POTENTIAL OF BUILDING INFORMATION MODELLING FOR SEISMIC RISK MITIGATION IN BUILDINGS

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SUMMARY

The seismic assessment of an existing building is often required, possibly due to a change in use, changes in legislation (as recently occurred in New Zealand), for insurance purposes or to permit continued occupancy following a major earthquake. This discussion paper explores three ways in which Building Information Modelling (BIM) could assist in the assessment and mitigation of seismic risk: (i) BIM could provide valuable data on characteristics of both structural and non-structural elements within a building to permit a reliable and holistic seismic risk assessment to be undertaken; (ii) administer a self-diagnosis process utilising damage information received from structural health monitoring technologies prior to and following an earthquake, thus reducing the need for potentially dangerous and time-consuming physical post-earthquake inspections; and (iii) enabling realisation of an emergency management hub within a building management system for implementing control processes to monitor and eventually shutdown damaged mechanical services (e.g. gas pipes) following an earthquake, thus limiting the negative consequences of earthquake induced damage. By providing a leading-edge discussion of these three subjects, with reference to building damage observed in previous earthquakes, important directions for research in BIM are identified that promise to provide a more effective means of seismic risk assessment and mitigation.

INTRODUCTION

The severe consequences of earthquakes are a frequent reminder of the seismic risks that face our society. When attempting to quantify the seismic risk for a building, whether in terms of its adequacy to withstand an anticipated seismic intensity or the more unfortunate scenario of determining its condition following a significant earthquake, there are numerous uncertainties and unknowns that must be addressed in order to properly define its condition such that remedial and mitigation actions can be taken. This paper discusses some of the key aspects of seismic risk mitigation that could benefit from a better knowledge of structural and non-structural conditions and explains how the use of Building Information Modelling (BIM) technologies may further its capabilities.

The current state of BIM is reviewed with respect to the development of the state of the art, and main issues concerning the extension of BIM capabilities. Different features of BIM technology are discussed as pertinent to various forms of seismic risk mitigation in buildings.

OVERVIEW OF BIM

The term Building Information Modelling (BIM) can be defined as a process producing and utilising a digital representation of a built entity that allows physical and functional information to be shared amongst multiple parties; in a manner that supports decision making throughout the life of a facility [1,2]. Conceptually, BIM has been discussed in the literature since the 1970s [3], yet it wouldn't be until the 1990s that the term was actually used when, seemingly, computing capabilities were able to coalesce with the clear and present demand for integrated building information within the Architecture, Engineering and Construction (AEC) community [4,5].

Advancements in BIM technology have allowed for the synchronisation of spatial data between design and construction processes in order to enhance the following: preplanning and early collaboration, consistency of design throughout the construction life cycle as well as prevention of geometrical conflicts (clash detection) and change orders [3,6]. Further, the real-time, object-oriented, capabilities of using BIM data extend beyond three-dimensional (3D) functions to assist in numerous aspects of project management such as: quantity surveying, process visualisation and scheduling (4D) and cost estimation (5D) enabling integrated project delivery [3,7-9].

In addition to utilising BIM for AEC processes, much recent research has focused on the extension of BIM to include numerous aspects of facility management (FM) that are required in the maintenance and operations of a facility over its entire life cycle [3,6,10,11]. The field of FM is quite broad, with suitable BIM applications that include:

- Rapid updating of digital assets (e.g. location, details, and maintenance schedules of equipment) [3,9,11];

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- Using as-built data to guide renovations and retrofitting [12,13];
- Monitoring and controlling a range of building performance parameters using sensing technology (e.g. heating, energy) [11,12,14,15]; and
- Emergency management and risk scenario planning [16,17,18].

Notably, the latter two points involve communicating between external systems that perform specific functions such as those within building management systems (BMS) (more recently referred to as building automation systems, BAS) or emergency management systems (EMS). BMS operations can include control of temperature or ventilation (e.g. HVAC) based on pre-determined tolerances or management of lighting based on current building occupancy. An EMS is typically used to alert proper personnel and authorities when particular emergency situations are detected (e.g. fire or flooding). Although these systems can function on their own, the advantage of operating these systems on a BIM platform is the ability to allow instant access to as-built building information necessary for implementing certain functions (e.g. HVAC automation [15]) while maintaining real-time feedback in order to optimize decision making.

The current state of BIM application has had varied results in terms of adoption within a range of industries; primarily due to the lack of interoperability between different BIM platforms and additional software tools due to proprietary interests of software developers [3,6,19]. However, it is noted that legal (e.g. data-ownership, responsibility) as well as managerial (e.g. unwillingness to change training and collaboration processes) issues are also relevant [3,6,19-21].

In order to cope with issues relating to information exchange, much effort has been made by group initiatives such as the National Institute of Building Sciences (NIBS) smart Building alliance [22]. This group aims to provide non-proprietary ("open-BIM") guidelines for the treatment of information regarding model object development, specialized systems (e.g. HVAC), transfer from construction to operations (e.g. facility management), and effective preservation of information for building automation systems, among others [23-26].

Despite the issues involved with widespread adoption of BIM, recent surveys report numerous cases where BIM is being adopted by various disciplines as well as an increasing trend for planned BIM adoption in the future [20,27-29]. Further, it is not uncommon (in North America at least) for owners or decision-makers to require as-built BIM models upon completion of a project [27]; highlighting the potential that further implementation of BIM technology could have on various components of the building industry in the future. Furthermore, it could be argued that most of the capabilities and benefits of using BIM have only been well-documented for the AEC project cycle [3,30,31]. However, there have also been other implementations with respect to more advanced applications such as monitoring and control [15,16,32,33]. In combination with substantial research within both academic and professional literature, this suggests that as acceptance of BIM implementation broadens, the largest benefits may lie within the consideration of the full life cycle of a building [10,34,35].

This brief overview of BIM is not for the purpose of providing an all-encompassing review of its capabilities, but to give a clearer image of where BIM technology stands today. Put simply, it is a technology with seemingly ever-broadening bounds in terms of application potential, yet, just as other technologies that have posed a burden for society; it's likely that it will rely on the inevitable passing of time to bring it to a state of ubiquity. The remainder of this paper explores, conceptually, the possible developments that could be made to BIM systems for the purposes of reducing seismic risk.

BIM FOR SEISMIC RISK ASSESSMENT AND MITIGATION

Overview of Seismic Assessment

The seismic assessment of a structure aims to provide building owners and other affected parties with an indication of the risk of damage and life threatening collapse. Seismic risk assessments may be necessary under a number of circumstances including; change in ownership or occupancy of a structure, determining appropriate insurance policies and mandated investigations of a building following a seismic event. Further, structural assessments may be conducted due to changes in legislation as it is currently occurring in New Zealand [36].

Modern seismic assessment methods [37-39] can range in complexity yet principally rely on the same fundamental concepts. Pre-defined displacement thresholds or limit states are defined in order to represent different levels of seismic performance ranging from the onset of damage requiring repair to the displacement associated with imminent collapse. The relationship between damage and lateral stiffness degradation which in turn elongates the fundamental period of vibration, T, is illustrated in Figure1a. The risk or likelihood of exceeding a given limit state is estimated by comparing expected seismic demands with capacities; where seismic demands are typically expressed probabilistically. This is reflected in most seismic codes and supplemental assessment guidelines [40,41] by attributing different return period events (i.e. events possessing a different probability of occurring over

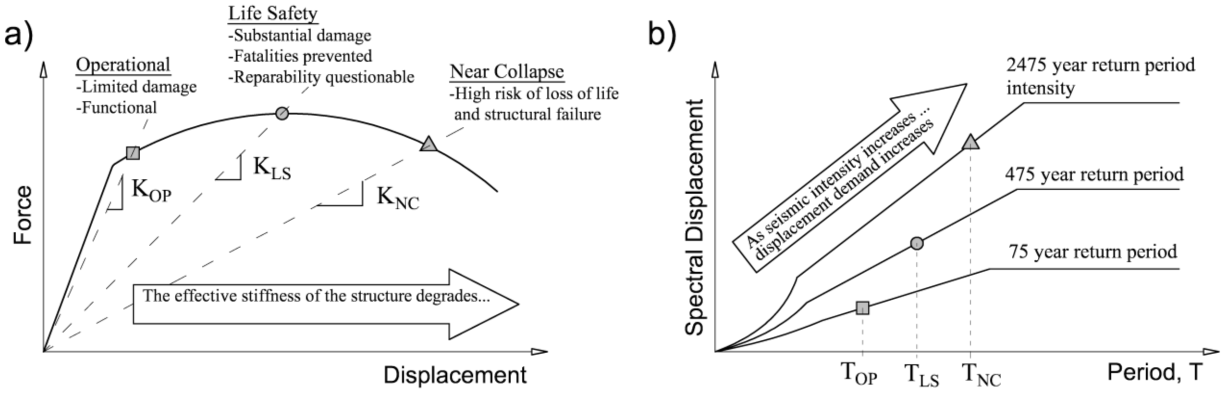

Figure 1: ***(a) Limit state definition showing the degradation of lateral stiffness with increased damage, (b) General relationship between seismic intensity, effective period, and displacement demand.***

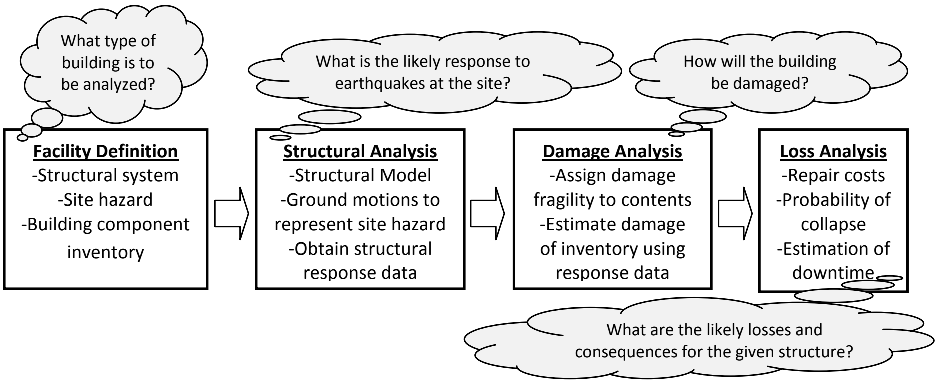

Figure 2: ***Conceptual illustration of conducting loss assessments within the PEER PBEE methodology* [44].**

a time frame) to the assessment of primary limit states as shown in Figure1b.

The seismic risk assessment of buildings is a relatively complex task because of the difficulty in properly establishing material properties and structural details, to the point that the characterisation of a structure can become one of the main challenges of an accurate assessment [42].

Evolution of Seismic Assessment Methods and Measures

In recent decades a number of conceptual improvements have been made to seismic assessment methods. Firstly, it has been recognised that a seismic assessment should lead to performance indicators that are appropriate for decision makers [43], providing indications of likely losses and downtime for repairs, in addition to the risk to human lives. Secondly, assessment methods should include probabilistic treatment of the uncertainties inherent to seismic risk assessment. In the U.S., this line of thought has lead to the development of the Pacific Earthquake Engineering Research Center's (PEER) Performance-Based Earthquake Engineering (PBEE) methodology [44,45]. The framework includes four stages which, as shown in Figure 2, consist of Facility Definition, Structural Analysis, Damage Analysis, and Decision Analysis.

The first two stages represent more traditional features of seismic assessment where the structural characteristics are identified and a model of the structure is subjected to seismic excitation simulations in order to determine its likely maximum response (displacement, forces, and accelerations). A particularly novel aspect of the PEER-PBEE methodology lies within the final two stages. The Damage Analysis stage requires that (ideally) all damageable components within a structure are identified and assigned damage fragilities which, for this discussion, can be viewed as probabilistic representations (refer [46]) of a component experiencing a given level of damage with respect to its critical seismic response parameter (displacement, acceleration) obtained from the structural analysis stage. Given the numerous types of structural and non-structural elements that can be present in a building, the availability of component fragility functions is the product of extensive experimental investigations (e.g. [47-50]. Upon defining the likely damage of components within the structure, the Decision Analysis stage transforms the likely structural response and damages into decision variables such as monetary loss due to repair costs, loss of use of facility (downtime) and the likelihood of injury or fatality due to either collapse of the building or failure of components within the building. This is typically carried out by the development of consequence functions that utilize survey data from contractors in order to attribute unit repair costs (or repair times) to test specimens that have been subjected to varying degrees of damage.

The task of building-specific loss estimates puts a much higher premium on the knowledge of the details within a building, particularly in regards to non-structural elements. This reflects the fact that recent seismic events have shown that the damage to non-structural elements have had a major impact on resulting losses and consequences [51-55]. The major importance of non-structural elements can be summarised by the following key points:

- Non-structural elements represent the major portion of the total investment in typical buildings;
- Non-structural damage can severely limit the functionality of critical facilities, such as hospitals; and
- Damage to non-structural elements typically occurs at seismic intensities much lower (and more probable) than those required to produce structural damage.

The significance of non-structural elements in the seismic performance of buildings has led to guideline documents being developed in both the U.S. [56] and New Zealand [57] to allow current knowledge about non-structural detailing (i.e. from previous events and testing) to be made readily available. However, the main concern with non-structural elements is seemingly rooted in their secondary position within the construction sequence, making it difficult for good seismic detailing practice to be regulated; despite existing knowledge of good detailing. The Christchurch, New Zealand earthquake sequence (September 2010 and February 2011) was a recent reminder of the issues with non-structural construction practice with some key reported observations as follows:

- There were numerous cases of non-structural systems (e.g. partitions, ceilings) being damaged in the September 2010 event and replaced with similar traditional detailing only to endure similar damage following the February 2011 event [58,59];
- Non-structural failures occurred due to improper consideration (or neglect) of system interaction (e.g. ceiling, mechanical) with cases in which one system was seismically upgraded only to be damaged by a different non-structural system [59]; and
- Non-structural systems incorporating seismic detailing and installation practices generally showed better performance [59,60] but are still not widely adopted.

Given these observations and current advancements in seismic assessment techniques, it is likely that detailed information about a building can not only allow for sources of seismic risk to be quantified and conveyed in a useful manner, but also allow informed decisions in order to mitigate them; such as the case of non-structural elements.

How Can BIM Contribute to Seismic Risk Mitigation?

The use of Building Information Modelling (BIM) within a seismic assessment can provide crucial information necessary to eliminate uncertainties and enhance the quality of analysis results. Further, the real time geometrical capabilities of BIM during the construction process can greatly increase the feasibility of conducting seismic assessments of building components and contents (i.e. architectural, mechanical) at the most critical stages where changes in detailing may still be cost effective.

In terms of the structural assessment of a building, BIM can provide readily available information on structural details and as-built properties that would greatly enhance the accuracy of a seismic assessment. Reinforcement schedules for concrete structures, connection details for steel buildings, and mill certificates for material properties are all well within the primary capabilities of BIM [20,61]. Also the ability for BIM to accurately update the expected weights of components within the building [3] allows for accurate estimates of seismic mass; an input parameter that can be a significant source of uncertainty in seismic risk assessments [62-64]. Further, the real-time export of structural details in order to perform structural analysis has been addressed within the confines of structural safety assessments during the construction process [61].

In the case that a loss assessment is required, via say the PEER-PBEE approach, BIM could provide precious information on the detailing and quantities of both structural and non-structural elements. The detailing of elements is essential to properly attribute damage characteristics (fragility) or, conversely, reduce the error involved when consulting experimental data that is already likely to be limited. Moreover, the knowledge of component quantities is important for the proper estimation of unit repair costs (consequence functions). The use of BIM can also provide records regarding the installation costs at the time of construction as well as manufacturer details [11,20] of mechanical and service equipment which can significantly reduce the inventorying process prior to conducting a seismic loss assessment. The specific case of obtaining information for a particular building with light gauge steel-framed gypsum partition walls is used to illustrate how BIM can assist in seismic loss assessment. Figure 3 shows that BIM could allow for the rapid calculation of the quantity of partitions while providing accurate details on the fastener spacing, top/bottom connections and stud characteristics which can then be used to attribute proper damage fragilities. Finally, based on the quantity and quality of the partitions within the building, construction estimators (or the literature) may be consulted in combination with any existing costing information from original installations in order to determine the unit repair costs for various methods of repair; further enabling an accurate estimate of how unit costs may vary depending on the number of partitions to be repaired.

The time delay between initial construction and later assessment invites nearly limitless changes in the layout of a building, which could render original architectural and mechanical drawings useless for inventorying. As BIM allows for constant updating of building details throughout a building's life-cycle [3] this problem could be avoided, potentially saving valuable time that would be required for physical inspections. Furthermore, from a non-structural intervention standpoint, the typical design-construction sequence, in interests of efficiency, rarely allows for structural engineers (or seismic consultants) to become involved in the phases that include the design and installation of architectural and mechanical contents [65]. However, the use of BIM could allow for the real-time cost estimates and feasibility of implementation of various changes in the seismic detailing of non-structural systems [3,66]. Regardless of the age of a building, the on-hand information that can be provided via BIM can greatly enhance the quality and efficiency of seismic risk assessment. Although still in need of future development [6], much research has been conducted in order to assist in the development of building information models for existing structures [12,13,67,68].

The capability of BIM to organise and export information to external software [3] could greatly increase the feasibility of conducting comprehensive seismic risk assessments as a common practice. The development of specific tools/software to interpret data for various aspects of building operation can be connected with BIM to best utilize and interpret the available information. Specific tools or software can (or could be developed to) process data for structural elements, architectural components, utility systems, and building contents or inventory to quickly provide information for professionals of the respective fields (refer Figure 4). Further, the multi-disciplinary information required for a seismic loss assessment could be accessed efficiently through the development of specialized risk assessment programs that would be compatible with the external programs operating off of the central information platform provided by BIM. Through further developments, the manner in which data could be obtained for seismic risk assessments using BIM would increase both reliability and feasibility by reducing uncertainty and allowing for much faster and efficient analyses to be conducted. In essence, BIM would act as a central master building repository for seismic assessment.

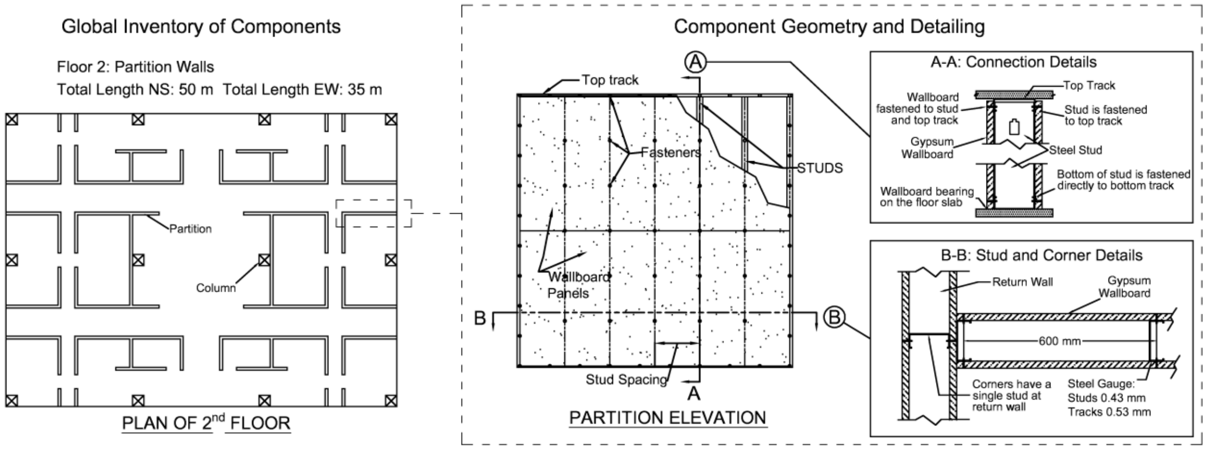

Figure 3: ***Example of information for partition walls that can be made readily available using BIM, that would otherwise be difficult to obtain, and would be useful for seismic assessment.***

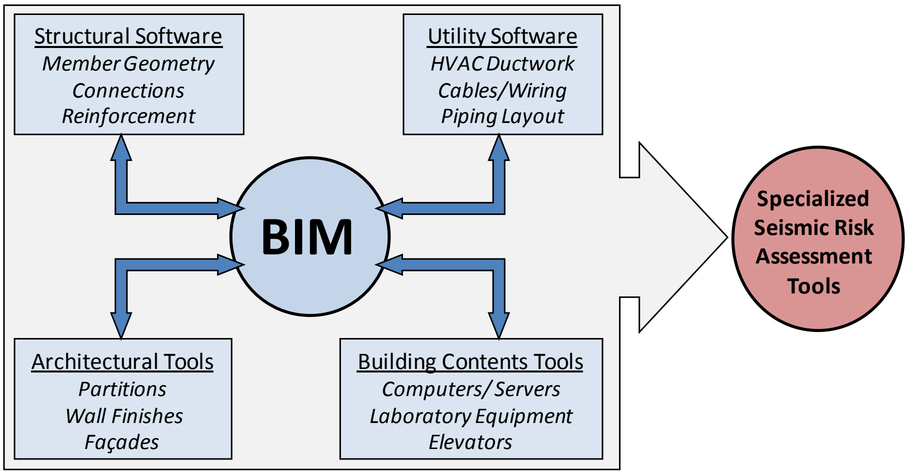

Figure 4: ***How BIM could be used as the master building repository to exchange data between multidisciplinary software platforms and compatible seismic risk assessment tools.***

BIM FOR POST-EARTHQUAKE INSPECTIONS AND RECONNAISSANCE

Post-Earthquake Inspection

In the weeks and months that follow an initial earthquake state of emergency, engineering assessments of buildings are required to allow people to regain safe access to their properties. As such, one of the main processes involved in the response to a seismic event is the post-earthquake inspection of buildings. The size of the affected area, magnitude of the event, and available resources all play a significant role in carrying out an inspection operation. The location of the affected area can also determine the extent to which exterior personnel may need to be contacted (metropolitan area versus a more rural or underdeveloped region) noting that inspectors are required to have sufficient engineering knowledge and ideally possess experience with post-event inspection [69]. Figure 5 illustrates the visual post-earthquake inspection process.

Figure 5: ***An example of volunteer inspectors during post-earthquake inspection (Photo courtesy of EUCENTRE).***

The typical protocol for carrying out post-earthquake inspections is through the use of a "tagging" system by which buildings can be quickly identified with a commonly adopted green, yellow and red system such as the ATC-20 (United States) or Building Safety Evaluation (New Zealand) guidelines [70,71] where:

- Green signifies that the building is "inspected" and occupancy is permitted (bearing in mind that the use of the word permitted here would suggest that the undamaged building was deemed safe);
- Yellow represents the presence of some hazard within the building and receives a "restricted use" placard typically with notes describing the risks and extent of entry;
- Red represents the case of a clear hazard to human life and returns an "unsafe" placard that prohibits any re-entry or occupation of the building.

Since the number of buildings to inspect can be tremendous but the task force of inspectors is likely to be limited, the inspection operation in the United States is typically carried out in waves of inspections of increasing detail and time allotment: rapid visual evaluation of the exterior (30 minutes), detailed visual evaluation of interior/ exterior (hours), engineering evaluation (weeks) [70].

The main purpose of the different levels of inspection is to ensure that the most dangerous hazards are quickly identified while other structures will require further investigation in order to assess their condition. For example, if a building is seemingly pristine or already partially collapsed the issuance of a green or red tag is quite straightforward, yet the common situation of not understanding a buildings actual damage and residual strength requires that a yellow tag be issued with certain restrictions so that more time can be allocated for a more in-depth investigation [72]. Note that in the case of green-tagged buildings, such assessments make no evaluation of the seismic risk of the undamaged building and does not use rigorous engineering approaches to identify the actual damage state. This suggests that the issuance of a green tag, while allowing continued occupancy, can give a false interpretation of the structural state of the building without properly identifying whether "negligible" visible damage has changed the seismic risk of the structure or if the undamaged state of the structure is at risk in the case of future earthquakes or aftershocks. The latter was unfortunately witnessed during the Christchurch earthquake sequence where multiple buildings were green-tagged following the September 2010 event and then collapsed during the February 2011 aftershock [60].

Issues Involved with Post-Earthquake Inspection

The main limitation of visual post-earthquake inspection is that its quality depends on the capability of physical inspectors and that many key characteristics of a structure (stiffness, strength, mass, deformation capacity) cannot be gauged from a visual inspection. From an accuracy standpoint therefore, the capabilities of visual inspections are severely limited due to both time and physical constraints where the short allotment of time combined with rapid visual assessments cannot achieve accurate estimations of the structural condition. Moreover, the effect of human judgement can lead to widely varying interpretations of structural safety, even amongst engineering professionals. The implementation of inspection guidelines (e.g. ATC-20 [70]) conceptually is a logical solution to minimize this problem, yet they are not always followed and there is no practical method to enforce them; unfortunately allowing poor (and dangerous) assessment decisions as was witnessed in some cases following the 1994 Northridge event in California [55].

A more rigorous engineering assessment would involve the evaluation of structural characteristics such as the strength, stiffness, mass and deformability. The initial period of vibration and material properties of a building can be assessed through relatively inexpensive non-destructive in-situ testing; providing very useful insight to the dynamics, strength and deformability of a structure. Despite the relatively low costs of obtaining this information, the strict time limitations on a post-event assessment may lead to hurried analysis without adequate understanding of the building [73], thus drastically reducing the reliability of results. Nevertheless, even if proper actions are taken, hidden structural information, such as quantities of reinforcement or foundation details will mean that assessments are highly uncertain if accurate building drawings are not also available.

Another issue with visual inspection is the risk it poses to (voluntary) inspectors. After a major earthquake, one should always expect aftershocks in the days, weeks and months that follow. Clearly, such aftershocks can provoke the collapse of buildings, highlighting the fact that during post-earthquake assessments, inspectors are likely to be putting their lives at risk when entering buildings. Building occupiers may also be more at-risk since there is the chance that even if their building was green-tagged following a visual inspection, it may have suffered unseen damage or can still be vulnerable to future earthquakes or aftershocks.

Given the substantial financial and injury-related losses that can occur over an earthquake stricken area there are also many legal complications that can arise from visual inspections. Anagnostopoulos and Moretti [69] suggest that governing authorities should take all necessary steps in order to fully insure inspection teams both against injury and any liability that can result from their assessment or tagging decisions. Notably, liability coverage does not have the intent of allowing poor assessments to be made without consequence, but should be aimed at avoiding overly-conservative assessments due to inspectors' fears for subsequent legal implications [69,73,74].

How Can BIM Contribute to Post-Earthquake Inspections and Reconnaissance?

The use of BIM technology in combination with current structural health monitoring technologies and in-situ testing techniques could provide essential information for the post-earthquake assessment of buildings. Structural health monitoring uses physical information about a building in its present state in combination with continual or periodic data acquisition in order to detect changes in structural behaviour. For example, if the period of vibration of a building were measured before and after an earthquake, any lengthening of the period would imply that its lateral stiffness had been reduced and therefore the structure is likely to be damaged. Information on damaged electrical systems or gas and water mains could help prevent people entering a hazardous area and would also assist people locating where repairs need to be made. The changes measured could be subtle displacements (e.g. sagging of beams) due to the aging and creep of a building under normal operation or abrupt changes in structural properties (e.g. lateral stiffness) as the result of earthquake loading [75]. The detection of earthquake damage is typically performed by monitoring the changes in the dynamic properties of a structure following the same principle outlined in Figure 1 where a structure will lose its lateral stiffness due to damage and subsequently have a longer fundamental period (see Figure 6). Notably, the use of modal properties can only relay the global condition of a structure whereas the use of acoustic emissions (AE) has been shown to be a viable method for assessing and locating structural damage for numerous applications [76-79]. Further, as these technologies represent a field outside the typical scope of BIM, it is noted that the use of an external information hub (such as BIM) may allow for their full potential to be realized [76]. The implications of having readily available information about a structure quite easily address many of the shortcomings of visual post-event inspection outlined in the previous section. The use of structural health monitoring

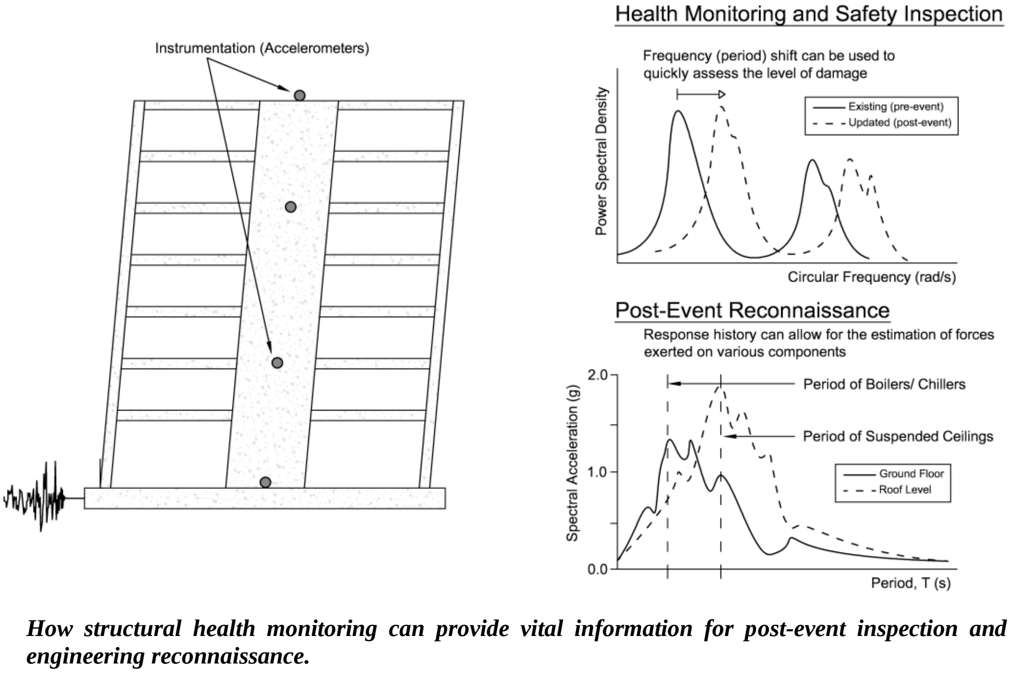

Figure 6: ***How structural health monitoring can provide vital information for post-event inspection and earthquake engineering reconnaissance.***

operating on a BIM interface could:

- Provide building owners with rapid information on whether or not their building has likely been damaged;
- Reduce the uncertainty in the safety assessment of buildings that have questionable visible damage;
- Help to alleviate liability pressures imposed on post-earthquake inspectors;
- Reduce the personnel required to investigate an affected area; and
- Allow for the effects of aftershocks to be readily assessed which simultaneously reduces risk for inspectors and reduces the number of inspections required.

Notably the last two of these points also suggests numerous benefits of BIM for an entire region and the data produced by increased monitoring and assessment activities will provide a better understanding of how various structural and non-structural elements respond in earthquakes (Figure 6). Further, existing strong-motion instrumentation efforts, such as the CSMIP [80] (United States) and GeoNet [81,82] (New Zealand) programs, could provide enhanced feedback by accompanying structural response data with explicit knowledge of the structural details that could be provided by BIM. This information, and particularly the possibility of cataloguing databases and sharing the information with building officials, could greatly further the entire field of seismic risk assessment by aiding the preparation of improved seismic design and assessment guidelines.

BIM WITHIN A BUILDING MANAGEMENT SYSTEM FOR MONITORING AND CONTROL OF EMERGENCY SHUTDOWN

Importance of Preparedness

A significant source of earthquake related losses can come from the secondary effects that damaged buildings may have on lifelines. If gas lines are ruptured or interior partition walls are damaged during an earthquake, the likelihood of fire ignition and spreading are increased and in fact, fire has historically been one of the most devastating secondary effects of earthquake hazard such as the 1906 San Francisco earthquake [83], where subsequent fires caused approximately 80% of the total damage following the earthquake [84]. Similarly, the 1923 Kanto, Japan event reportedly had 450,000 buildings destroyed by fire while only 130,000 were severely damaged by the earthquake [83]. In comparison to the aforementioned events, the extent of post-earthquake damage related to fire has decreased over the past century, yet more recent earthquakes would still show that it is a prevalent risk such as the 1971 San Fernando (California), 1994 Northridge (California) and 1995 Hanshin (Kobe, Japan) events [85]. Evidence has shown that ignitions are typically due to arcing from electrical wiring while, rather intuitively, the most common ignition material is natural gas [85] highlighting the significant risk associated with seismic interaction between structures and utilities.

Ironically, another major source of post-earthquake damage is due to the failure of fire suppression systems and other water distribution systems. Following the 1994 Northridge event, the single most significant source of damage was attributed to the rupture of water lines within buildings [55]. More importantly, many hospitals that are essential facilities after a seismic event were subjected to severe water damage due to the rupture of pressurised sprinkler lines. At least 13 hospitals in the area suffered devastating damage that rendered the facilities completely or partially inoperable [86]. Similarly, the aftermath of the 2010 Maule, Chile event revealed similar problems related to water line failure. The two main airports in Chile were severely damaged (and disrupted) by pipe breaks mainly due to interaction with ceiling systems (Figure 7). There were four hospitals that completely lost functionality and over 10 that were estimated to have lost 75% of their functionality due to damage of fire sprinklers [51]. Similarly, the February 2011 earthquake that struck Christchurch led to numerous instances of water damage due to failed utility lines [87] and the evacuation of two levels of the Riverside building of Christchurch Hospital due to failed sprinkler systems [60]. More recently, the BNZ building suffered severe water damage reportedly due to insufficient bracing of sprinkler systems following the July 2013 earthquake in Wellington [88].

One of the unique yet troubling attributes of water related damage is that minor failures (a few pipe leaks) can either be identified and controlled or let to exacerbate and cause significant damage [55]; with very similar consequences resulting from fire. Given this, the prevention and control of these secondary seismic vulnerabilities can have tremendous impacts on risk reduction, especially when considering hospitals that must be in operation following a seismic event.

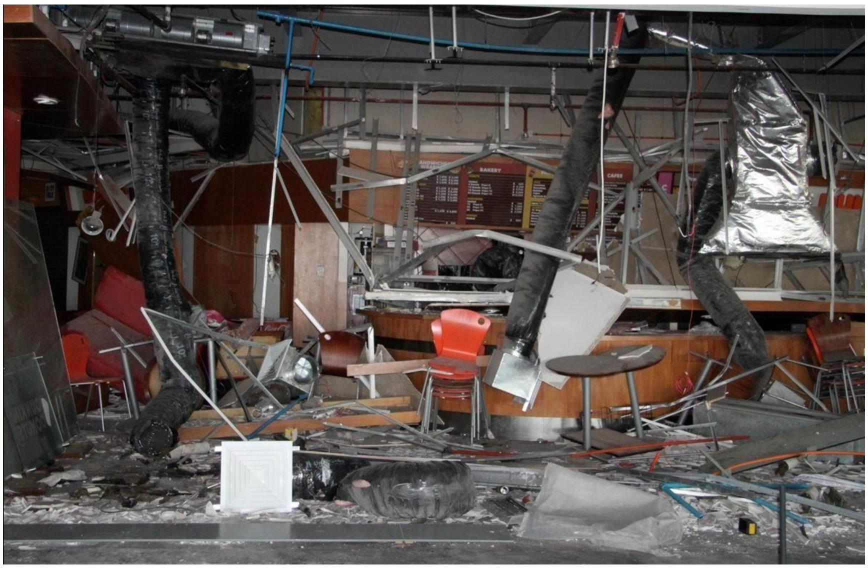

Figure 7: ***Damage to piping and other suspended systems at the Santiago International Airport following the 2010 Chile earthquake (Photo courtesy of Eduardo Miranda).***

The control of gas utilities during earthquakes to reduce the likelihood of fire has been underway for decades with standardized regulations in seismic prone areas (refer [89]) such as California that now mandates once optional systems in response to their witnessed effectiveness following seismic events [90,91]. The need for control of water related damage following earthquakes has been widely recognised, both from previous experience [55] and the potential for risk mitigation [75]. The current literature suggests, however, that various technologies still require some development to ensure these risks may be effectively mitigated.

How can BIM Contribute to Monitoring and Control of an Emergency Shutdown?

The use of BIM in combination with current monitoring and control system technologies could permit effective emergency shut-down of critical systems (or sub-systems), such as gas pipes and water pipes, following a damaging earthquake. The field of structural health monitoring typically relates to the monitoring of global dynamic properties and structural members to ascertain whether a structure has been damaged or not. Similarly, such techniques could also be extended to mechanical components and distribution systems [75].

The use of active structural monitoring and control technologies requires the formulation of a building automation system (BAS) consisting of a distribution of sensors, a data acquisition system (DAQ) to record and process input information, control processors, and physical intervention systems (e.g. actuators). The key role that BIM could play is to offer the necessary interface on which these elements can provide feedback, take actions, and update the current condition of the monitored facility. Although the implementation of BIM as such an interface is still under development, there have already been numerous successful implementations of BIM for structural monitoring and environmental control [15,16,32,33] suggesting that a step towards emergency post-seismic response solutions should not be far away.

Implementing monitoring and control capabilities for seismic shutdown of vulnerable systems and components requires a few additional considerations with respect to operational or environmental monitoring. Increased monitoring needs for high loading could be considered one of the prevalent challenges for monitoring systems [75]. By the same principle, the number of sensors must be carefully selected to provide the most useful data while minimizing sampling and processing requirements. With respect to the emergency monitoring and shut down of distribution systems, a few critical capabilities could include (but are not limited to) the use of pressure gages to detect leaks in water pipes and gas lines with local shut-off actuators and strain gages in tank or large component supports that interact with distribution systems [75,92]. The initiation of the seismic shutdown process could be conditioned on the exceedence of a threshold ground acceleration caused by a seismic event. This trigger event could also allow activation of remote/additional data acquisition systems and could permit a change in the sampling algorithm [93] in order to accommodate the increased monitoring needs with respect to operational conditions.

One of the main limitations of adopting real-time structural control systems for extreme scenarios such as earthquakes is the reliance on a constant energy supply [94]. The implications of interrupted power supply are furthered when considering essential facilities such as hospitals where a failed control system could lead to undetected leaks which have been shown to nullify attempts to provide backup power supplies [55]. Future research aimed at increasing the functional rigidity of advanced control systems and identifying how shut-down sequences can maximize reliability in terms of both damage prevention and resilience could greatly benefit seismic risk reduction. Further, as the current state of the art shows vast capabilities in the monitoring and control of building systems, it is expected that the effectiveness of relayed information will be a direct function of the preparedness and training of personnel for the physical changes required for maintaining operations [11].

In addition to allowing the automatic control of safety shutdown processes, the immediate access to information on the building condition that BIM can provide allows for efficient communication of essential information to emergency management personnel or first responders [16]. Regardless of precautions taken using advanced control technologies, the handling of emergency situations will always benefit from immediate information about a facility in order to efficiently make decisions to identify, prioritize, and manage risks [95].

CLOSING REMARKS

Many aspects of seismic risk mitigation were reviewed and discussed within this discussion paper. It was argued that the goal of performance-based earthquake engineering is often challenged by a lack of detailed information on building components and it was pointed out that Building Information Modelling (BIM) could help reduce these deficiencies in knowledge. The capabilities of BIM to provide readily available and detailed information about structural and non-structural elements can greatly enhance the quality and practicality of comprehensive seismic risk assessments. When combined with structural monitoring and control technologies within a building automation system, BIM can provide a platform that could allow for an unparalleled line of protection against secondary earthquake hazards such as fire and water damage; hazards that pose a significant risk for entire communities when it is considered how they could affect the operations of critical facilities such as hospitals. The ability to relay real-time structural information following an earthquake can provide improved rapid assessment of buildings during post-earthquake inspections, which can allow for more informed decisions in order to clearly convey structural safety while minimizing the need for inspectors to enter damaged buildings. In closing, the current capabilities of BIM technologies suggest that the field of earthquake risk mitigation could be greatly enhanced through future development of its application and hopefully this discussion will help prompt further research in the area.

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