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MAINTENANCE OF BUILDING STRUCTURAL SYSTEMS

M. Sofi*, Z. Zou, E. Lumantarna, P. A. Mendis, L. Aye

Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Victoria 3010, Australia

**E-Mail: massoud@unimelb.edu.au, TP: +613 9035 8472*

Abstract: The aim of this paper is to review the current literature on maintenance of building structural systems. It emphasises the importance of maintenance as an item for consideration from the beginning of the conceptual design stage. Building sustainability concept is generally understood to have better energy efficiency focus and maintenance of structural components ensures they serve their designed service life and beyond. The conventional design approach considers structural maintenance during the "product use" phase. This paper argues that if the accessibility of the building and maintenance (inspection, repair and retrofitting) are considered from the early conceptual design stage, it would save resources and maintenance cost. Case studies of buildings subject to earthquake loading and corrosion and their maintenance are presented.

Keywords: building; maintenance; systems approach; cost effective;

1. Introduction

There has been a rapid increase of tall building development due to the ongoing worldwide urbanization. The United Nations estimates indicate that the global population will reach almost 11 billion by the turn of the century and 8 billion by 2025, UN [1]. The number of people expected to live in the cities by 2050 is projected to be equal to total number of human population today, UN [2]. The roles of high rise buildings are diverse, ranging from commercial offices as the traditional usage to residential, mix-use, and hotel tower development. Apparently, with growing population, urbanization is going to happen. Approximately 50% of global energy usage and greenhouse gas (GHG) emissions are attributed by construction, operation and maintenance of buildings. Consequently, sustainability associated with high rise buildings needs to be given more emphasis in order to bring about benefits to social, environmental and economic aspects of the society. As regards building structures, sustainability relates to the choice of materials for construction, function different elements making the building and maintenance of these throughout the building service life. The aim is to reduce degradation to the environment and to minimize the use of natural and human resources. Without proper maintenance, the service life of building structural systems and components will decrease. A systems approach would therefore reduce wastes from construction, demolitions and disposal, decreasing GHG emissions and energy use and any other factors that would adversely affect the environment.

There are currently numerous buildings more than 300 million under construction around the world and further tall buildings are planned worldwide for both residential and commercial markets. The design and construction of tall buildings present many challenges for the design team (from engineers, architect through to the concrete technologist and the builder). Both safety and sustainability aspects are important in planning and designing tall buildings [3]. Sustainable buildings commonly understood to refer to the way buildings operate including the infrastructure needed to support them. This includes land use and planning [4], effective energy use for maintaining environmental quality and lifecycle GHG emissions [5, 6] for the technologies involved.

Sustainability indicators that have been published around the world include more than 894 entries registered in the database of the Compendium of Sustainable Development Indicator Initiatives [7]. The criteria used in this tool for assessing the sustainability performance of a building are built upon existing rating tools, such as Green Star, NABERS [8], LEED [9], LBC [10], WELL [11] and BREEAM [12]. In a nut shell, the criteria allocation of the above rating tools [8-12] can be approximated to indoor air quality (15%), energy (15%), water (15%), management (20%), accessibility (15%), land use (10%) and amenity (10%). Amongst these, management has been given the largest percentage of weighting (20%) due to its significant impact on building sustainability. However, this includes the mostly the performance of building services and outdoor facilities to ensure the occupants' comfort. Amongst these what is overwhelmingly marginalized is the maintenance of building structural and non-structural components.

It is the contention of this paper that ensuring building's effective operation during their designed service life ensures their durability. Therefore, a consideration of maintenance of structural system of the building needs to be considered from the conceptual design phase and be incorporated as a part of effective sustainable development. Genuine sustainability in buildings can be achieved by adopting a holistic approach. For example, adequate accessibility to critical elements of the building need to considered at the conceptual design stage to ensure effective diagnostics and optimum levels of reparability for proper functioning of a building throughout its design life. The resources, labours, and rate of maintenance can therefore be minimized by adopting a good maintainability in design. This will also ensure a reduced life-cycle cost and negative environmental impacts of the building. Specific design objectives for sustainable building construction will also include the choice of construction materials and a consideration of recycling and disposal of the material when the building is demolished.

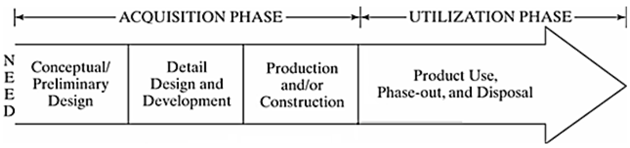
This paper discusses the important of adopting a systems approach towards building design at conceptual stage with a focus on accessibility, maintenance (inspection, repair and retrofitting), recycling and disposal of the structural systems. It is understood that adding extra features facilitating access to the building will inevitably add to the initial cost, however when considered over the life of the building this will be only a small proportion of the repair and maintenance cost.

This paper discusses the maintenance of structural system as an important addition item for consideration early at the conceptual design stage. It argues that simple steps such as accessibility to selective items, a proper choice of material and a better strategy for maintenance will undoubtedly increase the lifespan of the building. Consideration of controlled damage and/or repairs of buildings already take place in the building industry. Sample cases of the building maintenance affected by earthquake and corrosion are presented. These are the two most common issues maintenance engineers face.

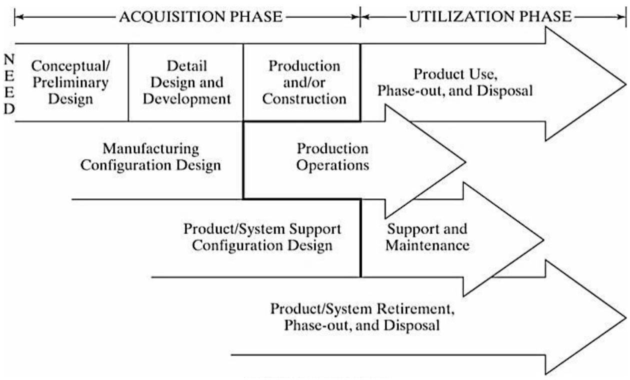
2. Consideration for Building Structural Maintenance at Conceptual Design Stage

A building is a "system of systems" where different elements such as electrical, plumbing, heating, ventilation, air-conditioning and the like are functioning in the same overall setting, each responding to a different set of requirements Blanchard and Fabrycky [13]. Amongst these the structural system (or the building skeleton) is one of the most important ones as it supports the dead loads (includes the all other systems), live loads and environmental actions. When designing such a system, one of the challenges is to ensure that it operates satisfactorily and does not degrade because of systems operating at the same time. For examples, if a building has multi-storey carparks at the basement, the corrosion risk of steel materials need to be considered at the conceptual design stage. This will allow using a careful design, better choice of materials and accessibility to those elements in the building where maintenance inspections need to be carried out. Currently, this is not emphasised.

The difference between the conventional design approach and the systems engineering approach is illustrated in Figure 1. It is noted that manufacturing, product support configuration and even disposal of the product is considered at the conceptual stage.



a. Conventional approach



b. Systems engineering approach

Figure 1: Conventional approach and Systems engineering approach considering maintenance life cycle (Blanchard and Fabrycky, 2011) [13]

The major functions of the system engineering process during conceptual design are the establishment of performance parameters, operational requirements, support policies, and the development of the system specifications [13]. The anticipated levels of maintenance, strategies for repair, organisational responsibilities, design criteria for the various elements of support (accessibility, test equipment, spares and associated inventories, transportation, facilities) maintenance arrangement, and environmental requirements relating to the maintenance works are defined at the conceptual stage. This will ultimately lead to a comprehensive maintenance plan.

3. Design for Maintainability and Accessibility

Maintenance cost is found to be the largest part of cost over a building's life cycle and it is currently not really considered in the early design phase [14]. Some design mistakes that make maintenance activities difficult or even impossible to perform can further increase maintenance cost during the operational phase of the building [15]. Arditi and Nawakorawi [16, 17] claimed that 50% of the maintenance related problems can be eliminated if design defects can be prevented during the design phase. Additionally, flexibility is high and design change cost is low in the early design phase. Consequently, design of good maintainability can eliminate maintenance costs, reduce downtime and improve safety [18].

Other benefits of good accessibility are to building components that require maintenance will reduce maintenance time and frequency, reduce special resources required for maintenance, help save repair and rehabilitation time and impedes maintenance errors. It will also facilitate comprehensive and precise diagnostics particularly using Non-Destructive Testing (NDT) equipment which will assist the rapid and positive identification of faulty items. The process will reduce the active repair time and precludes the likelihood of removing and replacing the wrong items (i.e., promoting the costly "maintenance–by–substitution" possibility). The fulfilment of all of these design objectives will, of course, result in a reduction of maintenance cost and, thus, system life–cycle cost [13]. Consideration of access for maintenance of other systems such as electrical and plumbing is managed using tools such as building information modelling (BIM) system.

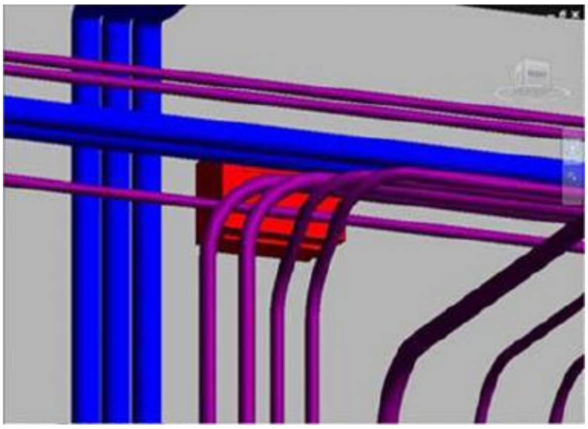
3.1 Use of BIM towards maintainability of structural elements

BIM has been developed to facilitate the design for building facility maintenance during the design phase of the building. Facility managers are the ones who finally operate and maintain the designed and constructed buildings for years. Mohammed and Hassanain [19] pointed out that if the facility manager's involvement can be brought into the design phase, major repairs and alterations in the lifespan of the facility will be reduced. However, it is difficult to get the facility manager involved early at design stage because the facility management team may not have been established yet during the design phase. Thus, BIM can serve as a solution to this problem by bringing the facility management team's knowledge like facility maintenance requirements at design stage without the physical presence of the facility management staff [14, 15].

Liu and Issa [14] provided an example of how to solve the maintainability problems in the design phase using the Revit Add-in as a BIM tool to identify unfriendly designs for maintenance which can inhibit the access to an exhaust fan. The exhaust fan and its surroundings are provided in Figure 2a and the Revit model of it is shown in Figure 2b.

The Revit add-in then output its results by highlighting the elements that would become obstacles for maintenance activities conducted for the exhausted fan [14, 15]. In this Revit model, the pipes and conduits within 76 mm of the selected point were highlighted in red [14, 15]. With the use of Revit add-in as a BIM tool, designers can decide whether this is a realistic design or whether to move the corresponding item, without having to transfer the Revit results to another software platform.

a. Actual exhaust fan location



b. Revit add-in of exhaust fan location

Figure 2: Location of an exhaust fan [14, 15]

4. Maintenance of Structural Elements

Maintenance related issues can equally occur for structural elements especially when they suffer from extreme events like earthquake and fire. For instance, the loss of strength and stability of load bearing elements due to earthquake can cause safety issues for personnel undertaking repair or maintenance work, thus making maintenance activities inaccessible to the building. It is presumed that by making use of BIM tools to model the possible scenarios of structural elements after earthquake, better design decisions are likely to be made to improve the performance of structural elements and further improve the building accessibility and maintainability. Examples of building structural maintenance and repair work are presented as followed.

4.1 Examples of post-earthquake repair

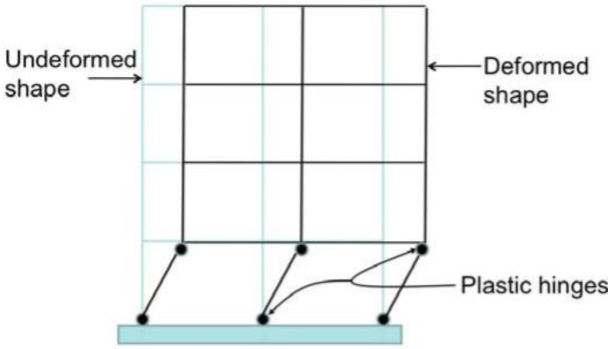
One of the major concerns for the structural design of a building is its responses to earthquakes actions which are determined by considering the site hazard and the type and configuration of the structure. The Australian Standard (AS 1170.4, [20]) provides the means for reducing earthquake loads on a structure by achieving set levels of ductility. Materials design standards then provide detailing to enable the selected structural ductility to be achieved. The aim is to avoid collapse. This requires the structure (and indeed the whole building) to be able to deform with the earthquake and absorb energy without vertical supports giving way. Therefore, it is not expected that a structure subject to the design earthquake would be undamaged, but rather that the damage had not progressed to collapse [21].

When a building element can be expected to be deformed, albeit by absorbing energy, it can be expected that it that particular element is damaged. Hence, design of the building can be managed so that this element is accessible. In regions of very high seismic risk, it is economically impractical to design structures to resist severe but rare earthquakes without damage. Instead, the building codes have adopted a design philosophy intended to provide safety by avoiding earthquake-induced collapse in severe events, while permitting extensive structural and non-structural damage [22].

Inelastic behaviour in steel special moment frame structures is intended to be accommodated through the formation of plastic hinges at beam-column joints and column bases. Plastic hinges form through flexural yielding of beams and columns and shear yielding of panel zones. It is expected that beams will undergo large inelastic rotations at targeted plastic hinge locations, which might be at the ends of beams, at deliberately weakened portions of the beams with reduced beam section designs, or within the beam span if large gravity moments are present. Failure modes can include excessive local buckling (Figure 3) and lateral torsional buckling. Each mode by itself, or the combination of both, leads to a continuous decrease in strength and stiffness and is very costly to repair after an earthquake [22].

Other features that have been used in buildings to absorb shock and deform include steel bracings which are found to improve strength and stability which in turn make it easier for maintenance work after an earthquake event. Good maintainability can be achieved by considering the steel bracing at the design stage for buildings and in particular the tape of connection needs special care. There are various types of steel bracing which can be used in combination with reinforced concrete frames. The study by Maheri and Sahebi [23] indicated that the addition of merely one diagonal of steel brace to a concrete frame largely increases the in-plane shear strength. Seismic load tests conducted by Maheri et al [24] showed that the yield capacity and the strength capacity of a ductile reinforced concrete (RC) frame can be increased and its global displacements can be decreased to the desired levels by directly adding either an X- or a knee-bracing system to the frame. These additional features are also low cost, light weight, energy-absorbing designed for resisting seismic actions. In addition, they are easily maintained, repaired or replaced [25].

a. Typical local buckling of beam flanges and web in zone of plastic hinging



b. Formation of a single story frame mechanism, also termed a "weak story" mechanism

Figure 3: Localised deformation in structural systems (Hamburger et al [22]).

4.2 Examples of corrosion and maintenance

Almost all engineering materials, such as steel, plastics and concrete, are subjected to corrosion and degradation. This includes all vehicles, buildings and infrastructure. Corrosion can result in dreadful tragedies such as train derailments, oil spills, collapsed bridges, gas shortages and severe power outages. Estimates are that corrosion may have cost Australia up to $32 billion per annum which is more than $1,500 for every person in Australia each year [26].

Service life of a building can be ensured through improving the resistance of its structural elements to corrosive chemicals so that less maintenance or retrofitting work is required to repair the damaged parts. Among the most common chemical attacks on building structures, chloride is identified as a critical agent, a small amount of which can initiate the corrosion of steel reinforcement and cause the degradation of RC structures [27]. During the corrosion process, the chloride on the steal surface is not used up, thus the reaction will continue until all the steel and oxygen are consumed [28] [29].

Defects associated with chlorides can range from aesthetic concerns (e.g. staining and deposits on soffits, walls, columns, etc.) to structural damage (e.g. localised corrosion and loss of bond strength of reinforcement and spalling concrete). Corrosion tends to develop in patches (due to chloride concentration or carbonation) leading to spalling and delamination. Where the concrete is saturated and chloride ingress is localised, pitting corrosion (black rust) can develop leading to localised and rapid corrosion of reinforcement (Henderson et al, 2002). Mild steel fixings for cladding and edge protection systems are particularly prone to corrosion and can cause failure of cladding and edge protection systems. The case studies found that in many instances the use of galvanized mild steel only delayed the onset of corrosion and did not prevent it from occurring. In particular, galvanised holding down bolts for edge protection systems can be susceptible to corrosion.

Electrochemical techniques for the repair of reinforced concrete structures damaged from chloride induced corrosion are being widely recognized as an effective long-term solution to stop reinforcement corrosion [28]. Cathodic protection (CP) is one of the most widely used and effective electrochemical methods which features a protection mechanism resembling the reactions occurring in a battery [29]. In a battery, there is generation of electricity because two dissimilar metals are exposed to an acidic

a. Chloride-induced corrosion of reinforced concrete with subsequent dripping of salt water and calcium carbonate onto vehicles below

b. Chloride-induced corrosion of fixing bolts for cladding

Figure 4: Typical examples of corroded building elements, Henderson et al, [29]

solution which corrodes one metal and creates a harmless reaction in the other. This corrosion reaction at the 'anode' generates electrons that are consumed by the 'cathode'. As a result, the steel reinforcement as 'cathode' is protected by sacrificing the 'anode' material. The reaction is illustrated in Figure 5 [30].

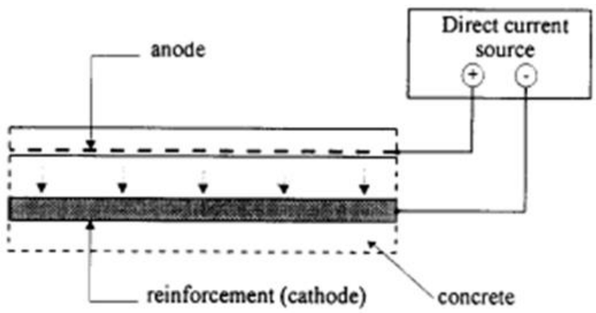


Figure 5: Schematic diagram of cathodic protection, Pedeferri [30]

A successful example of the application of cathodic protection for building elements is the Trident Building in Manly (NSW) whichunderwent a major refurbishment work during 1996-1997. The refurbishment work incorporated the cathodic protection to a variety of elements of the building [28].

The anode material for the external elements of the structure was selected to be ribbon anode LIDA® grid due to its flexibility of application regarding the variation of anode spacing to satisfy the variation in current requirements [28]. The cathodic protection system was divided into 3 separate sections (A, B and C). Each section was divided into 15 separate electrical zones to satisfy the conditions including building geometry, the different corroding conditions of the elements to be protected, Variation in concrete resistivity, the extent of deterioration of the elements to be protected, and the size of power supply units. Each section of the system was divided into five separate main electrical zones. The demonstrations of the cathodic protection system installed for the building are illustrated in Figure 4 and Figure 5 [28].

After finishing the installation of CP system, the builder provided a 10-year warranty for concrete repair as a part of a 10-year maintenance program for the building [28]. Over the maintenance period until so far, although various concrete defects were identified and rectified by the builder, the overall repair work is localised to a smaller extent and is relatively minor comparing with the extensive damage found at the building prior to the refurbishment. Therefore, the project of the application of CP system to building structural elements turns out to be successful and it proves that the CP system can be an ideal method to protect the corrosion of building structures.

Another important implication of this project is that improvement of maintainability at the design phase of a building can be achieved by employing a CP system for the building to resist the corrosion of critical structural elements. Although maintenance work is still required to ensure the fully operation of the CP system, major repair work tackling with the corrosion of reinforced concrete structural elements can be reduced to a large extent, especially for structures subject to corrosive agents in a coastal or underground environment.

Figure5: Typical main zoning of the cathodic protection system for sections A, B and C (picture above – the actual building [28]

5. Conclusions

The current literature on maintenance of building structural systems was reviewed in this paper. Considerations for maintenance at conceptual design stage of building structural elements were discussed and the importance were emphasised. Examples of post-earthquake repairs and corrosion preventions have been presented. Whilst it is uneconomical to design for buildings to prevent damage under an extreme event, designing for pre-determined locations of damage would allow for post-earthquake repairs to be effectively carried out. Design approach needs to consider hard-to-inspect locations from the initial stages. It is shown that BIM can support the design process and should consider accessibility for structural health monitoring related issues at the onset of design process. Buildings are prone to deterioration due to environmental factors. In particular, it is reported that corrosion of reinforcement is difficult to manage, poses a problem to asset owners worldwide and can be very costly to repair if it is not maintained adequately. This problem if often neglected at the design stage.

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