Causes of defects associated with tolerances in construction: A case study

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Abstract

Defects associated with dimensional and geometric variations (tolerance issues) are amongst the most costly and recurring defects in construction projects, yet the identification and mitigation of the causes of tolerance issues appear to be lacking in the construction industry. To enable the development of widely acceptable solutions for the perennial challenge of tolerance management, a more in-depth understanding of causes of tolerance issues should be established. The aim of the research presented in this paper is to identify the potential causes of tolerance issues in construction based on a literature review and empirical studies. This research uses a case study approach. The empirical data is collected through direct observations, group interviews, semi-structured interviews and document reviews. Having triangulated the findings, a list of eighteen potential causes were derived for the eleven observed tolerance issues in two case study projects. The contribution of this paper to knowledge in engineering management is fourfold: (1) the limitations of prior studies on causes of tolerance issues are revealed, (2) the empirical studies led to not only verifying and refining the causes collected from the literature by considering them in the context of the identified tolerance issues, but also finding new causes in the context of tolerance management when compared to literature, (3) the identified causes provide insight into reasons behind the recurrence of tolerance issues across the industry, and (4) it investigates the causes of tolerance issues while balancing managerial and engineering views. The findings of this study provide a pivotal basis for construction practitioners to develop effective solutions for tolerance management whereby tolerance risks can be identified and mitigated in a prescient manner, which can result in a significant amount of savings.

Keywords: Tolerance issues, tolerance management, quality control, defects, dimensional and geometric variations.

Introduction

Defects associated with tolerances, called tolerance issues hereafter, are amongst the most common and recurring defects in construction projects (Landin 2010; Talebi et al. 2020a). Tolerances issues (e.g. lack of fit, misalignment between components, aesthetically unacceptable gaps) can adversely impact structural safety, constructability, aesthetic, functionality, and can lead to delays, cost overruns and material wastage (Rausch et al. 2019).

Over the last two decades, several authors have tried to develop ways of mitigating tolerance issues (i.e. solutions for tolerance management) (e.g. Milberg 2006; Talebi 2019) whereby designers and practitioners can gain proactive insight into avoiding tolerance issues. However, the construction industry is yet to find a widely accepted solution for tolerance management (Enshassi et al. 2020; Seymour et al. 1997). As a result, tolerance issues are often mitigated at the time and place of the construction process reactively with intensive rework (Milberg and Tommelein 2009; Savoini and Lafhaj 2017).

Liker (2004) states that solving a problem by finding suitable and workable solutions first requires the identification of its causes. More specifically, designing a solution to move from being reactive to proactive in managing tolerances requires the identification and elimination of causes of tolerance issues (Meiling et al. 2014). However, as far as it is known, very little literature exists with the main focus on thoroughly collating causes of these specific types of defects. The definition of tolerance issues and their causes remain vague as the existing literature either merely presents the authors' (e.g. Talebi et al. 2016) or participants' perceptions (e.g. Jingmond et al. 2011) rather than finding causes through rich empirical data (Forsythe 2006; Rausch et al. 2020). As such, there is a need for a study based on empirical data to thoroughly identify causes of tolerance issues prior to any attempt to develop a solution for tolerance management.

The aim of the research reported in this paper is to present potential causes of tolerance issues in construction. The paper is structured as follows. First, the causes of tolerance issues from the literature are discussed. The research method adopted to collate and analyse data is addressed. The causes of tolerance issues identified during the empirical studies are presented.

The findings and contributions to knowledge are discussed. Finally, conclusions drawn from the research and areas for further research are presented.

Causes of tolerance issues in construction

It is important to first investigate causes of tolerance issues in the literature. Berg and Holicky (1989) state that ambiguous communication of tolerance requirements, insufficient tolerance information in specifications, and negligence of tolerances during the tender process are some of the causes of tolerance issues. Seymour et al. (1997) add two more causes: (1) poor workmanship, and (2) an over-reliance on unsuitable tolerances in reference documents. Poor workmanship can be due to the inaccuracy of the execution of work on site (e.g. when erecting prefabricated walls) and inaccuracy of equipment used for installation (Jingmond et al. 2011). Milberg (2006) argues that (1) incomplete or missing tolerance information in specifications, which results in multiple interpretations of tolerance requirements by contractors and inspectors, (2) incompatibility between the specified tolerances and process capabilities, and (3) poor datum selection, being the main causes. Process capability in the context of tolerance management, is defined as "the likelihood that a process…will result in an outcome that meets a given tolerance specification. It may be represented by a probability distribution to describe the variation in the geometry of the material output of a process under normal operating conditions" (Tommelein and Ballard 2018). A datum is a theoretically exact geometry from which the geometric or location characteristics of a feature are established (Sun and Gao 2018). The latter two causes show that tolerance management in construction has its roots in the manufacturing industry.

Jingmond and Ågren (2015) adopt an approach based on the use of cognitive mapping and the notion of process causality in order to identify causes of defects in construction. They believe that causes of defects associated with tolerances are due to the unforeseen behaviour of materials and the inaccuracy of measuring devices. Regarding the latter cause, measuring devices range from moderately accurate (e.g. measuring tapes) to extremely accurate (e.g. automated electronic devices) (Chen et al. 2020). The inaccuracy of measurement devices may be considerable relative to allowable deviations of structures and components that are connected to the structures. Conventional instruments heavily rely on sampling techniques, which makes the results prone to the risk of being inaccurate (Arashpour et al. 2020; Phares et al. 2004). The challenge with the application of recently developed measurement instruments (e.g. terrestrial laser scanner) is their high cost (Puri et al. 2018) and a lack of adequate research on how to best utilize their level of accuracy (Rebolj et al. 2017). This is especially important in the context of tolerance management since the allocation of a specific level of accuracy from a measurement device needs to mitigate risk in a cost-optimal manner.

The construction industry is currently in a transitional state. It is neither completely craft-based, nor fully industrialised (Kagioglou et al. 2001). Hence, it is essential to establish reference documents and to understand what normal (or expected) tolerances are (Price et al. 2019). However, there are still many construction tolerances that are not covered in industry standards (Ballast 2007; Jingmond and Ågren 2015), and the existing standard tolerances may be either unreasonably "tight" or "loose" (Milberg and Tommelein 2019; Talebi et al. 2016). Holbek and Anderson (1977) state that although tolerances in the construction industry have been developed for materials, such as steel and concrete, there is little input on the issue of conflicting tolerances at the interfaces between different materials and components. Many years later, the industry still struggles with the same challenge and the subject of interfacing between components is yet to be resolved (Enshassi et al. 2020).

The verification of the compliance with tolerance requirements on site is performed according to the reference documents listed in specifications provided by the designers (Frank 2012). Shammas-Toma et al. (1996) argue that this is an ineffective quality control process and should be replaced by quality control documents in which achievable tolerance values based on project conditions can be found. However, quality control documents often do not include adequate tolerance information (Shammas-Toma et al. 1996).

All building components are subject to such variation in their size, form, orientation and position, which cannot be precisely determined at the design stage (Davison and Owens 2012; Rahman 2014; Vorlíček and Holický 1989). In the case of mixed-material building systems (e.g. hybrid steel, concrete, timber, etc.), there is a greater systemic interaction of material types, which can give way to more tolerance issues (Alexander 2014; Lawson et al. 2014). The building process itself adds more inevitable geometric variations to components because loads being applied to the building structure gradually increase during the construction process, and this leads to more building movement (Landin and Kämpe 2007). Variations are accumulated through components and assemblies, possibly resulting in the lack of fit or malfunction of assemblies (Abdul Nabi and El-adaway 2020; Shahtaheri et al. 2017). Designers must not only account for the impact of variation sources individually, but also the impact of variations when combined with the dimensional and geometric characteristics of components and assemblies (Talebi et al. 2019). However, the industry lacks accurate and validated guidance to quantify expected movements (Alexander 2014) and designers frequently ignore the accumulation effects of combined deviations (Ballast 2007; Milberg 2006; Milberg and Tommelein 2019; Rausch et al. 2019; Rausch et al. 2017; Safapour and Kermanshachi 2019).

During construction, building structures are not protected but are exposed to environmental conditions; particularly changes of temperature, rain, snow and humidity, sometimes for a long time. Such environmental conditions may lead to changes in form and size of components after they are constructed and subsequently result in tolerance issues (Alexander 2014). This is evidently seen in bridge construction and in large buildings where expansion joints are necessary for ensuring that a structure is not over-constrained due to thermal changes. Changes in temperature, including temperature difference across a component or changes in the average temperature of an assembly, are a source of building movement, especially in steel structures. Rain and snow can directly damage the accuracy of the final work (e.g. flatness of fresh concrete on metal decking in composite construction) (Alexander and Lawson 1981) or can result in ponding. Ponding occurs when water collects on a surface (e.g. roof) to a sufficient depth, causing deflection. Also, according to (ACI 2014), when concrete is poured, humidity can significantly affect the amount of drying shrinkage, which can lead to deflection in beams and slabs if not properly managed.

Other causes of tolerance issues found in the literature include the lack of tolerance coordination between design disciplines and construction trades (ACI 2014; Jingmond and Ågren 2015), the lack of terminology to communicate tolerance information (i.e. characteristic of tolerances and tolerance values) (Alshawi and Underwood 1996; Ballast 2007; Berg and Holicky 1989; Jingmond and Ågren 2015; Milberg 2006; Talebi et al. 2020a; Talebi et al. 2020b), poor product design (e.g. the lack of the provision of appropriate connections to absorb deviations) (ACI 2014; Milberg and Tommelein 2019), unforeseen special causes (e.g. tool breakdown) (ACI 2014).

Table 1 summarises the identified causes of tolerance issues in the literature and indicates the authors discussing each cause. The review of the literature shows that prior studies concerning the causes of tolerance issues are restricted due to one or more of the following reasons in addition to not being based on empirical data: (a) they do not investigate the causes of tolerance problems in a broad construction setting, from project management to engineering and from design to construction; however, investigating causes of tolerance issues would require an amalgamation of different disciplines (Talebi 2019), and (b) they mainly focus on a few causes of tolerance issues and a unified list of causes for tolerance issues is missing. All in all, according to Landin (2010) and Jingmond and Ågren (2015), the extant research tends to discuss causes in a somewhat superficial manner by placing the responsibility with designers, operatives, and quality systems. For these reasons, tolerance defects continue to emerge within projects and create challenging barriers to overcome.

Table 1. List of causes related to tolerance defects identified in the literature.

Research Method

This research adopts a case study approach. Such an approach is suitable when describing, explaining, and exploring a contemporary phenomenon, and gaining an in-depth understanding of real-world events (Yin 2013). In other words, the purpose of the case study is not to simply describe the events within a real-world context but rather to investigate underlying reasons as to why and how those events actually occur (Eisenhardt 1989). The case study approach is suitable for this research because it aims to thoroughly investigate why and how tolerance issues occur.

Although surveys are a common research method to identify the causes of defects (Knight and Ruddock 2009), using them do not necessarily invoke new understanding or in-depth verification of the causes identified in existing literature (Rosenfeld 2013; Ye et al. 2015). According to Robson and McCartan (2015), understanding why a real-world problem occurs requires asking those involved in practice. The case study approach in this research facilitates the collection of data in the context for which tolerance issues are experienced. The data is collected in the two case projects through direct observations on site, two group interviews, sixteen semi-structured interviews and document reviews.

Rationale for case selection

No widely accepted strategy exists for the selection of right cases beyond the advice to select cases which are 'most likely' to address the research aim (Brinkmann 2013). Accordingly, purposive sampling was adopted for the selection of cases and participants in the interviews. The purposive sampling highlights the importance of conscious decision-making and is used when dealing with a small sample and particularly when informative samples are meant to be selected (Saunders et al. 2016). The following criteria were considered for the selection of cases: (1) the acknowledgement of the need to develop a solution for tolerance management whereby tolerance issues can be managed proactively, (2) provision of access to construction sites and documents, and (3) the stage of development of the project. Regarding the latter criterion, only those projects where the connection between the structural frame and other components had not been constructed yet were considered since tolerance issues frequently occur in such connections (Talebi et al. 2020a). Eleven of the pre-identified tolerance issues were also identified during the empirical studies, that is, the selected cases were informative and the purposive sampling in this study ensured that appropriate cases have been selected. Details of the case projects and their development stages can be found in Table 2.

Table 2. Details of case projects and their stage of development.

Data collection and analysis

The direct (non-participant) observation (O'Leary 2004) was carried out on sites of both projects. The observation period in project A was 10 months and it lasted 5 months in project B. There were seven tolerance issues in A and four tolerance issues in B. The observations stemming from A included the installation of curtainwalls, the partitioning, the fins (architectural features that were attached to the building envelope for aesthetic purposes) and the cladding. The observations from B covered the erection of the steelwork and the installation of cladding and doors. The identified tolerance issues are presented in Table 3.

Table 3. Details of the tolerance issues identified in projects A and B.

Two group interviews were then conducted to validate and refine the description of the tolerance issues. The details of the participants in each group interview are given in Table 4.

The managing directors of the general contractors in projects A and B suggested interviewees based on the following criteria: (1) all of them had more than 10 years of experience in dealing with tolerance issues, (2) they were involved in the project from the beginning, and (3) were fully aware of the identified tolerance issues in each project. This ensured that purposive sampling had been followed carefully and the right participants had been invited to those group interviews, which is more important than the number of participants (Brinkmann 2013).

Table 4. Role and position of interviewees in projects A and B.

Sixteen semi-structured interviews were conducted with the same group of interviewees who were involved in the group interviews in order to capture opinions of the industry practitioners (Brinkmann 2013) concerning the causes of tolerance issues. The semi-structured interviews were conducted in 2016 and 2017. Having experts with different backgrounds helps to obtain a balanced view of the research topic and avoid subjectivity from a particular role's viewpoint (Saunders et al. 2016).

Of note is that the literature review in this research was carried out in two stages. The first stage was completed before starting the semi-structured interviews in 2016, and led to a list of causes of tolerance issues. The list was sent to the participants of face-to-face interviews for their reference. In particular, the participants were asked to consider unique characteristics of tolerance issues identified in their own project. The second stage of literature review continued, and it covered the most recent and pertinent literature. However, as can be seen from Table 1, no new causes were identified from publications since 2016. In other words, if the authors were to conduct the interviews again today, the same list of causes would be sent to the interviewees as the one sent in 2016. The second stage of literature review was to augment the first stage and make the research relevant to today's body of knowledge, and subsequently, to enable the authors perform more informed analysis on the collected data.

Interviews were conducted face-to-face and they took between 30 and 50 minutes. After completing the interviews, transcriptions from the recorded interviews were generated at this stage. Verbatim comments are included in quotations in this paper to communicate the 'lived experience' of the practitioners undertaking the work.

Document reviews were then used to corroborate evidence collected from interviews and to verify information given by interviewees through cross-checking transcriptions with the information in the reviewed documents. The review of documents review led to increased credibility and internal validity of this research (Taylor et al. 2015). Data collected from document reviews is indicated in the findings section. Documents used to disseminate tolerance information (i.e. specifications) were reviewed at this stage.

Content analysis was applied to interview transcripts for identifying the causes of tolerance issues. Other methods exist to analyse causes of defects such as cognitive mapping (CM), causal loop diagram (CLD) and Fishbone diagram (FD). The use of qualitative diagrammatic aids such DM, CLD and FB are based on heuristic rules (Love, Edwards, & Smith, 2016). Love et al. (2016) contend that the use of such heuristic rules may contribute to the stagnation in research on causation, and subsequently, impair improvements in practice. The deployment of content analysis in this research was to recognise the foremost facets of a data set by thoroughly interpreting the interview transcripts rather than simply counting the number of times a topic is raised or presenting direct responses about what the causes are (Fellows and Liu 2015). The content analysis deployed presents information extracted from interviewees that address 'why' and 'how' tolerance issues in each project occurred. A summary of findings is presented in the next section. Quotations from interviews are improved for readability and it is indicated where the data collated from interviews and document review is used. Consolidating the findings from the literature and interviews resulted in the identification of eighteen causes of the tolerance issues.

Findings: Causes of Tolerance issues

Causes of Tolerance Issue 1

According to the project brief developed by the client, “a decorative polished concrete floor system should be used in the Atria Space, Social Space and Circulation Spaces”. However, the project brief does not specify the exact flatness tolerance or construction method to achieve highly flat concrete slabs (Interviewee 1). The general contractor, who was responsible for design and construction in project A, decided to use the composite steel deck floors because this construction method is normally cheaper than other flooring methods and enables quicker pouring of concrete (Interviewees 1, 3, 4, 5, 6). Using a cheaper work method made the general contractor more competitive when bidding for the project (Interviewees 1, 5, 6). If the project budget had been higher, the general contractor could have used other alternatives for the floors (Interviewees 3, 6) such as pre-cast planks (Interviewees 1, 4, 6). In that case, slabs would have had less deflection and “likely the tighter flatness tolerances when concrete is the final finish could have been achieved” (Interviewee 3). Given the challenge with the excessive deflections when using the composite steel deck floors, the mitigation strategy to fix the unacceptable deviations in flatness of concrete slabs was to use a concrete floor levelling compound to achieve the required flatness tolerance (Interviewees 5, 7). In other words, interviewees infer that due to the ***inconsistency between the tolerance requirements of the project and its budget***, the contractor had to select an ***inferior type of construction method*** (Interviewees 1, 3, 4, 5, 6), which led to not achieving the flatness tolerance requirement. As a result, the recessed skirting and door frames were either conflicted with the concrete slab or there was a gap between the them and the slabs (see Figure 1). In (BSI 1994), it is stated that if the soffit deflection is considered important, the permitted deflection tolerance should be reduced. However, the designer only relied on the given tolerance values in the reference document and did not assign tighter tolerances to control flatness (i.e. ***overreliance on reference documents***) (Interviewee 1, 2, 3). Moreover, although the project brief asks for a decorative polished concrete floor system, it does not specify the structural system required to have the polished concrete as the final finish. As a result, the general contractor decided to put the price based on an inappropriate working method for this purpose and then call upon contingency fund for remedial actions to achieve the requirements after being awarded the project (i.e. ***an incomplete project brief given by the client***) (Interviewees 1, 2, 3, 4). The Interviewee 7 pointed out that raining exacerbated the situation with the flatness of slabs (i.e. ***environmental condition***).

Fig. 1. Excessive gap between the skirting and the concrete slab.

Cause of Tolerance Issue 2

The concrete subcontractor had to stop working in the evenings when pouring upper floors due to complaints from residents living around the site to the Environment Agency of the Local Authority and could not use the power float when it started to rain (Interviewees 1, 7). Rain as an ***environmental condition*** (Interviews 6, 8) and people's complaints as an ***unforeseen special cause*** (Interviewees 2, 8) "made it difficult for the concrete subcontractor to achieve the required [flatness tolerances in] surfaces" (Interviewee 8) (Figure 2).

Fig. 2. Flatness of concrete slabs affected by special issues.

Causes of Tolerance Issue 3

According to the concrete specification, "the general contractor is responsible for obtaining the positions and sizes of all holes, brackets etc., from all subcontractors and should accurately set out and form them". However, due to the ***poor communication*** between the general contractor, cladding subcontractor and concrete subcontractor, "the position of the brackets and permissible deviation in the position of the slab edge was not coordinated" (Interviewee 4). The Interviewees 2 and 7 state that none of the specifications and reference documents considered conflicting tolerances in interfaces between the concrete elements, steel elements, and cladding system and they only revolved around tolerances of one component. Hence, “the clash between the cladding bracket and concrete slabs when the concrete slabs are protruding the target surface had not been detected” (i.e. ***Insufficient tolerance information in specifications***, ***the lack of tolerances for interfacing components in reference documents***) (Interviewee 7). CONSTRUCT Concrete Structure Group (2010) states that the permitted deviation for the position of the slab edge relative to the actual position of the slab edge is ±10 mm. However, “as soon as the concrete slabs at the roof level start to deviate towards outside the building, they will conflict with the cladding brackets” (Interviewee 7), which shows the ***over-reliance on reference documents to specify tolerances*** resulting in this tolerance issue. Given that the concrete edge protruded more than permitted from the surface of the steel beam, the bracket could not be installed without cutting the edge of the slab (Interviewees 1, 8, 9) (Figure 3).

Fig. 3. Modified edge of the concrete slab.

Causes of Tolerance Issue 4

The Steel Framing Systems (SFS) studs were out of plumb (Figure 4). “None of the Quality Check Sheets included information about the permissible deviations of the plumbness of the SFS studs” (Interviewee 1), or “how and when they should be measured” (Interviewee 1). As a result, the tolerance problem with the SFS studs was recognised after they were handed over by the cladding subcontractor (Interviewee 7), when “they started to build their system on the SFS studs” (Interviewee 7). Thus, this problem was due to ***ineffective quality control documents***. Also, Interviewee 4 says that given “the operatives had to complete their work as quickly as possible, they were not that much concerned about the quality of their work”. Hence, ***poor workmanship*** was another cause behind this tolerance issue.

Causes of Tolerance Issue 5

The cladding subcontractor developed a design in which the offset from the steelwork to the face of the stone panels was 272 mm. In this case, the cladding system could absorb 32 mm of deviations due to the inclination of steel columns and stone panels. The Architect later increased the offset to 290 mm (Interviewees 1, 2, 6, 8) (Figure 4). This was to accommodate the installation between the steelwork and cladding. “There was ***miscommunication*** between the architect and the cladding subcontractor about the required distance from the steel to the face of the stone panels” (Interviewee 2). The subcontractor’s input was delayed (Interviewees 1), and “the architect was not convinced to change the design” (Interviewee 1) as “the connection type between the steelwork and cladding system had been designed” (Interviewee 5). Later during construction, “the architect, structural engineer, steel subcontractor and cladding contractor could not conclude how deviations of the steelwork would impact the geometric accuracy of the steelwork and the cladding system” (Interviewee 6) due to poor tolerance communication. As a result, the cladding system was not capable of accommodating the deviations (Interviewees 9). Indeed, the steel frame, “was not stiff enough due to the poor structural design” (Interviewee 9) and columns in the Elevation 4 were leaning into the building more than it was anticipated (i.e. ***unforeseen behaviour of materials and the lack of accurate guidance to anticipate the exact building movements***) (Interviewees 1, 6, 7, 9).

Fig. 4. Excessive perpendicularity variations of columns and stone panels.

Causes of Tolerance Issue 6

When the cladding subcontractor put the stone panels on and the dead load was applied to the steel frame, the stone panels started to sag. This meant that the cladding did not stay at the correct level and, in general, everything was sinking downwards. It was noticeable that the gap between the channel and the stone panel in some areas were bigger and the gap was not consistent all the way through (Figure 5). There was ***miscommunication*** between the steelwork contractor, cladding contractor, and the general contractor did not perceive the importance of having movement joints, thus, denied to have it (Interviewees 1, 7, 8, 9). In the specification for the cladding system prepared by a consultant, it was stated that "movement joints are not required". However, it turned out that this ***tolerance-related information in the specification was inaccurate***. The Interviewees 1 and 9 believed that using movement joints had been neglected because such joints would have been costly and exceeded the allocated budget for the cladding (i.e. ***inconsistency between tolerance requirements of the project and its budget***). Eventually, this tolerance issue occurred due to ***the exceeding deflection and twist of beams more than anticipated*** (Interviewees 7, 8, 9).

Fig. 5. Inconsistent gaps in some areas between the channel and the stone panel.

Causes of Tolerance Issue 7

According to the Interviewees 1, 2 and 9, no specification had been developed into a unified document to consider tolerances of the fins and steel structure but rather tolerance information for each component could be found in dispersed specifications (i.e. ***fragmented tolerance information in specifications***). In the specification called 'projecting feature fin system', it is stated that any points on the steel columns are allowed to have the tolerance of ±10 mm. It turned out this tolerance was not achievable by the steel subcontractor (Interviewees 2 and 8). This indicates not only ***inaccurate tolerance information in specifications*** (Interviewees 1, 2, 8, 9) but also ***incompatibility between the specified tolerances and process capability*** (Interviewees 1, 8) (Figure 6). Hence, the design of connections between the steelwork and fins had to change to accommodate more deviations (Interviewee 1, 6, 7, 9) as columns on level 3 were more than 30 mm out of plumbness (i.e. ***inferior design of connections***) (Interviewees 7, 9).

Fig. 6. Connection between the structural frame and a fin and the specified tolerances for the steel columns

Causes of Tolerance Issue 8

No information could be found in the specifications indicating that parallelism of stanchions is essential to ensure that the electrically operated shutter doors will fit in the doorways (i.e. ***insufficient tolerance information in specifications***) (Interviewees 10, 14). "There was ***no communication of tolerance information*** before construction whatsoever" (Interviewee 11). The only information communicated between the site manager and the steel subcontractor was whether deviations in the plumbness of installed columns and in the position of the installed base plates complied with the tolerances stated in BCSA (British Constructional Steelwork Association) (2010) (Interviewees 11, 12). As a result, despite the fact that the steel and cladding subcontractors were functioning in the project as one entity, the required tolerance for the steel work to fit the shutter doors was not communicated between them (Interviewees 10, 12, 14). Moreover, the structural designer had tried to use steel and ancillaries as little as possible (Interviewee 13). The two sides of the doorways were "neither connected to each other nor [were] they … fixed to the ground" (Interviewee 11), that is, they are free standing. The ***inconsistency between a tolerance requirement*** (i.e. fitting the shutter door without any rework) ***and its budget*** led to a situation that by aligning one side of a cladding rail, the other side was becoming out of alignment (Interviewees 10-12) (Figure 7). This inconsistency was to cut down the project costs but resulted in a tolerance issue (Interviewee 14). "Setting a datum to either side of the doorway could have helped the people on site to install the columns right in the first try" (Interviewee 11). This could also have assisted the site engineer to align the columns easier (Interviewees 11) (i.e. ***poor datum selection***). The Interviewee 15 believed that this tolerance issue shows that practitioners do not often have adequate knowledge about tolerances (i.e. ***lack of training on tolerance management***).

Fig. 7. Misalignment of stanchions.

Causes of Tolerance Issue 9

The purlins on the roof, which support the cladding panels, were neither straight nor in their correct positions (Interviewees 13, 16) (Figure 8). As a result, there were no fixing points for the panels (Interviewee 13). A document, 'Method of Erection', issued by the steel subcontractor, states that "the feature steelwork and stringers are to be co-ordinated into the structure as the work progresses". This implies that tolerances of the purlins and panels had to be coordinated to accommodate deviations in their joints. However, there is not any hint in this document about how to install the purlins and avoid the risk of having them be wavy (i.e. ***insufficient information in specifications***) (Interviewee 13). Moreover, ***poor workmanship*** is another cause of the issue with the purlins (Interviewees 10-12, 14, 15). If the steel subcontractor had been competent, they would have assessed whether the cladding subcontractor could be able to install the roof panels between the purlins (Interviewee 13).

Fig. 8. Wavy purlins on the roof.

Causes of Tolerance Issue 10

The building was erected from two sides: the first erected side initiated from Gridline 1 and continued to Gridline 30 and the second erected side started from Gridline 31 and was connected to Gridline 30. Hence, there was an interface between these two sides of the structure in Gridline 30. The columns in Gridlines 31 were out of plumb and they were leaning towards the inside of the building. Also, the entire columns in the first erected side of the structure were oriented towards the first erected side. As a result, the beam coming across the top between Gridlines 28E and 30E from the initial side overlapped Gridline 30E where it connects two sides of the building (Figure 9).

The decision of erecting the steelwork in two pieces was wrong from the tolerance point of view (Interviewees 10, 14), especially without considering any solution to make the deviations of both sides more compatible to each other (Interviewee 14) (i.e. ***inferior types of construction methods***). The Interviewee 14 believed that the accumulation of deviations when installing base plates and columns had been disregarded (i.e. ***neglecting the accumulation effects of deviations***). As part of the contract with the steel subcontractor, the general contractor could have asked for an engineer to monitor the steel erection on site continuously. This would somewhat yield to an additional cost for the general contractor (Interviewees 10, 12). Not having an internal site engineer due to ***inconsistency between the required accuracy and the project's budget*** resulted in a steelwork which is considerably out of tolerance, the lack fit on the roof, and a relatively high amount of rework (Interviewees 10, 12). Interviewee 13 added that even "if the steel subcontractor was more conscious about tolerances, the second erected side would have been erected as accurate as possible". However, "the second erected side had the worst deviations compared to the first side of the structure" (Interviewee 11). Interviewee 11 implied that the out of tolerance steelwork particularly in the second erected side was due to ***poor workmanship***.

Fig. 9. Lack of fit of the beam between two gridlines.

Cause of Tolerance Issue 11

The frames for personnel doors were neither plumb nor square. The personnel doors were 'squeezed' too tight, resulting in a non-square condition, and they could not be shut and opened properly. According to the Interviewees 13 and 15, the cladding subcontractor had measured the distance between the posts making the doorframes at the bottom and top using a conventional measuring tape. However, “they ignored the fact that the doorframes actually can be oriented either to left or right side even though when those distances are the same” (Interviewee 14) and a measuring tape is an ***inappropriate measurement instrument*** to check the plumbness tolerance of the doorframes (Interviewees 11, 13).

Discussion

The literature review in this study revealed the limitations of prior studies focusing on the causes of tolerance issues. The knowledge of these restrictions was gained after a thorough literature review and should be considered as a contribution to theory. These restrictions have made the causes of tolerance issues obscure and therefore, an in-depth study in this field is needed prior to any attempt to develop a solution for tolerance management. To tackle the existing shortcomings, the case study approach was adopted and a substantial amount of empirical studies were carried out, causes of tolerance issues were investigated from both the managerial and engineering aspects, and a list of causes based on the findings from the literature and empirical studies was generated.

Eleven tolerance issues were identified during observations in case projects A and B, and they were validated during two group interviews. The causes of these tolerance issues were then explored during sixteen semi-structured interviews with practitioners who frequently deal with such issues. Given that the definition of tolerance issues is still vague in the literature and that most of the existing literature is based on subjective views, this research contributes to the existing theory by providing a better understanding of the characteristics of tangible tolerance issues in practice and their causes.

The findings from the observations and interviews helped to verify and refine the causes collected from the literature by bringing them in the context of the identified tolerance issues, and also to find causes that had not been considered in the tolerance management body of knowledge. ‘Insufficient tolerance information in specifications’ is a cause for tolerance issues identified in the literature. This cause was refined further during this study as it was demonstrated that inaccurate and fragmented tolerance information in specifications led to tolerance issues 6 and 7. Accordingly, it was suggested that the ‘insufficient, inaccurate and fragmented tolerance information in specifications’ is the correct cause (Interviewees 1, 2, 4, 7, 8, 9). ‘Lack of tolerance coordination during the project’ was found in the literature, however, all the interviewees believed that it is a subset of ‘poor communication of tolerance information’ and should be eliminated from the list as an independent cause. ‘Negligence of tolerances during the tender process’ appears to be another cause identified in the literature. However, the findings from the interviews show that ‘an incomplete project brief’ is one of the reasons that leads to such negligence and should be considered as the actual cause for tolerance issues (Interviewees 1-4, 8, 10, 13). In addition, this research verified three causes that have been identified in settings outside the context of tolerance management, and it demonstrated that they should be equally considered as causes of tolerance issues. Those causes are ‘inconsistency between tolerance requirements of the project and its budget’, ‘an incomplete project brief’, and ‘inferior types of construction methods’. Refining and verifying the causes as well as finding causes that had not been identified in the tolerance management literature are contributions to knowledge from this research.

‘Unforeseen special causes’ and ‘lack of training on tolerance management’ were found in both the literature and empirical studies. Deming (2000) speculates that the majority of the causes of problems stem from the system (of production) and only a few of them are due to special causes, emanating from fleeting events (Deming 2000). In line with this statement, most of the identified tolerance issues in this study occurred due to causes stemming from the system (of production), and the ‘special cause’ as such was only recognised in the tolerance issue 2. Moreover, ‘lack of training on tolerance management’ was found only for the tolerance issue

8. Nevertheless, insufficient training is known to be often inherent in the occurrence of all tolerance issues (Milberg and Tommelein 2019; Talebi et al. 2016). Given that tolerance issues are amongst the most recurring defects, with potentially severe consequences, the subject of tolerance management should be included in the curricula for the designers and contractors (Milberg and Tommelein 2019).

Table 5 shows the refined list of the identified causes through the literature review and empirical studies, and in which tolerance issue (TI) those causes have been found.

Table 5. List of the causes found in the literature and empirical studies

There has been little quantitative analysis of the magnitude, cost, and consequences of tolerance issues. Brookes (2005) contends that more than 5 per cent of construction costs arise from the rework due to tolerance issues. Forcada et al. (2016) estimate that tolerance issues are among the most common and recurring defects in Spanish housing construction and make up more than 9 per cent of the overall number of defects. Such problems can significantly affect the quality of buildings, and their economic and functional lifecycle service (ACI 2014; Gibb and Pavitt 2003; Milberg and Tommelein 2009; Talebi 2019). Despite the importance of tolerances, their treatment in the literature is often limited to scattered and generic recommendations about how to proactively avoid tolerance issues and improve tolerance management. Arguably, a reason behind the none-existence of a holistic and widely accepted solution to improve tolerance management could be the lack of an in-depth understanding of the causes of tolerance issues (Milberg 2006; Talebi 2019). This is because solving a problem first requires identifying its causes (Liker 2004).

The existing scattered attempts within academia to tackle specific causes of tolerance issues found in each research work, rather than devising a solution to treat all of them, will not bring about a panacea for tolerance management. Existing solutions devised to proactively prevent these issues must be like putting together pieces of a puzzle, rather than creating isolated solutions to remedy a number of specific causes. This is because all the identified causes bear a responsibility for tolerance issues, as has been demonstrated through real-world examples in this case study research. In particular, an effective solution for tolerance management should put a major emphasis on the proactive identification of tolerance risks (Enshassi et al. 2019; Shahtaheri et al. 2017) and then on planning to mitigate those tolerance risks (Talebi 2019). The list of causes in this paper helps to develop a solution by which the identified risks and their causes can be tackled and also provides insights to practitioners about potential tolerance risks and their causes that need to be mitigated in projects. That is, knowing the causes will improve the competency in the industry to deal with tolerance risks in a prescient manner, which is a core principle of an effective tolerance management practice (Talebi et al. 2020a). Therefore, this research is expected to provide a pivotal basis for developing a solution for tolerance management whereby the identified causes can be tackled and a significant amount of savings can be made.

Conclusion

The aim of this research was to identify potential causes of tolerance issues in construction. The literature was used as a basis to create the preliminary list of causes. The case study approach adopted in this research allowed to collect empirical data through direct observations in two case projects, two group interviews, sixteen semi-structured interviews and document reviews. Direct observations and group interviews were to identify examples of tolerance issues in practice. Semi-structured interviews helped to collect rich data from which the experience of participants about causes of the observed tolerance issues could be captured. In other words, the semi-structured interviews were conducted to examine the causes of tolerance issues encountered in real-world to avoid the subjectivity of reflecting the authors' or practitioners' perceptions only. The document review was to corroborate evidence collected from the interviews and it was also used for verifying information about the case projects that had been presented in the interviews.

The findings from the literature and empirical studies were used to generate a list of eighteen causes for the observed tolerance issues in the two case study projects. This list is also expected to give an insight into causes behind the reoccurrence of tolerance issues in other projects across the industry. Three causes not included in the prior body of knowledge on tolerance management were found, namely 'inconsistency between tolerance requirements of the project and its budget', 'an incomplete project brief', and 'inferior types of construction methods'. The identified causes from the literature were refined and verified by putting them in the context of the observed tolerance issues. This was to verify that the identified causes have a practical basis and also to refine those causes if necessary. In particular, the cause of 'insufficient tolerance information in specifications' in the literature was further refined to 'insufficient, inaccurate and fragmented tolerance information in specifications'; the cause of 'lack of tolerance coordination during the project' found in the literature was eliminated for the apter cause of 'poor communication of tolerance information'; the cause of 'negligence of tolerances during the tender process' found in the literature was eliminated for the more descriptive cause of 'the lack of tolerance information in the project brief'; the causes of 'ineffective quality control documents' and 'inaccuracy of measurement devices' were replaced with the more comprehensive cause of 'ineffective quality control process'.

This paper also consolidates scattered insights on causes of tolerance issues into a refined and unified list of causes. The findings presented in this paper are expected to be a starting point when identifying causes of tolerance issues and developing solutions for tolerance management. Of note is that the construction industry is argued to lack a widely accepted solution for tolerance management due to the lack of in-depth understanding of causes behind the recurrence of tolerance issues.

Three limitations of this case study research should be explained. First, the empirical studies revolve around commercial and industrial buildings and future research may find more causes applicable to other types of construction projects. Second, this study was conducted in the UK and may be affected by the special characteristics of the construction industry in this country. However, it is arguable that these two limitations are partially mitigated as a result of reviewing the literature on tolerance issues in various types of construction projects conducted in different countries. Third, the causes identified for each tolerance issue were only inferred from the accounts given by the interviewees, that is, other causes for each tolerance issue may be conceivable. For example, a closer look at the tolerance issues and their causes reveals that 'ineffective quality control process' and 'poor workmanship' could be attributed to tolerance issue 8, 'poor communication of tolerance information' could be attributed to tolerance issue 10, and 'insufficient, inaccurate and fragmented tolerance information in specifications' could be attributed to tolerance issue 11. It can be argued that this limitation arising from the characteristics of the case study research was mitigated by sharing the potential causes of tolerance issues identified from the literature with interviewees in order to increase their awareness of the topic. Future research may attempt to undertake a similar study to find causes of tolerance issues in other projects in order to generalise the causes, that is, developing a list of causes without considering it in the context of a specific tolerance issue and project.

Data Availability Statement

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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Table 1

No.	Identified Cause	Source: (Holbek and Anderson 1977)	(Berg and Holicky 1989)	(Alshawi and Underwood 1996)	((Shammas-Toma et al. 1996)	(Seymour et al. 1997)	(Milberg 2006)	(Ballast 2007)	(Alexander 2014)	(ACI 2014)	(Jingmond and Ågren 2015)	(Talebi et al. 2016)	(Rausch et al. 2017)	(Rausch et al. 2019)	(Milberg and Tommelein 2019)	(Enshassi et al. 2020)	(Talebi et al. 2020a)	(Talebi et al. 2020b)
1	Poor communication of tolerance information (e.g. lack of terminology)		•	•			•	•			•						•	•
2	Insufficient tolerance information in specifications		•				•		•	•							•	
3	Incompatibility between the specified tolerances and process capabilities						•							•	•			
4	Poor datum selection						•								•		•	
5	Unsuitable tolerance values in reference documents											•			•			
6	Negligence of tolerances during the tender process		•															
7	Inaccuracy of measurement devices										•		•					
8	Poor workmanship		•		•	•					•	•						
9	Lack of tolerance coordination during the project									•	•							
10	Lack of training on tolerance management						•								•			

11	Overreliance on reference documents to specify tolerances					•		•	•							•		•
12	Unforeseen behaviour of materials (i.e. unforeseen movement) and the lack of accurate guidance to anticipate the exact building movements								•		•	•						•
13	Ineffective quality control documents				•					•								
14	Neglecting the accumulation effects of deviations						•	•					•	•	•			
15	Lack of standard tolerances for all components in reference documents							•			•							
16	The lack of tolerances for interfacing components in reference documents	•														•		
17	Environmental conditions								•	•								
18	Unforeseen special causes									•								
19	Poor product design at connection points									•					•			

Table 2

Case Project	Description	Development Stage
A	A commercial building circa 7500 m2	The building envelope and interior components were just to be installed.
B	A terraced warehouse circa 2.30 ha	The structural frame had been erected.

Table 3

Case Project	Corresponding No.	Description
A	Tolerance Issue 1	Depth of the concrete slabs
A	Tolerance Issue 2	Flatness of the concrete slabs
A	Tolerance Issue 3	Clash between the edge of the concrete slabs and cladding brackets
A	Tolerance Issue 4	Plumbness of the steel framing systems studs
A	Tolerance Issue 5	Clearance between the steelwork and the cladding
A	Tolerance Issue 6	Columns and cladding stone panels
A	Tolerance Issue 7	Columns and fins attached to the building envelope
B	Tolerance Issue 8	Structural frame and doorways
B	Tolerance Issue 10	Undulation of purlins
B	Tolerance Issue 11	Lack of fit in the steelwork

Table 4

Project A		Project B	
Interviewee	**Interviewee Position**	**Interviewee**	**Interviewee Position**
1	Project Director	10	Senior Engineer
2	Design Manager	11	Senior Surveyor
3	Architect	12	Planning Manager
4	Senior Planner	13	Envelope Package Manager
5	Quantity Surveyor	14	Senior Engineer
6	Quantity Surveyor	15	BIM Strategic Planner
7	Site Manager	16	Engineer of Concrete Subcontractor
8	Site Engineer		
9	Cladding subcontractor		

Table 5

No	Causes of Tolerance Issues (TIs) as Identified in the Literature and Empirically in Projects A and B	Literature	Empirical Studies										
			TI 1	TI 2	TI 3	TI 4	TI 5	TI 6	TI 7	TI 8	TI 9	TI 10	TI 11
1	Poor communication of tolerance information	•			•		•	•		•			
2	Incompatibility between the specified tolerances and process capabilities	•							•				
3	Poor datum selection	•								•			
4	Inconsistency between tolerance requirements of the project and its budget		•					•		•		•	
5	Insufficient, inaccurate and fragmented tolerance information in specifications	•			•			•	•	•	•		
6	An incomplete project brief		•										
7	Neglecting the accumulation effects of deviations	•										•	
8	Overreliance on reference documents to specify tolerances	•	•		•								
9	The lack of accurate guidance to anticipate the exact building movements	•					•	•					
10	Ineffective quality control process	•				•							•
11	Inferior types of construction methods		•									•	
12	Poor workmanship	•				•					•	•	
13	Poor product design at connection points	•							•				
14	Lack of training on tolerance management	•								•			
15	The lack of tolerances for interfacing components in reference documents	•			•								
16	The lack of standard tolerances for all components in reference documents	•											
17	Environmental conditions	•	•	•									
18	Unforeseen special causes	•	•	•									

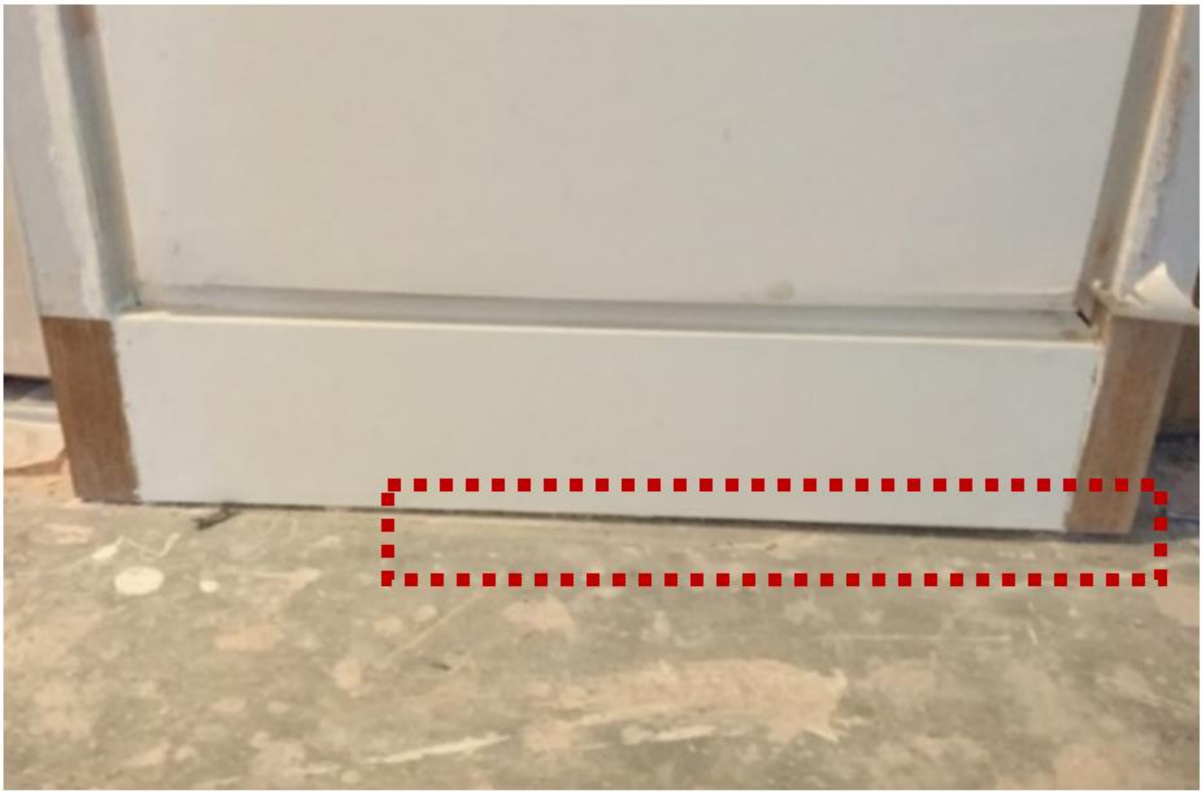

Figure 1

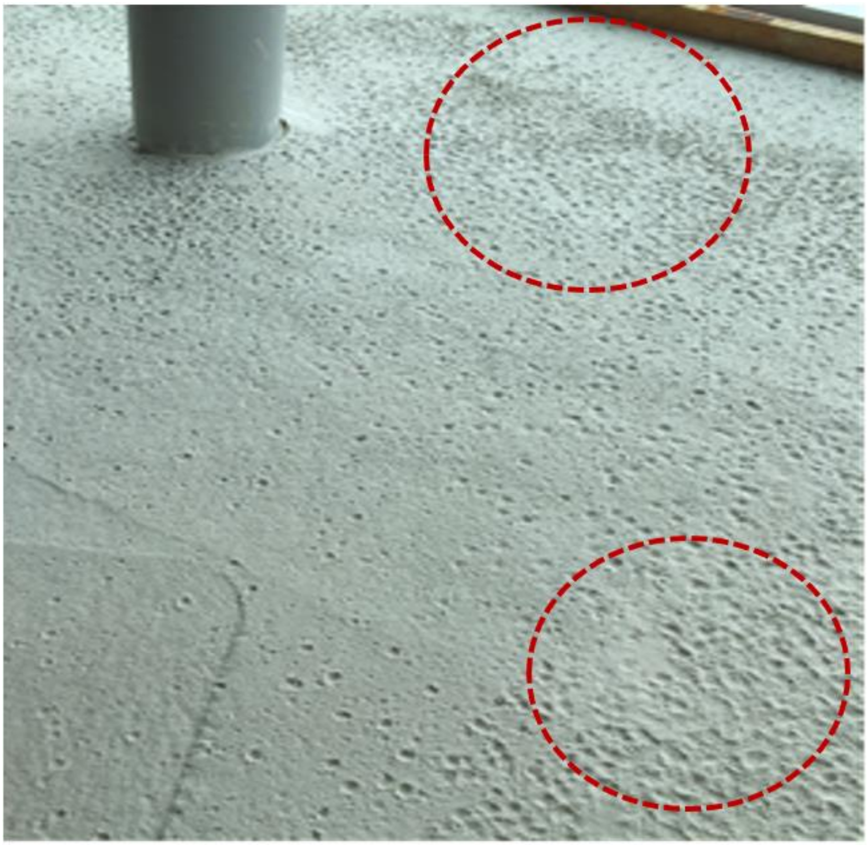

Figure 2

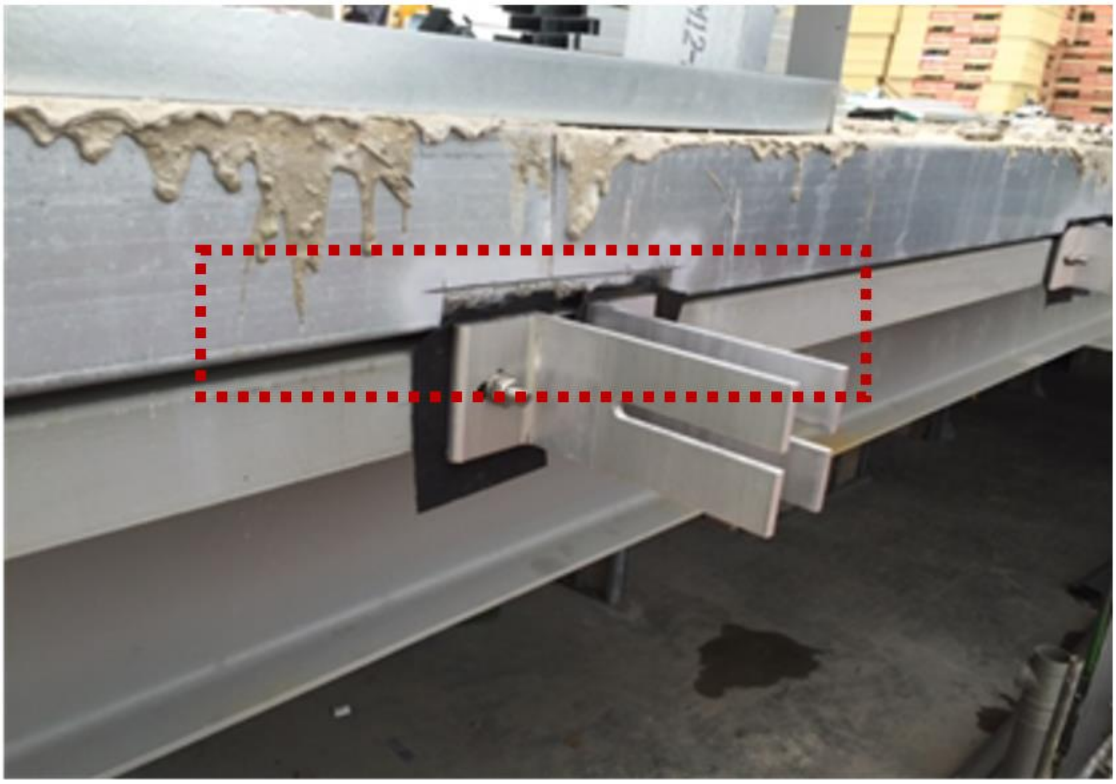

Figure 3

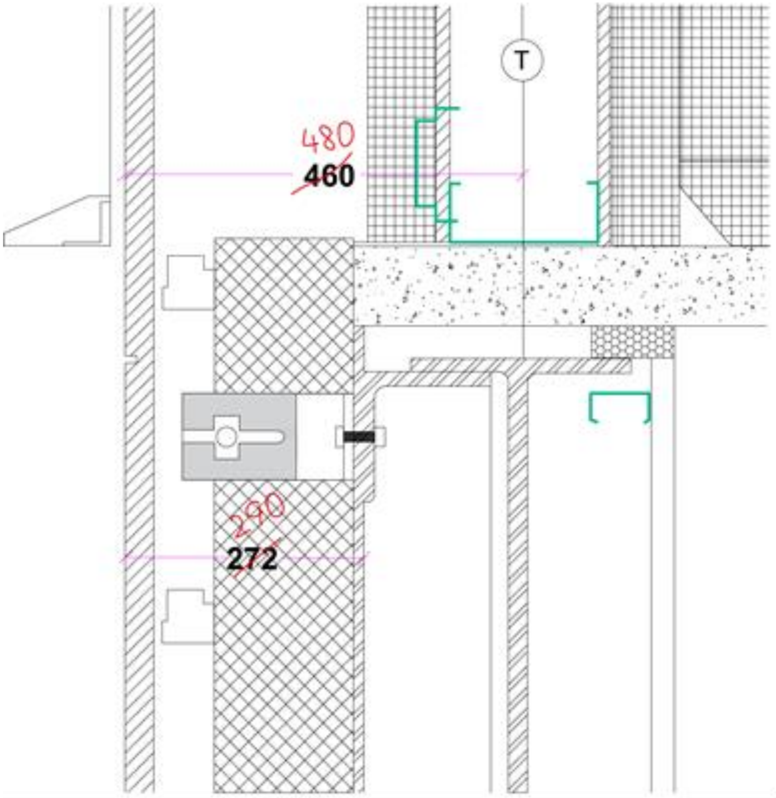

Figure 4

Figure 5

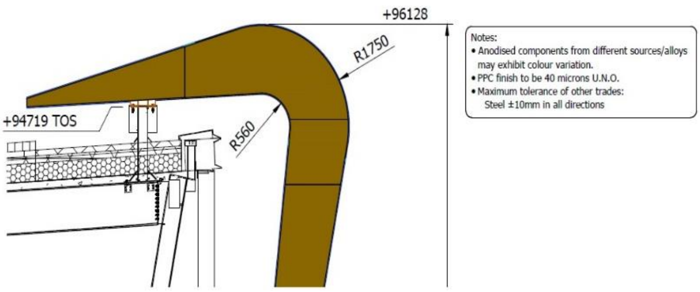

Figure 6

Figure 7

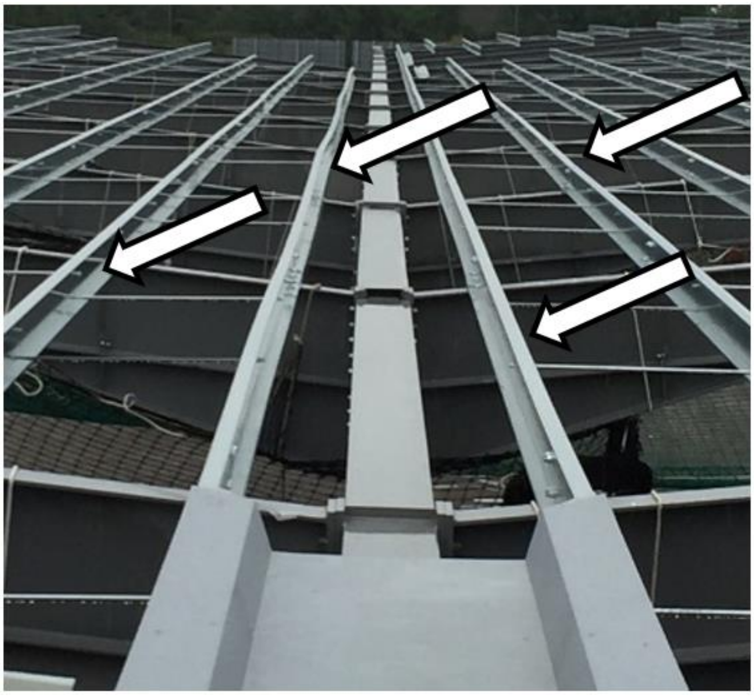

Figure 8

Fig. 9 Lack of fit of the beam between two grid lines