spacing and alignment of stirrups***						
18	***Undersized/oversized stirrup-hooks***						
19	Vertical/horizontal misalignment of columns					x	
20	***Insufficient size of extra top or bottom bar in the beam***						
21	Horizontal misalignment of the beam					x	

No.	Nonconformity identified	Previous studies					
		Pheng and Wee (2001)	Liu (2003)	Wasfy (2010)	Ahzahar et al. (2011)	MacArulla et al. (2013)	Tayeh et al. (2020)
22	Insufficient length of extra top-bars from the point of crank (l/4, l/3) to the support zone (slab)						
23	Slab bars in the wrong layer					x	
24	***Crank height of main bars less than designed height in slab***						
25	Improper leveling/alignment of slab					x	
26	Improper electrical piping creating structural problem in slab					x	
27	Improper openings for sanitary/water supply piping in slab					x	
28	Honeycombs in reinforced concrete elements				x	x	
29	***Mud/dust mixed sand used without netting***						
30	***Mud/dust mixed stone used for concrete mixing***						
31	***Mud-mixed water used for concrete mixing***						
32	Inaccurate (i.e., deviation from the specification) mixing ratio (cement-sand-stone)					x	x
33	Inaccurate water-cement ratio (excessive water use)						x
34	Insufficient curing of RCC elements						x
35	Premature stressing/overloading of immature concrete during construction						x
36	Insufficient concrete compaction/vibration						x
37	***Misalignment of shuttering (vertical and horizontal)***						
38	Defective formwork						x
39	Premature de-shuttering (early formwork removal)						x
40	***Pours/holes in the shutter/formwork***						
41	***Gap in shutter joints (leakage of cement mortar)***						
42	Use of corroded reinforcement	x			x	x	x
43	Poor quality sand (not well-graded, deviating from specification)	x			x		x
44	Poor quality of stone (having dead stones or not well-graded)	x			x		x
45	Poor quality bricks	x			x		x
46	Brick/block walls' misalignment or deviation from drawings/design			x	x	x	x
47	***Incorrect mortar ratio for masonry work***						
48	***Excessive time using cement mortar (day-long use)***						

No.	Nonconformity identified	Previous studies					
		Pheng and Wee (2001)	Liu (2003)	Wasfy (2010)	Ahzahar et al. (2011)	MacArulla et al. (2013)	Tayeh et al. (2020)
49	Inadequate curing of brickwork					x	
50	Misalignment of doors and windows					x	
51	Damage of columns during fitting doors/windows		x				
52	Cracks in plaster/concrete					x	
53	Efflorescence of plaster/paint					x	

The following five main recommendations are made.

(1) ***Improve work inspection/site supervision.*** The absence of a site engineer or lack of supervision of construction work is a major reason for nonconformities in BCSC. The experts confirmed that most private building owners do not appreciate the advantages of appointing full-time site supervisors to help assure construction quality and overall site-management. Instead, they mostly arrange a part-time or on-call inspection for some structural elements once the reinforcement is fabricated and formwork is ready for concrete placement. In these circumstances, there is little opportunity for an engineer to rectify any nonconformities in soil testing, and steel fabrication (such as stirrup alignment, spacing, hook sizes, stirrup bends, and vertical alignment of main bars). This is despite the Bangladesh regulatory authority mandating the owner to have an approved supervisory agreement with the engineer(s)/consulting firm(s), whereas in reality, they mostly trust the contractor's experience and skills instead – a situation corresponding with such previous studies as Pheng and Wee (2001), Ahzahar et al. (2011), and Tayeh et al. (2020) for example, who found poor site practices and supervision to be a critical cause of defects. Based on these findings, it is recommended that the owner appoint full-time onsite supervision engineer from soil testing to construction commission. The consulting firms

need to report to the regulatory authority if their clients (i.e., building owners) did not arrange for full-time site supervision of their buildings. Also recommended is that the regulatory authority checks the site supervision records and the fitness of each building before issuing a certificate of occupancy. If they cannot locate any full-time site supervision records, it would be effective for the site-supervision awareness-building of owners to refuse to issue a certificate of occupancy, make a significant financial penalty, or demolish the building.

(2) ***Increase material inspections and testing.*** Inexperienced owners are reluctant to supply good quality materials, as many of are unfamiliar with material quality, testing, and inspection systems, usually relying on the contractors' suppliers. The use of good quality stones is crucial in maintaining the design-specified quality, while such other materials as sand, cement, and mild-steel bars can be easily managed with good quality storage facilities, and frequent laboratory and field tests. It is important to increase the inspection and testing (i.e., both field and laboratory tests) of materials for identifying the pathway of counterfeit materials for their early detection within the supply chain (Minchin et al. 2017; Naderpajouh et al. 2015). An experienced fulltime site engineer can ensure these inspections and testing of materials take place in their supply chain. Moreover, the owners could incur a financial penalty and/or cancel the purchase order, and be made to seek assistance of the legal authority to follow local construction and procurement law if they receive any counterfeit materials or products during construction (Minchin et al. 2017). However, the suppliers' money-making policy would likely prevail; thus, controlling such counterfeiting requires the joint actions of the owners, contractors, policymakers, and law-enforcing authority (Engebø et al. 2017; Minchin et al. 2017; Naderpajouh et al. 2015).

(3) ***Increase the involvement of a design consultant during construction.*** The case study projects clearly show that the owners ignored the need for full-time site-supervision involving the design-consultants. The involvement of a design consultant in construction is significant for

interpreting or explaining the design/drawing to the contractor's representative(s) to ensure the specific project requirements are achieved, and manage any structural/non-structural changes encountered (e.g., displacement of pile positions encountered in the case study-1). Although there are rules set by the regulatory authority for involving a consultant in construction supervision, the owners rarely heed them. Hence, the owners are recommended to engage a design consultant throughout the construction period to ensure the project requirements are met. The Bangladesh construction regulatory authority also needs to take necessary actions to implement such rules.

(4) ***Provide more education/training to improve workmanship and read/interpret drawing/design detailing.*** As Liu (2003), Ahzahar et al. (2011), and Tayeh et al. (2020) point out, poor workmanship is another critical cause of nonconformities. This is partly due to a lack of knowledge and skills, with no training or education a significant factor (Pheng and Wee 2001; Tayeh et al. 2020) affecting the ability to read the drawings/design, poor workmanship, and a tendency to hurry finishing work. Thus, it is recommended that the respective authorities provide institutionalizing vocational schools/training centers for developing the knowledge and skills of the construction foremen/contractors for improving workmanship and educating reading/interpreting drawing/design detailing. The authority should insist on a foreman/contractor having a training certificate as a prerequisite to receiving a construction-work license.

(5) ***Consultants obliged to provide detailed drawings.*** Similar to the findings of Liu (2003) and Sommerville (2007), this study found the lack of detailed drawings to be another compelling cause of nonconformities in construction phases. The consultants are recommended to provide detailed drawings for each of the work items (i.e., civil work, electrical, mechanical, etc.). These drawings need to be handed over to the owner before bidding and contractor selection so that the contractors can be well-informed of the work to be performed. Taken in conjunction

with (4) above, this improvement should bring about a marked improvement in Bangladesh construction work.

Conclusions

This study investigated the nonconformities in the Bangladesh building construction supply chain from its initiation to completion phases. The potential nonconformities were retrieved firstly from the relevant literature, followed by a focus group discussion and workshops. Afterward, three case projects were studied to obtain in-depth knowledge of nonconformities in separate phases of BCSC. The potential and critical nonconformities, their causes, and actors were identified. The experts identified the most severe nonconformities to be improper soil investigation, poor quality materials, poor quality concrete due to a variety of reasons, insufficient or no concrete curing, defective formwork, and the early removal of formwork. In the case study projects, the most critical nonconformities were improper soil investigations; problems in layout setting (displacement of column positions); inadequate concrete cover; misalignment of structural elements; defective formwork; early removal of formwork; poor quality concrete; wrong size, shape, and spacing of stirrups; and misplaced openings in the RCC slab. Five main recommendations were made: to improve work inspection/site supervision, increase material inspections and testing, increase the involvement of a design consultant during construction, provide more education/training to improve workmanship and read/interpret drawing/design detailing, and oblige consultants to provide detailed drawings.

A specific contribution of the study is to provide a platform for building construction **practitioners and researchers** in developing countries to understand potential and critical nonconformities and their possible sources in the BCSC. These findings pinpoint the bottlenecks and inadequacies in managing nonconformities in current construction management practices and assist in searching for possible technical and managerial solutions for delivering sustainable building constructions. It also contributes to the existing **body of knowledge** by comprehensive case studies to provide practical insights into nonconformities in step-by-step phases of a building project. It informs **policymakers** of the reality of construction quality in the field, helps understand the pathway of nonconformities, and with findings that will subsequently assist them in evaluating existing construction quality assurance policies and their revision in assuring the expected construction quality. Overall, the study's outcomes will facilitate in achieving the intended performance of a delivered building in its service life for the owner(s)/occupants by helping reduce defective construction work (Brogan et al. 2018; Jonsson and Gunnelin 2019), rework and maintenance costs, and assist in ensuring construction safety related to defective work. However, this study will not help improve the quality of the construction works unless the outcomes are taken seriously into account.

The study is limited by not prioritizing nonconformities based on quantitative assessment. Further studies are needed to rectify this for informed decision making. Moreover, the case study was restricted to a few phases of three medium-sized projects, with experts mostly from private organizations. Further study is therefore needed of large-scale housing projects or public-funded building projects. Studies identifying the root-causes of nonconformities in such other phases of building projects as commissioning/handover, post-handover, and operation and maintenance can also be conducted in the future. This study did not investigate the impact of different procurement methods on producing/controlling construction nonconformities. Thus, further study can also be conducted of the selection of procurement methods and their influence on construction performance in privately funded buildings/infrastructures. Although there is Bangladesh construction and engineering law for controlling construction quality, this study also did not thoroughly investigate how these laws are implemented to control nonconformities. A study of 'practicing Bangladesh construction law by the major stakeholders involved and its impact on project quality performance' is also recommended.

Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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References

Abdelsalam, H. M. E., and Gad, M. M. (2009). "Cost of quality in Dubai: An analytical case study of residential construction projects." *International Journal of Project Management*, 27(5), 501–511.

Ahmad, S. (2015). "Housing demand and housing policy in urban Bangladesh." *Urban Studies*, 52(4), 738–755.

Ahzahar, N., Karim, N. A., Hassan, S. H., and Eman, J. (2011). "A study of contribution factors to building failures and defects in construction industry." *Procedia Engineering*, 20, 249–255.

Almarwae, M. (2017). "Structural failure of buildings: issues and challenges." *World Scientific News*, 66(June), 97–108.

Bortolini, R., and Forcada, N. (2018). “Building inspection system for evaluating the technical performance of existing buildings.” *Journal of Performance of Constructed Facilities*, 32(5), 1–14.

Brogan, E., McConnell, W., and Clevenger, C. M. (2018). “Emerging patterns in construction defect litigation: survey of construction cases.” *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, 10(4).

Chiel, de W. (2014). “Exploring the nature of nonconformities.” University of Twenty.

Dietz, K. (2013). *Learning from Building Failures _ A student report– Architectural Engineering program.pdf*.

Engebø, A., Kjesbu, N., Lædre, O., and Lohne, J. (2017). “Perceived Consequences of Counterfeit, Fraudulent and Sub-standard Construction Materials.” Procedia Engineering, The Author(s), 196(1877), 343–350.

Forcada, N., MacArulla, M., Fuertes, A., Casals, M., Gangolells, M., and Roca, X. (2012). “Influence of building type on post-handover defects in housing.” Journal of Performance of Constructed Facilities, 26(4), 433–440.

Forcada, N., Macarulla, M., Gangolells, M., and Casals, M. (2016). “Handover defects: Comparison of construction and post-handover housing defects.” *Building Research and Information*, 44(3), 279–288.

Forcada, N., MacArulla, M., Gangolells, M., and Casals, M. (2014). “Assessment of construction defects in residential buildings in Spain.” *Building Research and Information*, 42(5), 629–640.

Forcada, N., Macarulla, M., and Love, P. E. D. (2013). “Assessment of residential defects at post-handover.” *Journal of Construction Engineering and Management*, 139(4), 372–378.

Gashi, E. (2018). “Management of defective works in infrastructure projects.” *International Review of Applied Sciences and Engineering*, 9(1), 73–80.

Gutierrez, C., and Hussein, B. A. (2015). “Insights on the impact of conformity and commitment on project performance.” *Proceedings of the 2015 IEEE 8th International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, IDAACS 2015*, IEEE, 2(September), 543–550.

Heravi, G., and Jafari, A. (2014). “Cost of quality evaluation in mass-housing projects in developing countries.” *Journal of Construction Engineering and Management*, 140(5), 04014004.

Islam, M. S., and Suhariadi, B. T. (2018). “Construction delays in privately funded large building projects in Bangladesh.” *Asian Journal of Civil Engineering*, 19(4), 415–429.

Jonsson, A. Z., and Gunnelin, R. H. (2019). “Defects in newly constructed residential buildings: owners’ perspective.” *International Journal of Building Pathology and Adaptation*, 37(2), 163–185.

Kazaz, A., Birgonul, M. T., and Ulubeyli, S. (2005). “Cost-based analysis of quality in developing countries: A case study of building projects.” *Building and Environment*, 40(10), 1356–1365.

Lili, X., and Zhe, Q. (2018). “On civil engineering disasters and their mitigation.” *Earthquake Engineering and Engineering Vibration*, 17(1), 1–10.

Liu, A. M. M. (2003). “The quest for quality in public housing projects: A behaviour-to-outcome paradigm.” *Construction Management and Economics*, 21(2), 147–158.

Love, P. E. D., and Edwards, D. J. (2004). “Determinants of rework in building construction projects.” *Engineering, Construction and Architectural Management*, 11(4), 259–274.

Love, P. E. D., and Edwards, D. J. (2005). “Calculating total rework costs in Australian construction projects.” *Civil Engineering and Environmental Systems*, 22(1), 11–27.

Love, P. E. D., and Smith, J. (2016). “Toward error management in construction: Moving beyond a zero vision.” *Journal of Construction Engineering and Management*, 142(11), 04016058.

Love, P. E. D., Teo, P., Carey, B., Sing, C. P., and Ackermann, F. (2015). “The symbiotic nature of safety and quality in construction: Incidents and rework non-conformances.” *Safety Science*, 79, 55–62.

Love, P. E. D., Teo, P., and Morrison, J. (2018). “Unearthing the nature and interplay of quality and safety in construction projects: An empirical study.” *Safety Science*,103(October 2017), 270–279.

MacArulla, M., Forcada, N., Casals, M., Gangolells, M., Fuertes, A., and Roca, X. (2013). “Standardizing housing defects: Classification, validation, and benefits.” *Journal of Construction Engineering and Management*, 139(8), 968–976.

Minchin, R. E., Corona, F., Lucas, E. D., Zhang, Y., Pan, J., and Walters, R. C. (2017). “Chinese Organizations’ Actions, Attitudes, and Motivations When Faced with Counterfeit Items in Their Construction Supply Chains.” Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 9(2), 04516015.

Naderpajouh, N., Hastak, M., Gokhale, S., Bayraktar, M. E., Iyer, A., and Arif, F. (2015). “Counterfeiting risk governance in the capital projects supply chain.” Journal of Construction Engineering and Management, 141(3), 1–11.

Omondi, S. (2019). *The Worst Building Collapses in History*.

Pheng, L. S., and Abeyegoonasekera, B. (2001). “Integrating buildability in ISO 9000 quality management systems: Case study of a condominium project.” *Building and Environment*, 36(3), 299–312.

Pheng, L. S., and Wee, D. (2001). “Improving maintenance and reducing building defects.” *Journal of Quality in Maintenance Engineering*, 7(1), 6–24.

Rahman Tishi, T., and Islam, I. (2019). “Urban fire occurrences in the Dhaka Metropolitan Area.” *GeoJournal*, 84(6), 1417–1427.

Silvestre, J. D., and De Brito, J. (2011). “Ceramic tiling in building façades: Inspection and pathological characterization using an expert system.” *Construction and Building Materials*, 25(4), 1560–1571.

Sommerville, J. (2007). “Defects and rework in new build: An analysis of the phenomenon and drivers.” *Structural Survey*, 25(5), 391–407.

Tayeh, B. A., Maqsoom, A., Aisheh, Y. I. A., Almanassra, M., Salahuddin, H., and Qureshi, M. I. (2020). “Factors affecting defects occurrence in the construction stage of residential buildings in Gaza Strip.” *SN Applied Sciences*, 2(2), 1–12.

Wardhana, K., and Hadipriono, F. C. (2003). “Study of recent building failures in the United States.” *Journal of Performance of Constructed Facilities*, 17(3), 151–158.

Wasfy, M. A. F. (2010). “Severity and impact of rework, A case study of a residential commercial tower project in The Eastern Province-KSA.” King Fahd University of Petroleum and Minerals.

Zhang, D., Haas, C. T., Goodrum, P. M., Caldas, C. H., and Granger, R. (2012). “Construction small-projects rework reduction for capital facilities.” *Journal of Construction Engineering and Management*, 138(12), 1377–1385.

Appendix

Table A. Specific requirements of the case study projects

Work item/material quality	**Specifications**
Lapping of reinforcement in column and beam	It is recommended to provide the lapping of reinforcement at the compression zone of the beam, which means at mid-span for top rod and near columns or bottom rod of the beam. For column, at mid-height of the column and 50% of the bars at one floor. The lapping length should be equal to 40d, where d denotes the diameter of the mild-steel bar.
Bend and hook of tie and stirrup	The recommended bending angle for tie/stirrup is 135^{0}, and the hook size must comply with a condition, i.e., $6d_b > 62.5$ mm, where d_b denotes diameter of the tie/stirrup bar.
Placement of corner	This is a mandatory requirement for earthquake resisting buildings.

reinforcement at the slab	
Proper curing of column and beam	All the reinforced concrete elements (i.e., footing, column, column, slab, etc.) of the building must be watered for 28 days keeping wet enough for all the time.
Requirements at beam-column joints	There is an instruction to provide beam rod inside the column rods. Moreover, the tie of columns at beam-column joints must be provided.
Proper leak proof formwork	It is strongly recommended that all the formwork must be free from any leakage.
Release of formwork after maturity time	The column formwork must be removed not before 72 hours after concrete placement into the formwork. The slab should not be removed before 28 days.
Strength of concrete	The design (compressive) strength of the concrete, f_c', must be equal to 20.68 MPa. This can be achieved by the volumetric ratio of 1:1.5:3 of cement, sand, and stone.
Strength of mild-steel bar	The yield (tensile) strength of the mild steel, f_y, must be equal to 413.685 MPa.
Stone quality	Well-graded crushed stone should be used for any reinforced concrete element of the building. Stone size must be 20mm down-graded sized.
Sand quality	Well-graded sand with F.M. 2.70 to 3.0 should be used for any concrete mixing.
Cement	Ordinary Portland Cement is recommended. The initial time should not be less than 45 mins, and the final setting time should not exceed 375 mins. The compressive strength of cement must be not less than 20.68 MPa after 28 days of curing.