The influence of structural design methods on the embodied greenhouse gas emissions of structural systems for tall buildings

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Abstract

The construction of tall buildings generates a high spatial and temporal concentration of greenhouse gas (GHG) emissions. Research has shown that as building height increases, more resources per floor area are required to withstand the increasing effects of wind and earthquake loads. This has major implications for the environmental performance of tall buildings since the embodied GHG emissions (EGHGE) of structural systems tends to represent the greatest portion of the life cycle GHG emissions of tall buildings.

In mitigating the effects of climate change, life cycle assessment (LCA) has been proposed as an early stage design tool to facilitate the choice of structural systems and materials for tall buildings. Existing studies that use LCA to compare alternative structural systems and materials use incomplete and inconsistent structural design methods related to imposed loads, façade loads and lateral loads, both static and dynamic in nature. The aim of this paper is to evaluate the influence of these different structural design methods on the choice of structural systems for tall buildings to minimise their EGHGE.

The influence of structural design methods on the EGHGE of structural systems for tall buildings are evaluated using a total of 80 structural systems, parametrically designed and analysed using finite element modelling. A hybrid life cycle inventory analysis method is used to quantify the EGHGE of the designed structural systems.

The paper demonstrates that varying structural design methods can significantly influence the values of EGHGE of structural systems for tall buildings by up to 22%. The findings of this study confirm the need for clarity, consistency, transparency and comprehensiveness in structural design methods when conducting comparative LCA studies of structural systems for tall buildings.

Keywords: Embodied greenhouse gas emissions; Structural design; Premium for height; Structural systems; Tall buildings.

1 Introduction

In its recent landmark special report titled 'Global Warming of 1.5°C', the Intergovernmental Panel on Climate Change (IPCC) [1] declared that drastic changes are required by governments, industries and societies to limit global warming to 1.5°C above pre-industrial levels. To meet this target, global anthropogenic greenhouse gas (GHG) emissions, the most significant driver of climate change, must be reduced by at least 49% of 2017 levels by 2030 [1]. Rapid and far-reaching transitions in the building construction industry, which is responsible for 39% of global anthropogenic GHG emissions [2], are required to mitigate the effects of climate change.

Resources, such as energy, water and waste, flow throughout the life cycle of buildings and can be categorised into embodied flows and operational flows. Embodied flows are related to the construction of buildings and the production of building materials across their supply chains [3]. Operational flows are related to the operation of buildings which include heating, cooling, ventilation, domestic hot water, lighting, appliances and cooking [3]. Regulations and current attempts to improve the environmental performance of buildings have principally focused on operational energy. However, studies have revealed that the growing significance of embodied environmental flows in buildings is often underestimated [4]. Moreover, improvements in the operational efficiency of buildings is often achieved using assemblies of high embodied energy (EE) such as thermal insulation and advanced façade systems. Therefore, as the operational energy efficiency of buildings improves and their operational GHG emissions decreases, embodied GHG emissions (EGHGE) will progressively form a higher proportion of the life cycle environmental flows of buildings [5, 6]. In fact, the World Green Building Council [2], in its recently published report titled ‘Bringing Embodied Carbon Upfront’, estimates that EGHGE will be responsible for half of the entire GHG footprint of new construction between now and 2050, threatening to consume a large part of our remaining budget for GHG emissions .

The increasing rate of urbanisation has seen an accelerated trend in the construction of tall buildings in the aim of increasing population density near employment opportunities. From 2000 to 2018, the total number of buildings taller than 200 m increased by 460%, from 263 to 1,478 [7], globally. The number of tall buildings is expected to continue to grow as a solution to the challenges of urbanisation and as a means of establishing more compact cities that are attributed with less car dependency, better public transport services and better health outcomes [8, 9].

The construction of tall buildings generates a high spatial and temporal concentration of GHG emissions, a phenomenon described by Säynäjoki et al. [5] as a ‘carbon spike.’ These ‘carbon spikes’ are further exacerbated in the case of tall buildings that can have up to 60% more EE per gross floor area (GFA) than low rise buildings [10]. This increase in resource use with increasing building height is defined by Khan [11] as the premium-for-height and is mainly due to the cumulative effect of wind and earthquake loads on the structural systems of tall buildings. This has major implications for the environmental performance of tall buildings since the EGHGE of structural systems represents the greatest portion of the life cycle GHG emissions of tall buildings [12].

In practice, the structural design of tall buildings begins with selecting preliminary member sizes and proceeds by iteration to meet strength, stability and serviceability design requirements until an acceptable design solution is reached. However, this iterative approach does not guarantee that the final design uses the least amount of structural materials and yields the least amount of EGHGE. To overcome this shortcoming, several studies have used a comparative life cycle assessment (LCA) approach to examine equivalent structural systems for tall buildings [12-16]. Their results demonstrate the importance of the choice of structural system in the reduction of embodied environmental flows. However, these studies systematically neglect influential building parameters, use inconsistent and incomplete structural design and analysis methods, and/or adopt a process-based life cycle inventory analysis method that has been shown to suffer from systemic incompleteness [17-20]. Consequently, the approaches adopted by these studies do not yield reliable findings that can help accurately guide the structural design of tall buildings to minimise embodied environmental flows.

In meeting the challenges of climate change, there is a need to develop structural design frameworks for tall buildings that consider EGHGE upfront. In line with the ‘Reduce’ and ‘Optimise’ principles set out by the World Green Building Council [2], these frameworks ought to apply design approaches that minimise the quantity of construction materials required and their associated EGHGE. In order to facilitate the future development of such integrated design frameworks, the focus of this paper is to understand the influence of structural design methods on the EGHGE of structural systems for tall buildings.

1.1 Aim and scope

The aim of this study is to demonstrate the influence of imposed loads, façade loads and lateral loads on the embodied greenhouse gas emissions (EGHGE) of structural systems for tall buildings.

Due to the relative complexity and cost of life cycle assessment (LCA) studies, simplified LCA methodologies are often used to assess the environmental flows of tall buildings. The most common and widespread simplification in the LCA of tall buildings is to evaluate GHG emissions as the sole output. Such an approach is referred to as a life cycle GHG emissions assessment (LCGHGEA). By adopting the approach of LCGHGEA, this paper circumvents the relative complexity of a comprehensive LCA while still being sufficiently accurate to aid decision making in buildings across all life cycle stages, both in terms of resource use and environmental effects [21-23]. This conclusion stems from the well-established relationship between GHG emissions and climate change [24].

Structural systems are designed to perform their intended function throughout their design working life, with minimum maintenance and no structural repair being necessary [25]. Consequently, the recurring environmental flows of structural systems are considered to be negligible. Additionally, the environmental flows involved in the end-of-life stage of buildings are not considered due to them typically representing less than 1% of their total energy requirement [26] and due to the large uncertainties regarding the demolition and deconstruction processes decades into the future. As such, this paper focuses on the initial embodied GHG emissions of structural systems as it has been shown that they represent the greatest portion of the life cycle GHG emissions of tall buildings [12], even when underestimated due to the use of uncomprehensive life cycle inventory (LCI) analysis methods.

According to European standard *EN 15978:2011*, the life cycle of a building, as seen in Figure 1, is divided into four stages: product stage (A1-A3), construction stage (A4-A5), use stage (B1-B7) and end-of-life stage (C1-C4) [27]. The scope of this paper, as illustrated and summarised in Figure 1, encompasses the EGHGE of structural system for tall buildings in the product stage (A1-A3) and the construction stage (A4-A5) as influenced by imposed loads, façade loads and lateral loads.

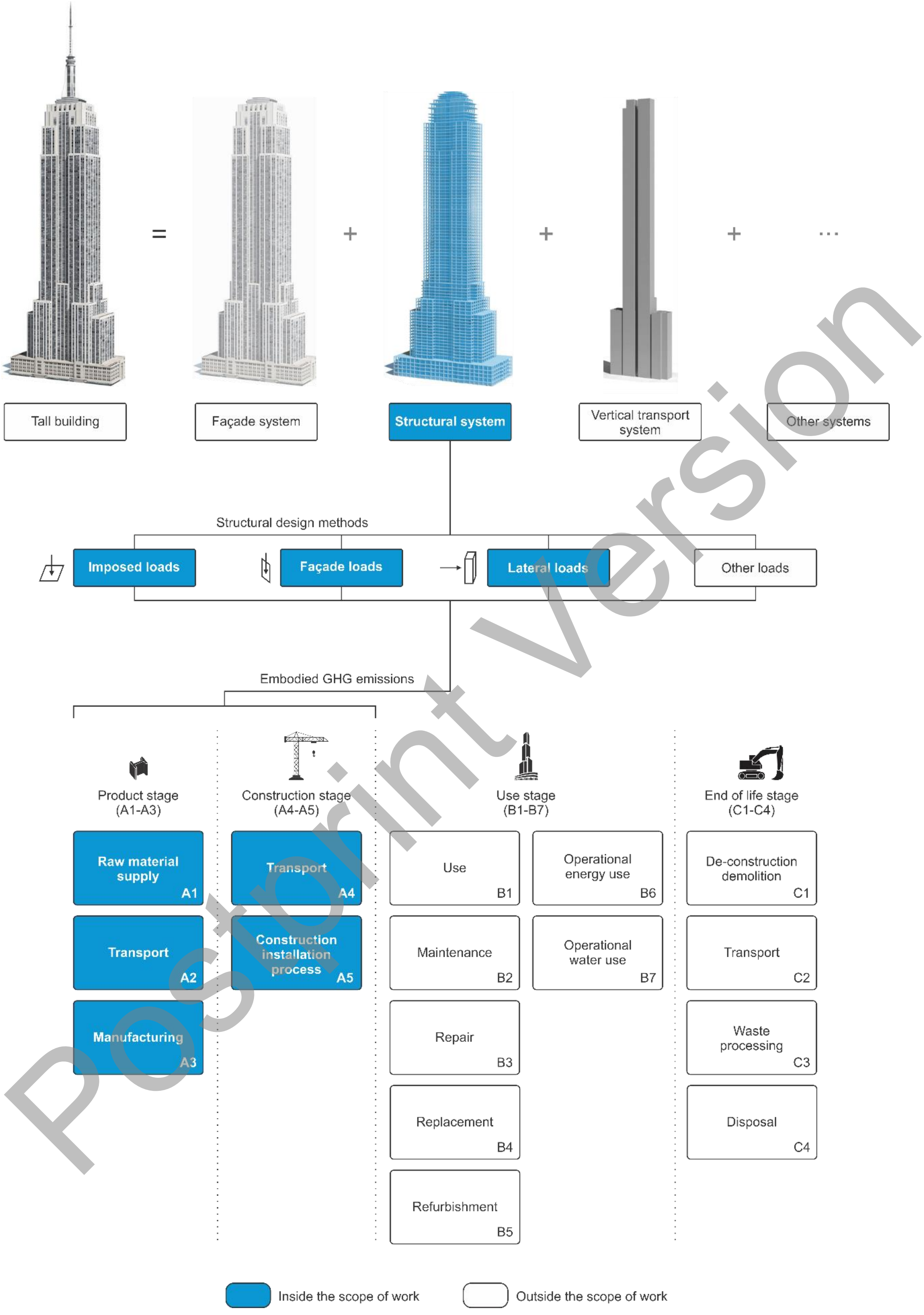

Figure 1 - Scope of the work according to EN 15978:2011

1.2 Notions and definitions

Among multiple possible definitions, this study adopts the definition for tall buildings proposed by Stafford Smith and Coull [28] coupled with a minimum height criterion. As such, this work defines a tall building as a building with a height of at least 35 m and a structural design which is significantly influenced, because of its height, by lateral forces due to wind or earthquake actions.

A structural system is an arrangement of structural elements (e.g. columns, beams, walls and slabs) capable of resisting loads. Tall buildings are generally composed of three structural sub-systems: a lateral load resisting system, which predominantly resists wind and earthquake loads, a vertical load resisting system, which predominantly resists gravity loads, and a foundation system, which transfers all of the loads to the ground [29]. Due to the high influence of lateral loads on the structural design of tall buildings, this paper classifies structural systems of tall buildings based on their lateral load-resisting systems.

1.3 Structure

This paper is structured in 6 Sections. Section 2 describes the inconsistencies in structural design methods between existing comparative LCA studies of structural systems for tall buildings. Section 3 describes the method used to demonstrate the influence of structural design methods on the EGHGE of tall buildings. A sensitivity analysis is also conducted and presented in Section 3 to better understand the applicability of the results to taller buildings. Section 4 presents the results of the environmental assessment of each structural system, designed using different structural design and analysis methods. Section 5 discusses the findings before concluding in Section 6. Appendices are included for supplementary information.

2 Inconsistencies in structural design methods between existing comparative life cycle assessment studies of structural systems for tall buildings

A total of five comparative life cycle assessment (LCA) studies of structural systems for tall buildings have been identified in the existing literature. The case study tall buildings range in height from 15 to 120 storeys and are designed to be built in South Korea, Italy or China. The identified studies assess a range of structural systems for tall buildings including rigid frame, braced frame, shear wall, outrigger and belt, and diagrid. The identified studies also consider reinforced concrete, steel and composite as alternative structural materials. This section presents a detailed review of these studies.

Cho et al. [13] conducted a comparative LCA to examine three alternative structural systems made of steel for the design of a 35-storey tall building in Seoul, South Korea. The structural systems (i.e. braced frame and outrigger and belt) were compared according to their life cycle carbon GHG emissions (LCGHGE). All other building parameters (i.e. number of storeys, inter-storey height, structural materials, etc.) were kept constant and thus their effects on the LCGHGE of structural systems remained unexplored. To ensure a sound comparison, the structural systems were deemed to be equivalent via a lateral deflection limit, equal to 1/400th of the building height, against a static wind load. Earthquake loads, which govern the design of some tall buildings in seismically active areas, were not considered in this study. The structural analysis conducted by Cho et al. [13] used finite element modelling while considering an imposed load of 200 kg/m^2 (1.96 kPa), which is typical for the design of residential structures. No reduction of imposed loads was established to reflect the low probability of simultaneously subjecting all imposed loads to the entire floor area of a tall building. Additionally, no consideration was given to super-imposed permanent loads that represent the weight of non-structural components such as façades and partitions, which have been shown to significantly affect the dynamic behaviour of tall buildings [30]. The LCGHGE were quantified by Cho et al. [13] using a process-based life cycle inventory (LCI) analysis approach, which has been shown to underestimate embodied environmental flows by a factor of up to four compared to hybrid LCI approaches [17]. The type of bracing in braced frames was shown to be significant for the LCGHGE of structural systems with the Chevron-braced system achieving 5.28% less LCGHGE per gross floor area (GFA) than the X-braced system. The study also found that the use of a braced frame structural system can result in approximately 16% less LCGHGE compared to the outrigger and belt structural system for a 35-storey steel tall building.

Foraboschi et al. [14] assessed the embodied energy (EE) of structural systems for tall buildings for heights of 20, 30, 40, 50, 60 and 70 stories and composed of a reinforced concrete (RC) shear wall and either an RC rigid frame or a steel rigid frame. Six different floor types were also considered including a steel-corrugated concrete slab, traditional RC slab and four types of RC slabs with different lightweight products. Other building parameters, which have a significant effect on the structural performance of tall buildings, were kept constant and thus their effects were overlooked. The structural analysis conducted by Foraboschi et al. [14] accounted for a super-imposed permanent load of 2.5 kN/m^2, a façade load of 4 kN/m (applied along the perimeter beams) and a live load of 3 kN/m^2. Similar to the study by Cho et al. [13], no imposed load reduction factor was applied as is consistently stipulated by structural design codes. Highlighting the inconsistencies in structural analyses between studies of this nature, the vertical loads considered by Foraboschi et al. [14] were up to 3 times higher than the vertical loads considered by Cho et al. [13]. Wind loads were analysed by Foraboschi et al. [14] according to the Eurocode 1 structural design code using the wind values and coefficients applicable to Genoa, Italy. Foraboschi et al. [14] justified their neglect of earthquake loads by stating that the dynamic behaviour of tall buildings is often governed by their first mode of vibration, which was claimed to not be significantly influenced by earthquake loads. However, this argument might not hold in seismically active regions, as shown by Mendis et al. [31]. To ensure structural equivalency among the considered structural systems, Foraboschi et al. [14] adopted two structural performance criteria: (1) a lateral drift limit for the entire building equal to 1/400th of building height and (2) a vertical displacement limit for horizontal structural elements (i.e beams and slabs) equal to 1/400th of the element span. Despite its systemic incompleteness, a process-based LCI approach was adopted using data from the Inventory of Carbon and Energy (ICE) database to assess the EE of the structural systems. The use of ICE data is problematic due to its averaging of coefficients, regardless of differences in system boundaries, temporal and geographic relevance and LCI techniques, without providing any information on the assumptions used to compile the coefficients [32]. Additionally, despite its major overestimation of material quantities, a static treatment of wind loading was applied. The study concluded that RC rigid frames can result in up to 44% less EE per gross floor area (GFA) than that of steel frames for certain tall building heights. The study also showed that the floor type is the most critical component for tall building structures regarding their EE and that the EE premium-for-height, as defined by the increase in EE/GFA with increasing building height, was not substantial. However, the actual significance of floor types might be substantially lower, and the EE premium-for-height substantially higher, had more realistic and less conservative vertical loads been considered. Interestingly, the study also found that lightweight floor systems possessed more EE/GFA than traditional floor systems and lead to a higher EE for the entire structural system [14].

Zhao and Haojia [12] compared three types of structural systems for a 69-storey building in Changchun, China according to their LCGHGE. The considered structural systems were: (1) an RC shear wall and frame system, (2) an RC shear wall (core) and frame with a steel outrigger and belt on the 44th floor and (3) an RC shear wall (core) and frame with two steel outriggers and belts on the 44th and 57th floor. By also using a process-based LCI method with ICE data, Zhao and Haojia [12] found that the EGHGE/GFA of the RC shear wall and frame structural system was 44.9% less than that of the single outrigger and belt structural system and 41.9% less than that of the double outrigger and belt structural system. The study failed to consider important building parameters (e.g. building height, height/width ratio, etc.) and failed to disclose how equivalency was ensured among the considered structural systems. The study also lacked transparency in its structural analysis by not disclosing what structural loads and magnitudes were considered. Thus, these findings by Zhao and Haojia [12] can be deemed questionable and unverifiable due to the lack of transparency in structural analysis and modelling approaches.

Moussavi Nadoushani and Akbarnezhad [15] examined rigid frames and braced frames, made of RC or steel, for buildings of 3, 10 and 15 storeys. The scenarios related to the 10 and 15-storey tall building are most relevant to this work. A process-based LCI approach was used by Moussavi Nadoushani and Akbarnezhad [15] to assess the alternative structural systems and materials according to their EGHGE/GFA using data from ICE. The method and criteria for ensuring structural equivalency among the considered alternative systems was not specified. The structural loads were clearly outlined and include a superimposed permanent load of 370 kg/m^2 (3.63 kPa) and an imposed load of 200 kg/m^2 (1.92 kPa). However, earthquake loads were the only lateral loads that were considered by Moussavi Nadoushani and Akbarnezhad [15], completely neglecting the effects of wind loads. Additionally, this study failed to apply an imposed load reduction factor as required by structural design codes. The combination of overestimating vertical loads and underestimating lateral loads could lead to false conclusions related to the relative importance of vertical and lateral load resisting systems on the embodied environmental flows of tall buildings. The results of the study by Moussavi Nadoushani and Akbarnezhad [15] showed that the 15-storey steel braced frame had the lowest EGHGE/GFA of all the considered structural systems, 22.18% less than that of the RC rigid frame, 13.95% less than that of RC shear wall and 9.50% less than that of the steel rigid frame.

A research report by the Council of Tall Buildings and Urban Habitat (CTBUH) titled ‘Life Cycle Assessment of Tall Building Structural Systems’ examined the EE and global warming potential (GWP) of two types of structural systems, namely shear wall (core) and frame system and diagrid system, for

60-storey and 120-storey tall buildings [16]. The EE and GWP of the structural systems were quantified using a process-based life cycle inventory (LCI) analysis approach with data for steel from the EcoInvent and Worldsteel databases and data for concrete from various environmental product declarations (EPDs). In addition to various structural systems and building heights, this report also considered scenarios with various structural materials (i.e. RC, steel and composite) and dimensions of structural elements (wide/shallow beams and narrow/deep beams). Despite neglecting the effects of influential building parameters such as inter-storey height and height-to-width ratio, more building parameters were considered in this study than in any other study of a similar nature. However, this study by Trabucco et al. [16] lacks transparency in structural analysis methods and data by merely stating that the design of the tall buildings was assigned to the participating structural engineering firms. The report found that steel scenarios had better environmental performance as measured by GWP values while RC scenarios had lower EE [16]. The study also found that horizontal structural elements (beams, floor slabs, etc) represent a significant portion of the weight of tall buildings, yet their significance decreases as the height of buildings increases. Transportation of construction material and demolition waste was found to not be a significant factor in the LCA of tall buildings, with values ranging between 1% to 2.5% of total GWP and 0.9% to 3.2% of total EE [16].

In light of above, previous studies commonly consider the lateral loads acting on structural systems, such as wind and earthquakes, to be static in nature which could lead to a significant overestimation of the materials needed to satisfy structural design criteria [25, 31]. Moreover, none of the reviewed studies considered the simultaneous application of both wind and earthquake loads as stipulated by all structural design codes and standards. Incomplete structural analysis affects the validity of their conclusions regarding the environmental performance of structural systems. Additionally, the existing comparative LCA studies on the structural systems for tall buildings lack the required levels of transparency and data accessibility for their results to be comparable and reproducible and their conclusions to be validated. Figure 2.1 summarises the inconsistencies in structural design methods between existing comparative LCA studies of structural systems for tall buildings.

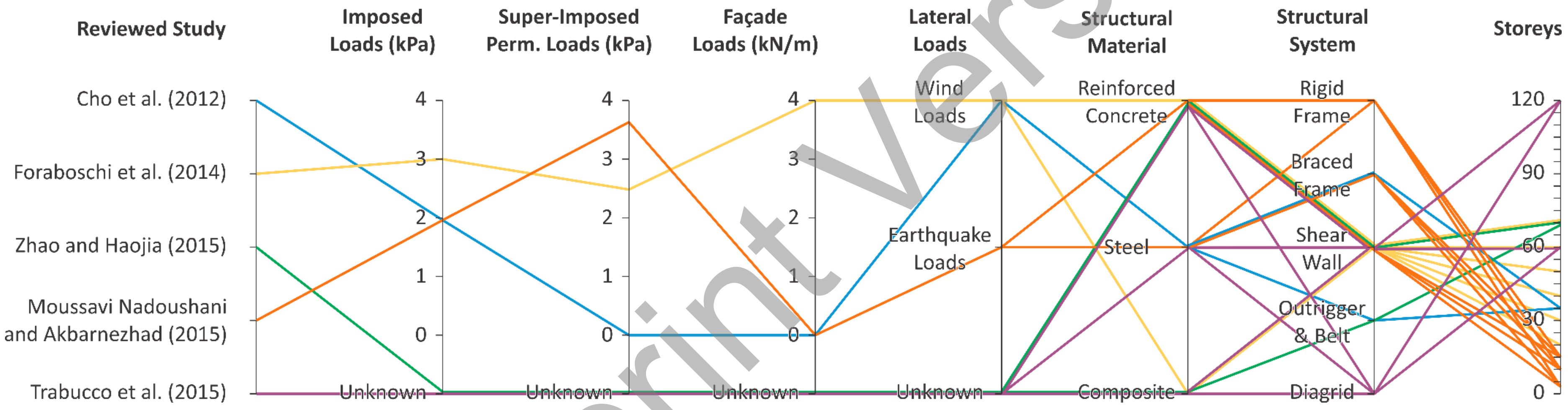

Figure 2.1 - Inconsistencies in structural design methods between existing comparative life cycle assessment studies of structural systems for tall buildings

In summary, existing comparative LCA studies of alternative structural systems for tall buildings use inconsistent and incomplete structural design methods and environmental assessment methods that have been shown to suffer from systemic incompleteness. Consequently, these studies do not yield reliable findings that can help guide architects and engineers in selecting structural systems for tall buildings to minimise their EGHGE.

This paper focuses on the influence of structural design methods on the EGHGE of structural systems to help guide future comparative LCA studies on alternative structural systems for tall buildings to reduce their embodied environmental flows. It uses a consistent and comprehensive hybrid LCI approach.

3 Method

Parametric modelling is adopted to assess the relationship between structural design methods and the required quantities of structural materials for tall buildings. This method of modelling is presented in Section 3.1. Due to the complex process of structural design for tall buildings, which involves equations with millions of unknowns, finite element modelling and analysis is used to ensure that structural systems are structurally adequate and meet the required performance criteria. The method of finite element modelling and analysis is presented in Section 3.2. The material quantities, which are derived and extracted from the finite element models, are then converted to embodied greenhouse gas emissions (EGHGE) using an input-output-based hybrid life cycle inventory method, as presented in Section 3.3. Finally, the method for sensitivity analysis is presented in Section 4.4 to assess the applicability of the results to taller buildings. Figure 3.1 summarises the overall research method and strategy.

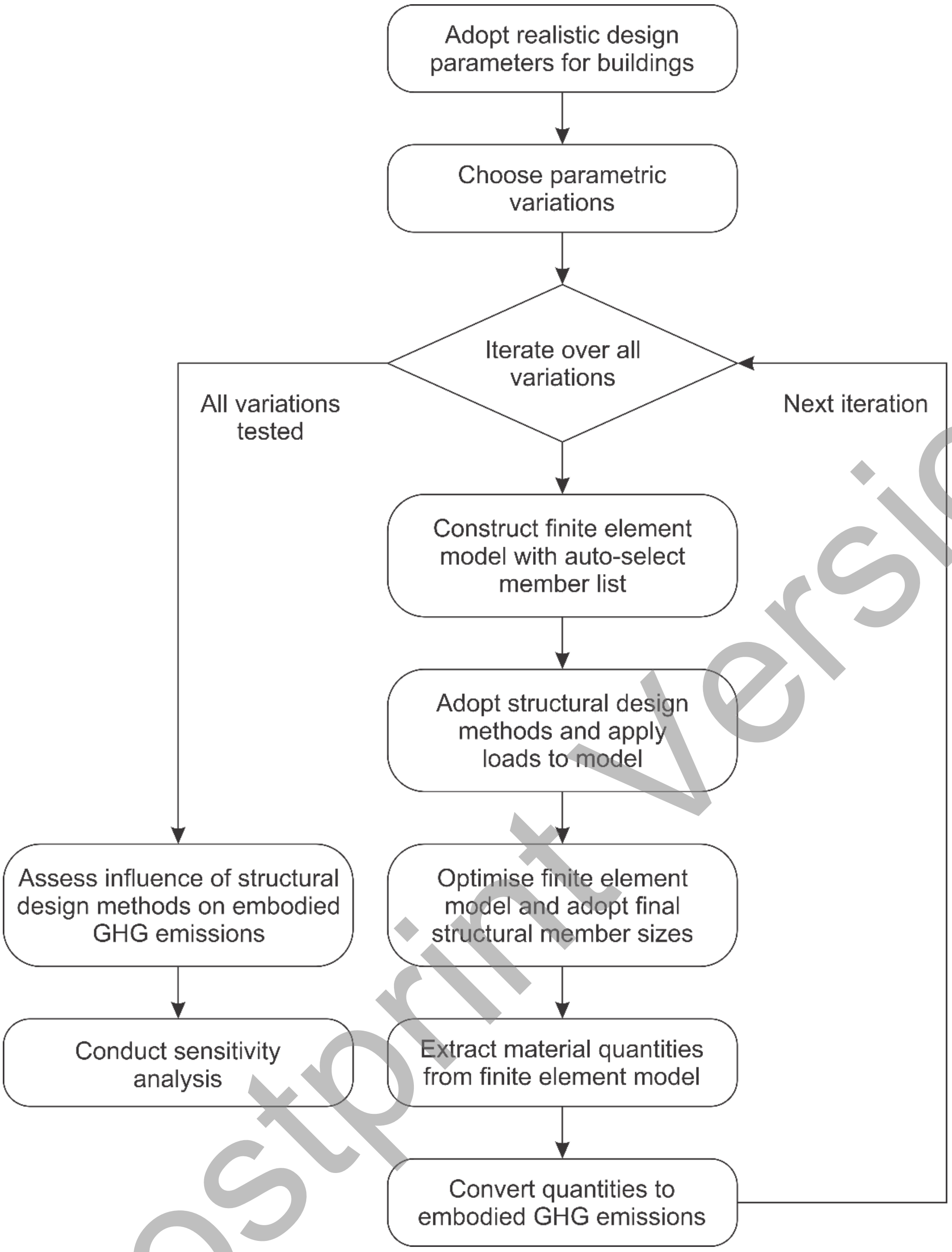

Figure 3.1 - Overall research method and strategy

3.1 Parametric modelling

To understand the influence of structural design methods on the embodied GHG emissions (EGHGE) of tall buildings, 80 finite element models were constructed using different structural design methods related to imposed loads, façade loads and lateral loads. The relevant Australian standards for structural design are adopted by this paper to ensure that all the constructed finite element models meet the required structural performance criteria. Reference is regularly made to other design standards to highlight the potential replicability of this study to other regions.

To isolate the influence of structural design methods, material properties and geometric properties related to floor plan shape and width, column span and inter-storey heights are kept constant. As seen in Table 3.1, these building parameters and their values were selected based on best and common practices in the design and construction of tall buildings.

Table 3.1 - Building properties and values used in all constructed finite element models

Building property	Values	Justification of values
Structural material	Reinforced concrete (32 MPa)	Reinforced concrete remains to be the most commonly used structural material for tall buildings [33].
Floor plan shape	Square	A 30 m to 40 m square floor plan represents the most commonly used floor plan shape and dimensions for tall buildings [25].
Width	36 m	
Column Span	7.2 m	Column spans for tall buildings are often dictated by the required column layout of the parking levels. A typical span of 7.2 m allows 3 cars to be parked within a span [34].
Inter-storey height	3.5 m	This value represents a typical inter-storey height for tall buildings [35].

Six finite element models with heights of 5, 10, 15, 20, 25 and 30 storeys were constructed to establish the base case models to which the rest of the finite element models are compared. The 5-storey buildings are included in this study to determine if the influence of structural methods on the EGHGE of structural systems differs between low-rise buildings and tall buildings. Figure 3.2 presents the floor plan drawing of the base case models. Figure 3.3 presents schematic 3-dimensional drawings of the 5, 10 and 15-storey base case models.

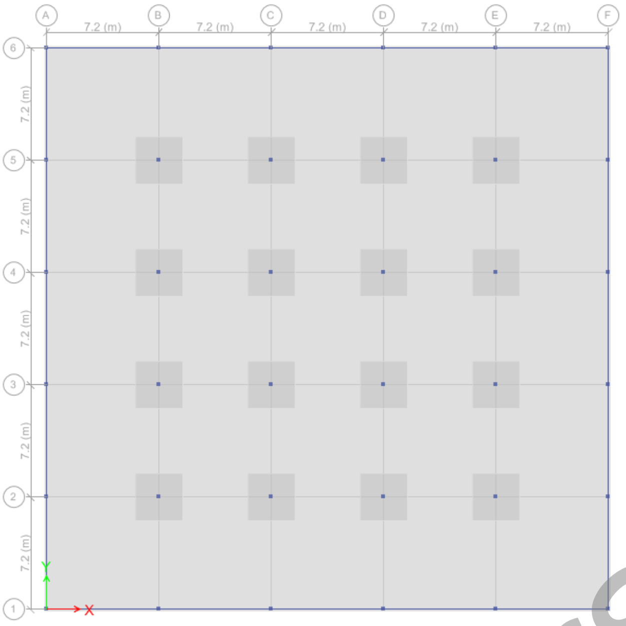

Figure 3.2 - Floor plan drawing of the base case finite element models (FEMs)

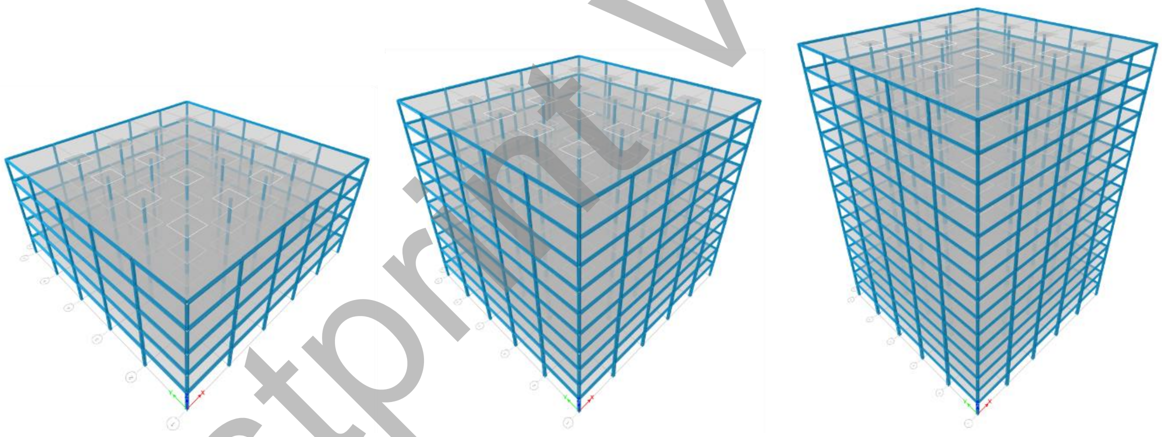

Figure 3.3 - Schematic 3-dimensional drawings of the 5, 10 and 15-storey base case models

No laterals loads were included in the design of the base case models. An imposed load of 2 kPa was uniformly distributed across their floor slabs to account for loads that result from the intended use of the structure. This is in line with the design requirements for residential structures as prescribed by Australian standard *AS1170.1:2002 Structural design actions: Part 1: Permanent, imposed and other actions*. Similar requirements are prescribed by the European structural design standard *Eurocode 1* (1.5 - 2 kPa) and the American structural design standard *ACSE 7-02* (1.92 kPa) for residential structures.

A façade load of 3.5 kN/m was imposed on the perimeter beams in the design of the base case models. This load represents the self-weight of the façade, which corresponds to a mass of approximately 357 kg/m. As prescribed by Australian standards *AS1170:2002*, a 1 kPa super-imposed permanent load was considered as a uniformly distributed load across the floor slabs to represent the weight of non-structural components such as partitions. Table 3.2 summarises the structural loads imposed on the base case models.

Table 3.2 - Structural loads considered in the design of the base case models

Considered loads	**Values**
Permanent loads	Based on building geometry and material densities
Imposed loads	2 kPa
Super-imposed loads	1 kPa
Façade loads	3.5 kN/m

Changes in structural methods were made in constructing the other 74 finite element models. A reinforced concrete shear wall was added to the models that consider lateral loads in order to increase their lateral stiffness against wind and/or earthquake loads. A shear wall structural system was chosen since it is the most commonly used lateral load resisting system for buildings of that height [29]. Shear walls have been shown to have substantial in-plane stiffness and strength which make them act as highly efficient braces for tall buildings [36]. Structural equivalency across the finite element modes is established by constraining lateral displacements to acceptable serviceability levels in response to wind and earthquake loads. Acceptable lateral displacements are adopted to limit damage to non-structural components, such as façade, partitions and interior finishes. A commonly used lateral displacement limit equal to 1/400th of the building height is adopted. These models were also designed by varying imposed loads, imposed load reduction factors and façade loads to assess their influence on the EGHGE of structural systems. Appendix A includes a list of these models, along with the adopted structural design methods.

The following section introduces the adopted finite element modelling method for the structural design and analysis of tall buildings.

3.2 Finite element modelling and analysis of structural systems

The finite element method is a type of numerical method for approximating the solution of complicated problems of engineering and mathematical physics. It involves subdividing complex systems into their individual components or ‘elements,’ whose behaviour is well understood, and reconstructing the original systems using these elements to study their overall behaviour [37]. This method of discretisation involves an approximation, which approaches the true solution of a continuous problem as the number of elements increases.

The finite element method emerged during the 1940s with the publication of seminal works by Hrennikoff [38], McHenry [39] and Newmark [40] who showed how approximations of 2-dimensional elastic continuum problems can be obtained by using an arrangement of line (1-dimensional) elements. Since then, the finite element method has expanded to many fields and is commonly used to analyse both structural problems (stress analysis, buckling, vibration analysis, etc.) and non-structural problems (heat transfer, fluid flows, distribution of electric or magnetic potential, etc.). When used for structural engineering purposes, the finite element method is a powerful method for computing the displacements of a structure under loading. Since the 1960s, with the advent of digital computers and their rapid rise in processing power, extensive advances have been made in the application of the finite element method to solve complicated engineering problems, particularly in the structural design of tall buildings.

The commercial software ETABS [41] is used by this study for the finite element modelling and analysis of tall buildings. ETABS is widely regarded as one of the most reliable and powerful structural analysis and design software for multi-storey buildings. The software provides both static and dynamic analyses for a wide range of loads. It has been used for the design and analysis of some of the most complex and iconic tall buildings in the world, including Burj Khalifa, which is the tallest building in the world as of 2019 [42, 43]. Sections 3.2.1 to 3.2.3 discuss the methods of modelling materials, sections and lateral loads, respectively.

3.2.1 Modelling material properties

Reinforced concrete is a composite material that exhibits nonlinear behaviour due to the complex interaction between its steel and concrete components [44]. Modelling this material nonlinearity is a challenge in the structural modelling of tall buildings and is typically simplified using a modified linear-elastic analysis approach [45]. The approach involves reducing the stiffness of individual structural members to account for material nonlinearity and the resulting effect of cracking in reinforced concrete structures. None of the studies reviewed in Section 2 mentioned any consideration taken for modelling the phenomenon of cracking in reinforced concrete. This may lead to a significant underestimation of material quantities, which might influence the selection of alternative structural systems and materials based on their EGHGE.

Structural design codes typically recommend the use of one stiffness modifier per structural element type [46]. However, some structural elements may have varying stiffnesses based on the magnitude of loading and their location within a structural system. Despite this simplification, single stiffness modifiers per structural element type tend to capture the central tendency of effective stiffness values across a tall building [46]. The Australian standard for concrete structures *AS3600:2009* omits the stipulation of structural modelling and analysis methods that account for material nonlinearity and cracking of reinforced concrete. As such, this study adopts the stiffnesses modification factors recommended by the European standard *Eurocode 8 (EN1998-3)* [47], which states that a 50% reduction in the elastic flexural and shear stiffness properties must be applied to reinforced concrete structural element. These modification factors are adopted in all the constructed finite element models to accurately model the behaviour of reinforced concrete and avoid underestimating the EGHGE of structural systems.

3.2.2 Modelling section properties

When creating finite element models composed of reinforced concrete frame objects (i.e. columns and beams), initial preliminary member sizes for analysis are not necessary. Instead, an ‘auto-select’ section property, which is a list of section sizes rather than a single section size, was applied to the frame objects. Upon assigning the auto-select function to the frame objects, ETABS optimises and selects the most economical, adequate section from the auto-select list. Columns of a square cross-sectional area, from 25 cm to 90 cm in width, were added to the column auto-select list using increments of 2.5 cm. Similarly, square beams from 25 cm to 45 cm in width were added to the beam ‘auto-select’ list using increments of 2.5 cm. This optimisation process ensures that the reinforced concrete structural systems can be compared according to their lowest possible EGHGE. Naturally, in the design and construction of tall buildings, other factors are considered when selecting section sizes, often to reduce complexity and improve constructability. However, this study favoured optimisation to assess the maximum potential savings in EGHGE when assessing alternative structural systems. This is further discussed in Section 5.3.

Floor slabs were modelled as rigid diaphragms and thus assumed to translate in plan and rotate about a vertical axis as a rigid body. This modelling techniques assumes that there are no in-plane deformations in the floor slab. The method of modelling floors slabs as rigid floor diaphragms for tall buildings has been used extensively in practice to lend computational efficiency to the complex solution process [42].

3.2.3 Modelling lateral loads

This section introduces the methods of modelling lateral loads. Sections 3.2.3.1 discusses the method of modelling wind loads and Section 3.2.3.2 discusses two different methods of modelling earthquake loads.

3.2.3.1 Modelling wind loads

Complex, large, and aerodynamically sensitive structures frequently require wind tunnel testing or more sophisticated dynamic analysis, such as computational fluid dynamics, to ensure occupant comfort during windstorms. However, buildings less than or equal to 200 m in height are typically designed using a quasi-static approach whereby a dynamic coefficient is used to increase the equivalent static wind load to an acceptable level [48, 49]. Since the tallest modelled building in this study is 105 m in height, this study adopts a quasi-static approach as stipulated by the Australian standard *AS 1170.2:2011 Structural Design Actions - Part 2 - Wind Actions* [49].

The Australian standard *AS 1170.2:2011* recommends modifying wind velocity measurements to account for variables such as direction, season, orography, height, roughness and turbulence using recommended empirical formulas based on stochastic modelling. Twelve wind coefficients are required and used as input to generate wind loads according to AS/NZS 1170.2:2002. These wind coefficients are listed in Table 3.3. These factors, which are similar across all design standards, globally, have the potential to affect the required material quantities and their associated EGHGE. None of the reviewed studies in Section 2 specify what values were used for these modification variables. This lack of transparency, in both methods and data, prohibits the comparability of structural systems for tall buildings based on EGHGE.

Table 3.3 - Wind coefficients to generate wind loads according to AS/NZA 1170.2:2002

Wind Load Inputs	**Values**	**Justification of values**
Regional wind speed (V_R)	46 m/s	Described in AS/NZS 1170.2:2011 Section 3.2
Wind direction multiplier (M_d)	1	Described in AS/NZS 1170.2:2011 Section 3.3
Terrain category ($M_{z,cat}$)	4	Described in AS/NZS 1170.2:2011 Section 4.2
Shielding multiplier (M_s)	1	Described in AS/NZS 1170.2:2011 Section 4.3
Topographic multiplier (M_t)	1	Described in AS/NZS 1170.2:2011 Section 4.4
Windward coefficient (C_{pw})	0.8	Described in AS/NZS 1170.2:2011 Section 5.2
Leeward coefficient (C_{pl})	0.5	Described in AS/NZS 1170.2:2011 Section 5.2
Area reduction factor (K_a)	1	Described in AS/NZS 1170.2:2011 Section 5.4.2
Combination factor (K_c)	1	Described in AS/NZS 1170.2:2011 Section 5.4.3
Local pressure factor (K_l)	1	Described in AS/NZS 1170.2:2011 Section 5.4.4
Porous cladding factor (K_p)	1	Described in AS/NZS 1170.2:2011 Section 5.4.5
Dynamic response factor (C_{dyn})	*	Described in AS/NZS 1170.2:2011 Section 6.1

*: For structures with a first mode fundamental frequency greater than 1 Hz, C_{dyn} =1.0. For structures with a first mode fundamental frequencies between 0.2 Hz and 1 Hz, C_{dyn} was computed in accordance with AS/NZS 1170.2:2002 Section 6.1. None of the modelled buildings had a first mode fundamental frequency less than 0.2 Hz.

Appendix B illustrates the process of calculating static wind loads as prescribed by the Australian standard *AS1170.2:2011*.

3.2.3.2 Modelling earthquake loads

The general purpose of designing structures for earthquake resistance is to ensure that in the event of earthquakes, human lives are protected, damage is limited and structures remain operational [50, 51]. Fulfilling these purposes might be incomplete and measured in probabilistic terms due to the random and severe nature of earthquakes. In order to assess the influence of different structural design methods related to earthquake loads on the EGHGE of structural systems, the following two methods of seismic analysis are adopted for different finite element models (see Table 3.1): Equivalent Lateral Force Method, which is a static linear analysis method, and Response Spectrum Analysis, which is a dynamic linear analysis method. The main purpose of adopting the two different methods is to assess the influence of static versus dynamic modelling of earthquake loads on the EGHGE of structural systems for tall buildings.

The Equivalent Static Force Method reduces the dynamic nature of earthquakes to an equivalent static load [52]. Structural design codes that propose using this method set limitations of its use related to the location, height, geometric regularity and material regularity of a structure [47, 51, 53]. Appendix C illustrates the equivalent static analysis procedure as presented in the Australian standard *AS1170.4:2007 Structural Design Actions - Part 4 - Earthquake Actions*

For the finite element models that were designed using the Equivalent Static Force Method (see Appendix A), a variety of factors were considered related to the building importance level, dynamic building properties, site conditions and the building weight and height distribution in line with Australian standard *AS 1170.4:2007 Structural Design Actions - Part 4 - Earthquake Actions*. The values of these factors alter the influence of earthquake loads, which affect material intensities and associated EGHGE. None of the reviewed studies in Section 2 contain this level of transparency, which is necessary for the comparability of structural systems across existing life cycle assessment (LCA) studies. The adopted values for the factors used to calculate the equivalent static earthquake loads are listed in Table 3.4.

Table 3.4 - Earthquake coefficients to generate earthquake loads according to AS1170.4:2007

Earthquake Load Inputs	**Values**	**Justification of values**
Site subsoil class	D	Described in AS/NZS 1170.4:2007 Section 4.2.
Probability factor (k_p)	1.1	Described in AS/NZS 1170.4:2007 Section 3.1.
Hazard factor (Z)	0.08	Described in AS/NZS 1170.4:2007 Section 3.2.
Performance factor (S_p)	0.77	Described in AS/NZS 1170.4:2007 Section 6.5.
Ductility factor (u)	2	Described in AS/NZS 1170.4:2007 Section 6.5.

To assess the influence of static versus dynamic earthquake modelling and analysis, the Response-Spectrum Analysis was used to calculate and assign dynamic earthquake loads to other finite element models (see Appendix A). This is a linear-dynamic statistical analysis method that measures the contribution from each natural movement patter to indicate the likely maximum seismic response of an essentially elastic structure [52]. These movement patterns, termed ‘mode shapes’ or ‘natural modes of vibrations’, represent natural properties of a structure in free vibration that depend only on its mass and stiffness. While the mass of a building is distributed throughout the building, it can be idealised as concentrated at floor levels and supported by a massless frame [54]. This assumption is generally appropriate for tall buildings because most of the building mass is concentrated at the floor levels. The Response-Spectrum Analysis method is illustrated in Appendix D.

The modal dynamic analysis method has the advantage of being able to model the effects of the higher modes of vibrations more explicitly and accurately than the Equivalent Static Analysis procedure. This accuracy in structural modelling and analysis has the potential of decreasing the resulting EGHGE of tall buildings.

3.2.4 Modelling simultaneous application of loads

All tall buildings will experience most, if not all, of the loads described in Sections 3.1 to 3.2.3. The challenge of structural design is to determine the governing combination of loads and design a tall building accordingly. To ensure safety and consistency, structural design standards recommend load combinations that reflect probable and conservative loading conditions. The load combinations that are adopted by this paper for the structural design of tall buildings, are listed in Section 4 of Australian standard *AS1170.0:2002*, and include 1.2×Permanent Load (G) + 1.5×Imposed Load (Q), 1.35×G, 1.2×G + 0.4×Q + Wind (W), 1.2×G + 0.4×Q + Earthquake (E) and 16 other load combinations.

3.3 Quantifying the embodied greenhouse gas emissions of structural systems

This section discusses the selection of the LCA technique adopted by this paper to convert the derived quantities of structural materials to EGHGE.

Having modelled, analysed and optimised the structural systems using finite element modelling, structural material quantities can be easily extracted from the models. A streamlined LCA can then be performed to quantify their EGHGE to understand the influence of various structural design methods.

The quantification of EGHGE can be undertaken using any of the conventional life cycle inventory (LCI) analysis techniques, which are process analysis, environmentally-extended input-output analysis or hybrid analysis.

Process analysis relies on data specific to the considered product or service to calculate its inputs, outputs and resulting environmental effects across its life cycle [55]. The specificity of process-based approaches yields a high level of accuracy but the cost of this specificity is systemic incompleteness due to the difficulty of exhaustively assessing the supply chain of a product [17, 20, 56]. Crawford [17] showed that this truncation error can be up to 87% of the embodied energy (EE) of a building material or product, thus demonstrating that process analysis can greatly underestimate EE in buildings.

By assuming that economic flows provide a fair indication of physical flows, input-output tables, which provide valuable information about the structure and interdependencies of economies, can be used to perform an environmentally-extended input-output analysis (EEIOA). This can be done by integrating environmental data of the correct format, such as gigajoules of energy or tonnes of carbon dioxide emissions, with macroeconomic consumption activity data [56, 57]. This procedure facilitates the calculation of upstream and indirect environmental effects, which are not exhaustively captured by the process-based LCI approach. Input-output data is typically aggregated at the industry and product group level. For example, the input-output tables of the Australian National Accounts of 2015-2016 show that $20.4b AUD of the Residential Building Construction product group was produced by the Construction Services industry while $10.3b AUD of the product group was produced by the Non-Residential Building Construction industry and so on, resulting in a total of $87.5 AUD of this product being produced by all industries [58]. Such aggregation in the assessment of a product system like residential buildings leads to a loss of useful specificity, such as the distinction between low-rise and high-rise residential buildings, making it difficult to assess specific products and services taking place within the same sector [20, 59].

To address the limitations inherent in both process and input-output based approaches, various hybrid LCI analyses techniques have been proposed to combine process and input-output data. The four main hybrid LCI approaches that have been identified in the literature are Tiered, Matrix Augmentation, Integrated and Path Exchange (PXC). These approaches are detailed in the study by Crawford et al. [19]. Only the PXC method is discussed below, as it is the method selected for this work.

Of all the developed hybrid analysis techniques, the PXC method, first developed by Treloar [60] and later formalised by Lenzen and Crawford [59], remains to be the most efficient LCI method, globally, while maintaining comprehensive coverage of the system. The PXC method, also known as an input-output-based hybrid method, involves the mathematical disaggregation of an input-output table to enable the identification and modification of mutually exclusive pathways [59]. Each pathway represents a series of nodes that corresponds to a chain of transactions leading up to a sector. The input-output pathways that are equivalent to the known process are replaced with specific process-based data. Doing so allows this method to maintain system boundary completeness while increasing specificity.

Due to its comprehensiveness and relevance to Australian construction material, this paper uses the Environmental Performance in Construction (EPiC) database of embodied environmental flow coefficients compiled by Crawford *et al.* [61] using the PXC method for hybridisation and detailed in Stephan *et al.* [32]. The embodied environmental GHG emissions of structural systems in tall buildings are calculated using the following equation:

$$EGHGE_{SS} = \sum_{m=1}^{M} \left(Q_{m,SS} + EGHGEC_{m} \right) \qquad \text{(Eq. 3.1)}$$

Where $EGHGE_{SS}$ = embodied greenhouse gas emissions of structural system *SS* per net floor area in $kgCO_2\text{-e/m}^2$; $Q_{m,SS}$ = quantity of material *m* per Net Floor Area (NFA) in structural system *SS* (e.g. steel in kg/m^2); and $EGHGEC_m$ = embodied GHG emissions coefficient of material *m* (e.g. 2.90 $kgCO_2\text{-e/kg}$ for hot-rolled steel and 0.17 $kgCO_2\text{-e/kg}$ for 32 MPa concrete).

Equation 3.1 yields the initial EGHGE per Net Floor Area (NFA) of structural systems. As previously discussed, the recurring EGHGE of structural systems are considered to be negligible because structural systems are designed to perform their intended function throughout their design working life with minimum maintenance and no structural repair being necessary [25]. Additionally, this study favoured the use of NFA, which is the area of functional spaces, over Gross Floor Area (GFA) due to the eminent loss of functional space when shear walls are added to the structural systems of tall buildings (e.g. 5% loss of functional space).

3.4 Sensitivity analysis

To assess the applicability of the results to buildings taller than 30 storeys, 2 finite element models are constructed for a 50-storey tall building. More specifically, since imposed loads and façade loads increase linearly with building height, whereas lateral loads increase exponentially, the 2 finite element models are only used to assess the applicability of the results pertaining to lateral loads. As such, one finite element model is designed with no consideration to lateral loads and the other is designed with consideration to the simultaneous application of both static wind loads and dynamic earthquake loads. The embodied GHG emissions (EGHGE) per Net Floor Area (NFA) of the models are compared to the trends identifies in the results.

4 Results

This section presents the results of the study. The material quantities of all 80 finite element models were extracted, converted to embodied GHG emissions (EGHGE) and normalised per net floor area

(NFA) to enable better comparisons. The influence of imposed loads, façade loads and lateral loads on the EGHGE of structural systems are presented in Sections 4.1, 4.2 and 4.3, respectively. In these sections, the influence of the loads on the EGHGE/NFA of the structural systems is first presented. Subsequently, the influence of the loads on EGHGE/NFA is quantified per load functional unit (i.e. per 1 kPa for imposed loads, per 1 kN/m for façade loads and per 10 MNm of overturning moment for lateral loads). A regression analysis is also conducted in these sections to develop regression lines that examine and predict the relationship between structural loads and the EGHGE/NFA of structural system. Finally, the results of the sensitivity analysis are presented in Section 4.4.

4.1 The influence of imposed loads on the embodied greenhouse gas emissions of structural systems

As mentioned in Section 3.1, a 2 kPa imposed load was applied to the 6 base case models ranging in height from 5 to 30 storeys. This typically represents the design requirements, pertaining to imposed loads, for designing residential structures [62]. To assess the influence of imposed loads on the EGHGE of structural systems, the imposed loads were increased to 3 kPa and 4 kPa, which typically correspond to the design requirements of office buildings and retail buildings, respectively [62]. The resulting EGHGE/NFA values are plotted against the number of storeys and presented in Figure 4.1.

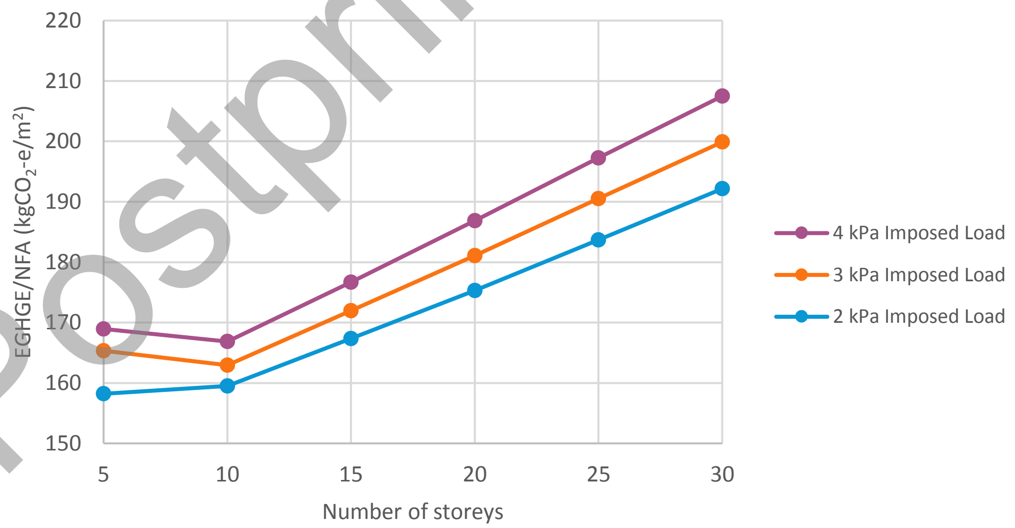

Figure 4.1 - Influence of imposed loads on the embodied greenhouse gas emissions per net floor area (EGHGE/NFA) of structural systems. Note: vertical axis starts at 150 kgCO$_2$*-e/m*^{2}*.*

Figure 4.1 shows that an increase of 1 kPa in imposed loads resulted in an increase of between 3% and 5% in the EGHGE/NFA of structural systems. The results also indicate that when lateral loads are not considered in the design of tall buildings, the EGHGE/NFA of structural systems increase linearly with increasing building height (approximately 10% in EGHGE/NFA per 10-storey increase in building height).

To better assess the influence of imposed loads on the EGHGE of structural systems, Figure 4.2 demonstrates the increase in EGHGE/NFA for a 1 kPa increase in imposed loads plotted against building height. The resulting trendline, which was constructed using a linear regression analysis, is displayed as a dotted line on Figure 4.2. The data points associated with the 5-storey models are excluded from the regression analysis to better describe the influence of imposed loads on the EGHGE of tall buildings.

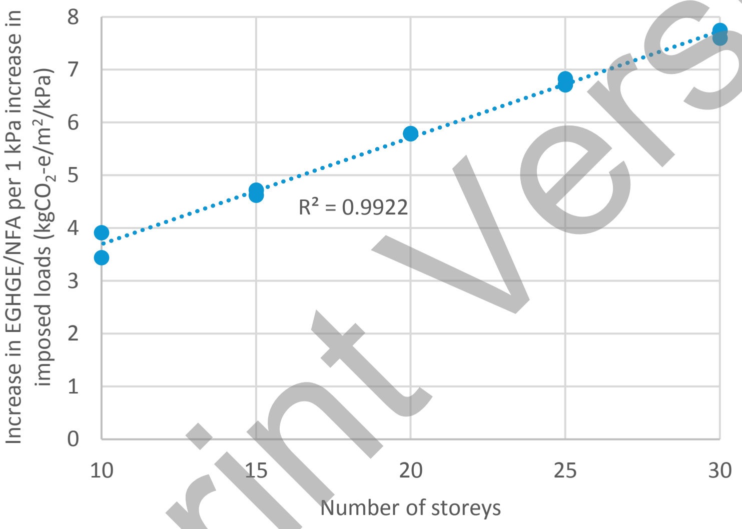

Figure 4.2 – Influence of 1 kPa increase in imposed loads on embodied greenhouse gas emissions per net floor area (EGHGE/NFA) of structural systems

As seen in Figure 4.2, there is a linear growth in EGHGE/NFA per 1 kPa increase in imposed loads with increasing height of tall buildings. The coefficient of determination (R^2) for the sample of derived values is significantly high and approximately equal to 0.99. This value represents the proportion of variance in the EGHGE/NFA values that is predictable from the increase in imposed loads. The equation for the linear regression line is expressed below:

$$\Delta EGHGE_{SS}/\Delta IL = 0.18NS + 2.07 \tag{Eq. 4.1}$$

Where $\Delta EGHGE_{SS}/\Delta IL$ = change in embodied greenhouse gas emissions of structural system SS per net floor area for 1 kPa increase in imposed loads in $kgCO_2$-e/m^2/kPa; and NS = number of storeys.

Equation 4.1 can be used to predict the increase in EGHGE/NFA by adopting a higher rating of imposed loads. More broadly, Equation 4.1 can be used to quantify the added EGHGE of structural systems for tall buildings when considering more conservative imposed loads. For example, by interpolation, Equation 4.1 predicts that a 27-storey reinforced concrete building would exhibit an increase of 6.93 kgCO_2-e/m^2 in EGHGE/NFA for an additional 1 kPa increase in imposed loads. With a 36 m by 36 m floor plan, this translates to a predicted increase of more than 240,000 kgCO_2-e. This is equivalent to the annual GHG emissions of more than 14 Australian citizens on average [63]. This is also equivalent to the GHG emissions produced by a fleet of 750 cars driving from Melbourne to Sydney and back, considering that the average GHG per kilometre of a new light vehicle sold in Australia is 0.182 kgCO_2-e/km [64].

Applying imposed load reduction factors, used to reflect the low probability of simultaneously subjecting all imposed loads to the entire floor area of a tall building, as required by Australian standard *AS1170.1:2002*, had no significant impact on the EGHGE/NFA of structural system. Upon application of the imposed load reduction factors, other load combinations, which exclude imposed loads, governed the design and produced similar results.

4.2 The influence of façade loads on the embodied greenhouse gas emissions of structural systems

In designing the base case models, a façade load of 3.5 kN/m was imposed on the perimeter beams of the structural systems. To assess the influence of façade loads on the EGHGE of structural systems, the façade load was changed to 4.5 kN/m and 5.5 kN/m in constructing 12 other models ranging in height from 5 to 30 storeys. The resulting EGHGE/NFA values are plotted against the number of storeys in Figure 4.3.

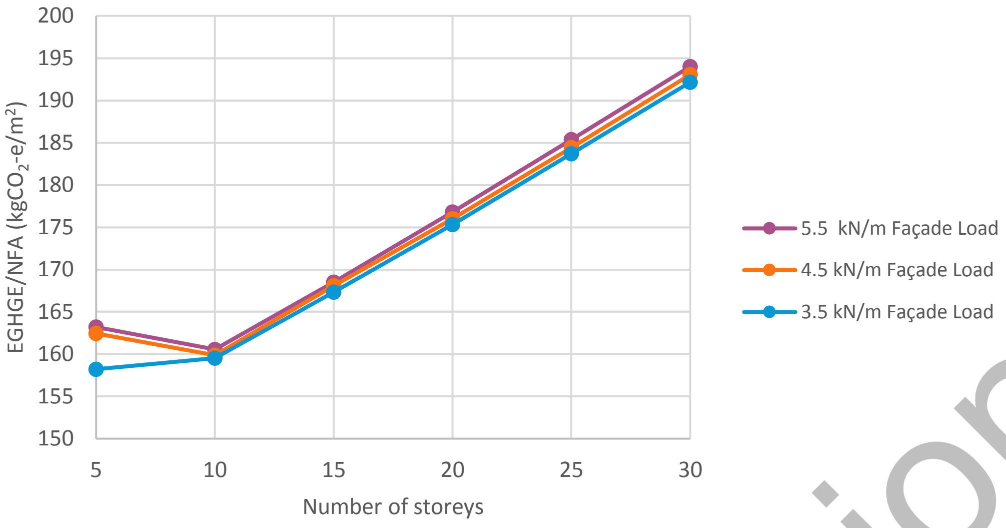

Figure 4.3 - Influence of façade loads on embodied greenhouse gas emissions per net floor area (EGHGE/NFA) of structural systems. Note: vertical axis starts at 150 $kgCO_2$-e/m^2.

Figure 4.3 shows that façade loads have a minor influence on the EGHGE/NFA of structural systems for tall buildings. Since façade loads are only applied to the perimeter of buildings, their influence on the required materials and subsequent EGHGE of structural system is limited.

To better understand the influence of façade loads on the embodied environmental flows of structural systems, Figure 4.4 demonstrates the increase in EGHGE/NFA for a 1 kN/m increase in façade loads. The resulting linear regression line is displayed on Figure 4.4. The values associated with the 5-storey models were also excluded from the regression analysis to isolate the effect of façade loads on the EGHGE of structural systems in tall buildings.

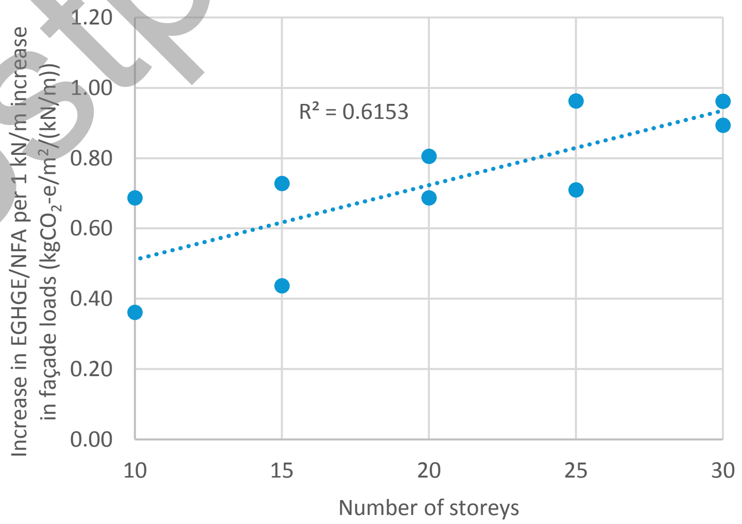

Figure 4.4 - Influence of 1 kN/m increase in façade loads on embodied greenhouse gas emissions per net floor area (EGHGE/NFA) of structural systems

As seen in Figure 4.2, there is a linear growth in EGHGE/NFA per 1 kN/m increase in façade loads with increasing building height. The coefficient of determination (R^2) for the sample of derived values is approximately equal to 0.62. The remaining proportion of variance could partly be attributed to the discrete optimisation process that selects the optimal frame member from a discreet list of structural members. The equation for the derived linear trendline is expressed below:

$$\Delta EGHGE_{SS}/\Delta FL \quad = 0.02NS + 0.3 \qquad \text{(Eq. 4.2)}$$
$$(R^2 = 0.62)$$

Where $\Delta EGHGE_{SS}/\Delta FL$ = the change in embodied greenhouse gas emissions of structural system *SS* per net floor area for every 1 kN/m increase in façade loads in $kgCO_2$-e/m^2/(kN/m); and *NS* = number of storeys.

With more limited correlation resulting in higher uncertainty compared to imposed loads, Equation 4.2 can be used to estimate the change in EGHGE of structural systems for tall buildings when comparing different façade systems of varying weights. As previously discussed, the influence of façade loads on EGHGE/NFA appears to be minor. However, since tall buildings have a substantial amount of NFA, the absolute increase in EGHGE is worth considering. For example, according to Equation 4.2, an increase of 1 kN/m in façade loads on a 29-storey reinforced concrete building would exhibit an increase of 0.88 $kgCO_2$-e/m^2. Assuming a square floor plan of 36 m by 36 m, this results in an increase of more than 33,000 $kgCO_2$-e in EGHGE, which is equivalent to the GHG emissions produced by a standard car circumnavigating Australia 12 times, assuming a single round trip distance of 14,000 km.

4.3 The influence of lateral loads on the embodied greenhouse gas emissions of structural systems

As discussed in Section 3.1, no laterals loads were considered in the design of the 6 base case models. To assess the influence of lateral loads on the EGHGE of structural systems, 18 finite elements models were constructed, each with either static wind loads, static earthquake loads, or dynamic earthquake loads imposed on their structural systems. The resulting EGHGE/NFA values are plotted in Figure 4.5.

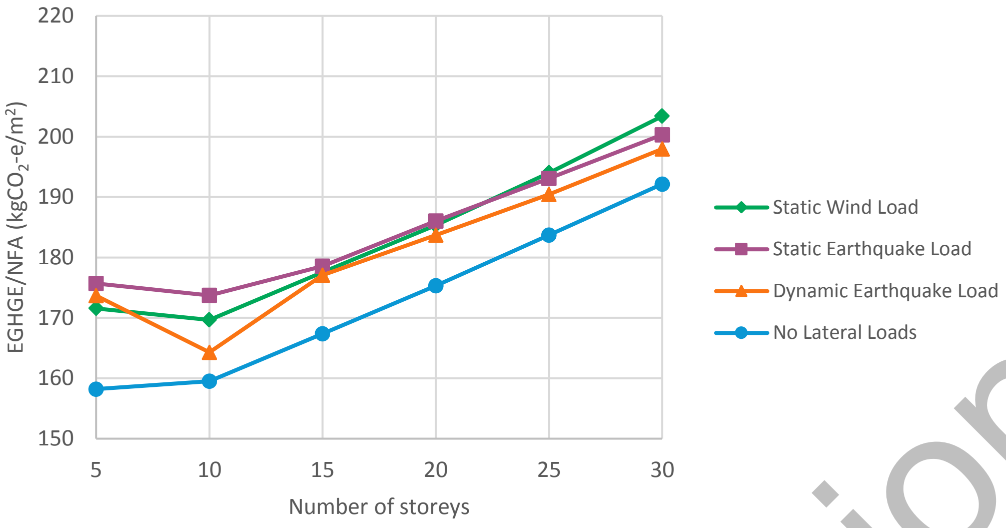

Figure 4.5 - Influence of lateral loads on embodied greenhouse gas emissions per net floor area (EGHGE/NFA) of structural systems. Note: vertical axis starts at 150 kgCO$_2$-e/m^2.

Figure 4.5 shows that modelling earthquake loads as static loads consistently results in structural systems with more EGHGE/NFA compared to modelling earthquake loads as dynamic loads. The relative influence of static wind loads, static earthquake loads and dynamic earthquake loads can be better visualised in Figure 4.6, which plots the percent increase in EGHGE/NFA for each lateral load.

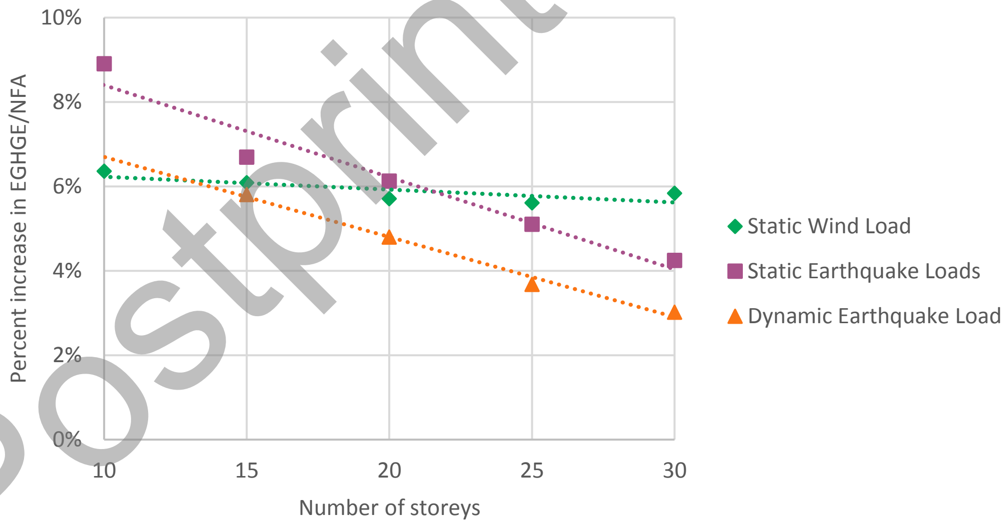

Figure 4.6 - Influence of lateral loads on the increase of embodied greenhouse gas emissions per net floor area (EGHGE / NFA) of structural systems

Figure 4.6 clearly indicates that the influence of both static and dynamic earthquake loads decreases with increasing building height whereas the influence of wind loads remains relatively constant at an increase of 6%. The results also indicate that if earthquake loads are modelled as static loads, the structural systems of tall buildings with 22 storeys or more are governed by wind loads, since their effect on EGHGE/NFA is greatest. Whereas, if earthquake loads are modelled as dynamic loads, the structural systems of tall buildings with 13 storeys or more are governed by wind loads.

As discussed in Section 3.2.3, lateral loads generate an overturning moment that buildings must be designed to resist for strength, serviceability and stability requirements. By calculating the resulting overturning moment of lateral loads, a relationship can be derived between the magnitude of lateral loads and the EGHGE/NFA of structural systems. Figure 4.7 plots the increase in EGHGE/NFA for a 10 MNm increase in overturning moment.

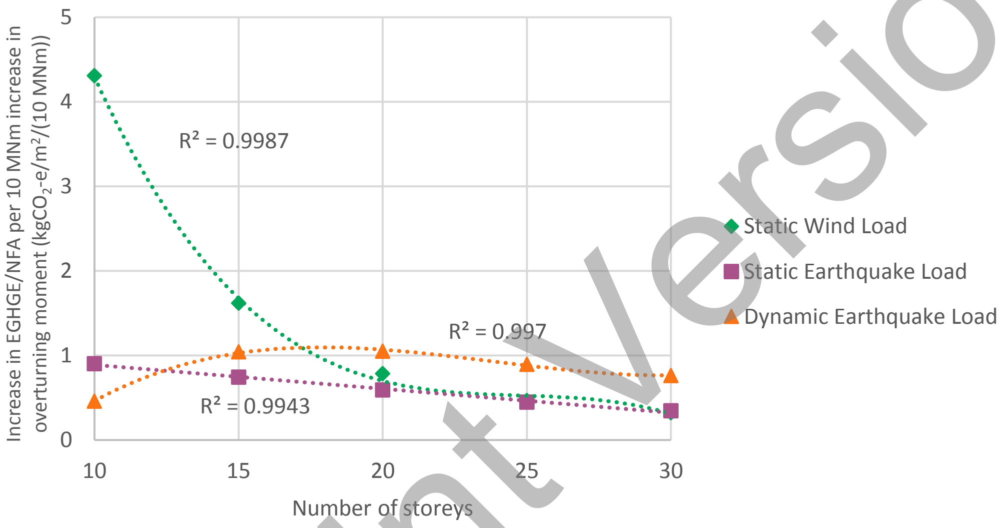

Figure 4.7 - Influence of overturning moment on the increase of embodied greenhouse gas emissions per net floor area (EGHGE / NFA) of structural systems

As seen in Figure 4.7, a regression line is constructed for each of the different types of lateral loads. The coefficient of determination (R^2) for the derives values for static wind load, static earthquake load and dynamic earthquake load are all close to 1. This demonstrates that the variation in EGHGE/NFA is effectively completely explained by the variation in overturning moment. This is due to the directly proportional relationship between lateral loads and the resulting overturning moment that structural systems experience. A linear regression analysis is conducted to construct the regression line for static earthquake load (Equation 4.3), while a polynomial equation of the 3rd order is used to construct the regression lines for both static wind load (Equation 4.4) and dynamic earthquake load (Equation 4.5). The regression equations are presented below:

$$\Delta EGHGE_{SS}/\Delta SEL = -0.028NS + 1.17 \quad \text{(Eq. 4.3)}$$

Where $\Delta EGHGE_{SS}/\Delta SEL$ = the change in embodied greenhouse gas emissions of structural system SS per net floor area for every 10 MNm increase in overturning moment resulting from static earthquake loads in kgCO$_2$-e/m^2/(10 MNm); and NS = number of storeys.

$$\Delta EGHGE_{SS}/\Delta SWL = -0.0011NS^3 + 0.0833NS^2 - 2.074NS + 17.82 \qquad \text{(Eq. 4.4)}$$

Where $\Delta EGHGE_{SS}/\Delta SWL$ = the change in embodied greenhouse gas emissions of structural system SS per net floor area for every 10 MNm increase in overturning moment resulting from static wind loads in kgCO$_2$-e/m^2/(10 MNm); and NS = number of storeys.

$$\Delta EGHGE_{SS}/\Delta DEL = -0.0004NS^3 + 0.028NS^2 - 0.63NS + 3.4 \qquad \text{(Eq. 4.5)}$$

Where $\Delta EGHGE_{SS}/\Delta DEL$ = the change in embodied greenhouse gas emissions of structural system SS per net floor area for every 10 MNm increase in overturning moment resulting from dynamic earthquake loads in kgCO$_2$-e/m^2/(10 MNm); and NS = number of storeys.

By knowing the number of storeys of a tall building, a structural engineer or architect can use Equations 4.3 to 4.5 to estimate the increase in EGHGE/NFA of structural systems as a result of the influence of lateral loads on tall buildings. This can help guide and justify structural design decisions that may lead to a decrease in overturning moment by quantifying the resulting decrease in EGHGE of structural systems for tall buildings.

To assess the inclusion of both wind and earthquake loads in the structural design of tall building, Figure 4.8 plots the resulting EGHGE/NFA of their structural systems. The results show that, upon designing structural systems for the simultaneous application both static wind loads and dynamic earthquake loads, the EGHGE/NFA of structural systems increased by approximately 11% for the 5-storey and 10-storey building and 6% for the 15, 20, 25 and 30-storey buildings. This significant increase emphasises the need for comparative life cycle assessment (LCA) studies on alternative structural systems of tall buildings to consider lateral loads during structural design.

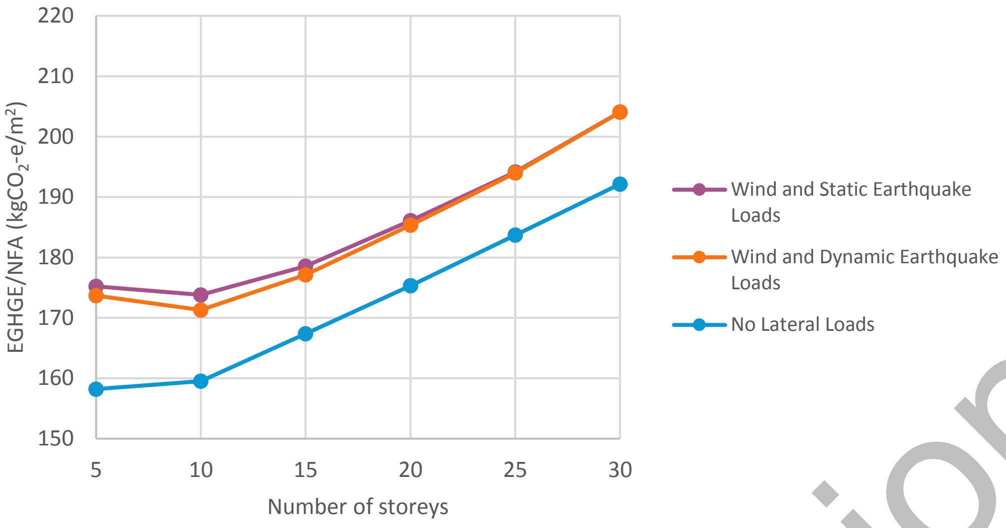

Figure 4.8 - Influence of combined lateral loads on embodied greenhouse gas emissions per net floor area (EGHGE/NFA) of structural systems. Note: vertical axis starts at 150 kgCO$_2$-e/m^2.

4.4 Sensitivity analysis results

As discussed in Section 3.4, 2 additional finite element models were constructed for a 50-storey tall building to assess the influence of lateral loads with increasing building height on the EGHGE of their structural systems. One of these finite element models was constructed without considering the effects of lateral loads and the other was designed to resist the simultaneous application of both static wind and dynamic earthquake loads. Figure 4.9 plots the EGHGE/NFA of the 50-storey buildings along with all the other finite element models that adopt the same structural design methods.

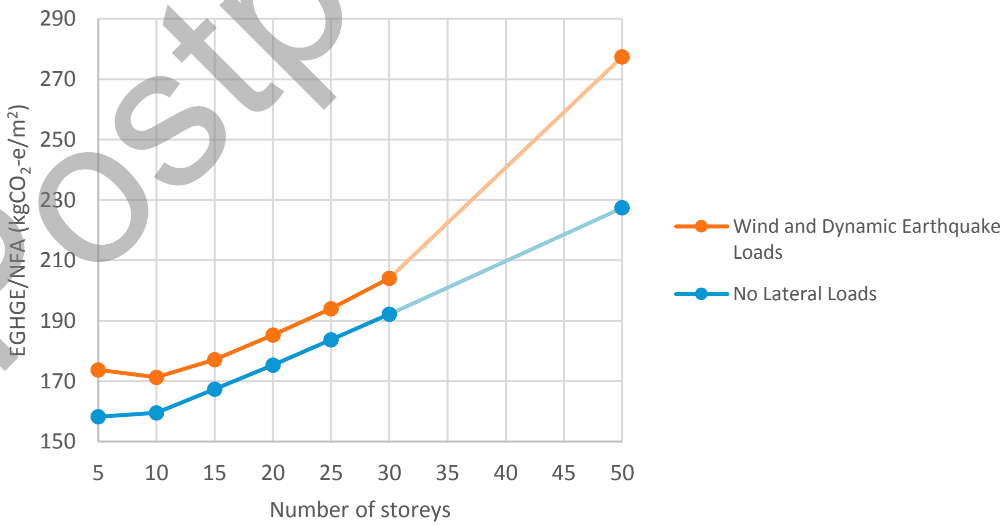

Figure 4.9 – Sensitivity analysis on influence of combined lateral loads with increasing building height on embodied greenhouse gas emissions per net floor area (EGHGE/NFA) of structural systems for tall buildings

The results of the sensitivity analysis clearly show the increasing influence of lateral loads on the EGHGE/NFA of structural systems with increasing building height. Designing the 50-storey tall building to resist the effects of wind and earthquake resulted in a 22% increase in EGHGE/NFA (from 227 $kgCO_2$-e/m2 to 277 $kgCO_2$-e/m^2). Conversely, tall buildings of 15 to 30 storeys in height experienced a more modest increase of 6% in EGHGE/NFA as a result of the effects of wind and earthquake loads. This finding corroborates the premium-for-height framework, which was described by Khan [11] as the increase in resource use with increasing building height due to the cumulative effect of wind and earthquake loads on the structural systems of tall buildings.

5 Discussion

The discussion is divided into three sections. Section 5.1 presents the contribution of this paper in comparison to previous comparative life cycle assessment (LCA) studies that assess alternative structural systems for tall buildings. Section 5.2 discusses the practical implications of the findings. Section 5.3 presents the limitations of this study and outlines future research directions.

5.1 Contribution

This study has quantified for the first time the influence of imposed loads, façade loads and lateral loads on the embodied greenhouse gas emissions (EGHGE) of structural systems, across a range of building heights. In comparison, most existing studies conduct a comparative LCA on alternative structural systems of tall buildings while lacking consistency and comprehensive in the adopted structural design methods. By demonstrating the influence of structural design methods on the EGHGE of structural systems, this paper demonstrates the need for clarity and transparency to increase the comparability between different comparative LCA studies.

The equations that were developed in this study can help guide researchers, architects and structural engineers to understand the influence of structural loads and methods on the EGHGE of structural systems. The developed intensities of EGHGE per Net Floor Area (NFA) can also help establish benchmarks for the embodied environmental flows of structural systems for tall buildings.

This study also developed and demonstrated the use of unprecedented functional units such as ($kgCO_2$-e/m^2)/kPa, ($kgCO_2$-e/m^2)/(kN/m), ($kgCO_2$-e/m^2)/(MNm) to quantify the influence of imposed loads, façade loads and lateral loads on the EGHGE of structural systems. This type of assessment, and the use of these new functional units, can effectively inform future design frameworks that integrated the environment assessment into the structural design of tall buildings to reduce their EGHGE.

5.2 Implications on comparative life cycle assessment of alternative structural systems for tall buildings

As discussed in Section 1, a comparative LCA approach is increasingly being used to reduce the EGHGE of structural systems for tall buildings [12-16]. However, these studies use inconsistent and incomplete structural design and analysis methods that have been shown to significantly affect the EGHGE of structural systems.

As previously seen in Figure 2.1, existing comparative LCA studies on the structural systems of tall buildings have either used an imposed design load of 2 kPa, as is the case in the studies by Cho *et al.* [13] and Moussavi Nadoushani and Akbarnezhad [15], or 3 kPa in the case of the study by Foraboschi *et al.* [14]. Having shown that varying imposed loads can significantly influence the EGHGE of structural systems for tall buildings, the comparison between alternative structural systems across these studies ought to include the adjustment of EGHGE values. The findings of this study suggest that the EGHGE per net floor area (NFA) adjustment could be up to 7.5 $kgCO_2$-e/m^2 per 1 kPa increase in imposed loads for the structural design of a 30-storey building. This can be very significant for studies like that of Cho *et al.* [13] that completely neglect super-imposed permanent loads while studies like that of Moussavi Nadoushani and Akbarnezhad [15] consider a super-imposed permanent load of 3.5 kPa. To perform such adjustments, comparative LCA studies of structural systems for tall building ought to be clear and transparent in their adopted structural design methods.

Similarly, existing comparative LCA studies have either used façade loads of 4 kN/m, such as the study by Foraboschi *et al.* [14], or completely neglected the inclusion of façade loads in the structural design of tall buildings, such as the studies by Cho *et al.* [13] and Moussavi Nadoushani and Akbarnezhad [15]. The findings of this study suggest that a difference of 4 kN/m in façade loads might lead to an increase of up to 3.6 $kgCO_2$-e/m^2 of EGHGE/NFA for the structural system of a 30-storey building. This adjustment is also expected to be greater with increasing building heights.

Moreover, as seen in Figure 2.1, none of the existing comparative LCA studies of structural systems for tall buildings indicate that both wind loads and earthquake loads were simultaneously considered during structural design. Cho *et al.* [13] and Foraboschi *et al.* [14] only considered wind loads whereas Moussavi Nadoushani and Akbarnezhad [15] only considered earthquake loads. The studies by Zhao and Haojia [12] and Trabucco *et al.* [16] did not indicate whether lateral loads were considered during structural. The results of this study indicate that wind and earthquake lateral loads can significantly influence the EGHGE of structural systems for tall buildings by up to 22%. Findings also indicate that this influence increases with building height in accordance with the premium-for-height framework. Thus, the influence of lateral loads ought to be taken into considerations when comparing LCA studies of alternative structural systems for tall buildings.

Therefore, it is crucial for researchers, architects and structural engineers, who undertake a comparative LCA approach, to understand the influence of structural loads and design methods on the EGHGE of structural systems. It is also useful for the designer to properly interpret and compare the results of existing comparative LCA studies of structural systems to help guide early structural design decisions.

5.3 Limitations and future research

This study suffers from several limitations. Firstly, this study assessed the influence of structural design method on reinforced concrete buildings with rigid frames and shear wall structural systems. Thus, the findings of the study are restricted to these structural materials and systems. The study also neglected the influence of standardisation in construction, which often dictates the selection of section sizes, in order to assess the maximum potential savings in EGHGE when assessing alternative structural systems. Further research could investigate the influence of structural design methods on tall buildings of different structural materials and systems.

Secondly, this study relies on Australian hybrid data for EGHGE, which are specific to the economic situation and energy mix of Australia. Despite the geographic specificity in the adopted material coefficients for EGHGE, the resulting material quantities, which were derived from the constructed finite element models, are still relevant. Given material coefficients for EGHGE that are specific to other regions, future research can convert the existing material quantities to more specific and appropriate values of EGHGE emissions.

Thirdly, this study used the Australian codes and standards of structural design to determine the relevant design loads, which differ in magnitude to the design loads required by other building codes and standards. However, by quantifying the influence of imposed loads, façade loads and lateral loads per load unit on the EGHGE/NFA of structural systems using increments of 1 kPa, 1 kN/m and 10 MNm, respectively, the study widened the applicability of its results. This approach, which normalises the effects of design loads per unit load, yields findings that are related to the first principles of structural design, which are the basis of all structural design codes and practices.

Despite these limitations, this study provides an unprecedented insight into the influence of structural design methods on the embodied environmental flows of structural systems for tall buildings.

6 Conclusion

This study assessed and quantified the influence of imposed loads, façade loads and lateral loads on the embodied greenhouse gas emissions (EGHGE) of structural systems for tall buildings using a total of 80 structural systems parametrically designed and analysed using finite element modelling. The study demonstrates that varying structural design methods and magnitudes of structural loads can significantly influence the EGHGE of structural systems by up to 22%.

This study also developed and demonstrated the use of unprecedented functional units such as ($kgCO_2$-e/m^2)/kPa, ($kgCO_2$-e/m^2)/(kN/m), ($kgCO_2$-e/m^2)/(kNm) in its integration of environmental assessment and structural design.

The findings of this study confirm the need for clarity, consistency, transparency and comprehensiveness in structural design methods when conducting comparative life cycle assessment (LCA) studies of structural systems for tall buildings. This will ultimately contribute to reducing the environmental effects of buildings and create a healthier built environment.

Data Availability

The data that support the findings of this study are openly available in [repository name e.g “figshare”] at http://doi.org/[doi], reference number [reference number]. The finite element models that were constructed for this study are also openly available in [repository name e.g “figshare”] at http://doi.org/[doi], reference number [reference number].

Author’s contributions

JH, AS and RHC designed the original research idea. JH developed the finite element modelling approach, conducted the analysis and collected the data. JH wrote the paper and designed the figures. AS and RHC reviewed draft manuscripts and provided feedback and guidance.

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Appendix A Constructed finite element models with adopted structural design methods

The follow table lists the constructed finite element models that were used for this study, along with their adopted structural design methods and structural load magnitudes.

Table A.1 - Constructed finite element models with adopted structural design methods

Finite Element Model Name (available on figshare)	Storeys	Imposed Load (kPa)	Imposed Load Reduction	Façade Load (kN/m)	Static Wind Load	Static EQ Load	Dynamic EQ Load
RC_RigidFrame_5Storeys_01	5	2	-	3.5	-	-	-
RC_RigidFrame_10Storeys_01	10	2	-	3.5	-	-	-
RC_RigidFrame_15Storeys_01	15	2	-	3.5	-	-	-
RC_RigidFrame_20Storeys_01	20	2	-	3.5	-	-	-
RC_RigidFrame_25Storeys_01	25	2	-	3.5	-	-	-
RC_RigidFrame_30Storeys_01	30	2	-	3.5	-	-	-
RC_RigidFrame_5Storeys_02	5	2	✓	3.5	-	-	-
RC_RigidFrame_10Storeys_02	10	2	✓	3.5	-	-	-
RC_RigidFrame_15Storeys_02	15	2	✓	3.5	-	-	-
RC_RigidFrame_20Storeys_02	20	2	✓	3.5	-	-	-
RC_RigidFrame_25Storeys_02	25	2	✓	3.5	-	-	-
RC_RigidFrame_30Storeys_02	30	2	✓	3.5	-	-	-
RC_RigidFrame_5Storeys_03	5	3	-	3.5	-	-	-
RC_RigidFrame_10Storeys_03	10	3	-	3.5	-	-	-
RC_RigidFrame_15Storeys_03	15	3	-	3.5	-	-	-
RC_RigidFrame_20Storeys_03	20	3	-	3.5	-	-	-
RC_RigidFrame_25Storeys_03	25	3	-	3.5	-	-	-
RC_RigidFrame_30Storeys_03	30	3	-	3.5	-	-	-
RC_RigidFrame_5Storeys_04	5	3	✓	3.5	-	-	-
RC_RigidFrame_10Storeys_04	10	3	✓	3.5	-	-	-
RC_RigidFrame_15Storeys_04	15	3	✓	3.5	-	-	-
RC_RigidFrame_20Storeys_04	20	3	✓	3.5	-	-	-
RC_RigidFrame_25Storeys_04	25	3	✓	3.5	-	-	-
RC_RigidFrame_30Storeys_04	30	3	✓	3.5	-	-	-
RC_RigidFrame_5Storeys_05	5	4	-	3.5	-	-	-
RC_RigidFrame_10Storeys_05	10	4	-	3.5	-	-	-
RC_RigidFrame_15Storeys_05	15	4	-	3.5	-	-	-
RC_RigidFrame_20Storeys_05	20	4	-	3.5	-	-	-
RC_RigidFrame_25Storeys_05	25	4	-	3.5	-	-	-
RC_RigidFrame_30Storeys_05	30	4	-	3.5	-	-	-
RC_RigidFrame_5Storeys_06	5	4	✓	3.5	-	-	-

Finite Element Model Name (available on figshare)	Storeys	Imposed Load (kPa)	Imposed Load Reduction	Façade Load (kN/m)	Static Wind Load	Static EQ Load	Dynamic EQ Load
RC_RigidFrame_10Storeys_06	10	4	✓	3.5	-	-	-
RC_RigidFrame_15Storeys_06	15	4	✓	3.5	-	-	-
RC_RigidFrame_20Storeys_06	20	4	✓	3.5	-	-	-
RC_RigidFrame_25Storeys_06	25	4	✓	3.5	-	-	-
RC_RigidFrame_30Storeys_06	30	4	✓	3.5	-	-	-
RC_ShearWall_5Storeys_01	5	2	-	3.5	✓	-	-
RC_ShearWall_10Storeys_01	10	2	-	3.5	✓	-	-
RC_ShearWall_15Storeys_01	15	2	-	3.5	✓	-	-
RC_ShearWall_20Storeys_01	20	2	-	3.5	✓	-	-
RC_ShearWall_25Storeys_01	25	2	-	3.5	✓	-	-
RC_ShearWall_30Storeys_01	30	2	-	3.5	✓	-	-
RC_ShearWall_5Storeys_02	5	2	-	3.5	-	✓	-
RC_ShearWall_10Storeys_02	10	2	-	3.5	-	✓	-
RC_ShearWall_15Storey_02	15	2	-	3.5	-	✓	-
RC_ShearWall_20Storey_02	20	2	-	3.5	-	✓	-
RC_ShearWall_25Storey_02	25	2	-	3.5	-	✓	-
RC_ShearWall_30Storey_02	30	2	-	3.5	-	✓	-
RC_ShearWall_5Storeys_03	5	2	-	3.5	✓	✓	-
RC_ShearWall_10Storeys_03	10	2	-	3.5	✓	✓	-
RC_ShearWall_15Storeys_03	15	2	-	3.5	✓	✓	-
RC_ShearWall_20Storeys_03	20	2	-	3.5	✓	✓	-
RC_ShearWall_25Storeys_03	25	2	-	3.5	✓	✓	-
RC_ShearWall_30Storeys_03	30	2	-	3.5	✓	✓	-
RC_ShearWall_5Storeys_04	5	2	-	3.5	-	-	✓
RC_ShearWall_10Storeys_04	10	2	-	3.5	-	-	✓
RC_ShearWall_15Storeys_04	15	2	-	3.5	-	-	✓
RC_ShearWall_20Storeys_04	20	2	-	3.5	-	-	✓
RC_ShearWall_25Storeys_04	25	2	-	3.5	-	-	✓
RC_ShearWall_30Storeys_04	30	2	-	3.5	-	-	✓
RC_ShearWall_5Storeys_05	5	2	-	3.5	✓	-	✓
RC_ShearWall_10Storeys_05	10	2	-	3.5	✓	-	✓
RC_ShearWall_15Storeys_05	15	2	-	3.5	✓	-	✓
RC_ShearWall_20Storeys_05	20	2	-	3.5	✓	-	✓
RC_ShearWall_25Storeys_05	25	2	-	3.5	✓	-	✓
RC_ShearWall_30Storeys_05	30	2	-	3.5	✓	-	✓
RC_RigidFrame_5Storeys_07	5	2	-	4.5	-	-	-
RC_RigidFrame_10Storeys_07	10	2	-	4.5	-	-	-
RC_RigidFrame_15Storeys_07	15	2	-	4.5	-	-	-
RC_RigidFrame_20Storeys_07	20	2	-	4.5	-	-	-
RC_RigidFrame_25Storeys_07	25	2	-	4.5	-	-	-
RC_RigidFrame_30Storeys_07	30	2	-	4.5	-	-	-
RC_RigidFrame_5Storeys_08	5	2	-	5.5	-	-	-
RC_RigidFrame_10Storeys_08	10	2	-	5.5	-	-	-

Finite Element Model Name (available on figshare)	Storeys	Imposed Load (kPa)	Imposed Load Reduction	Façade Load (kN/m)	Static Wind Load	Static EQ Load	Dynamic EQ Load
RC_RigidFrame_15Storeys_08	15	2	-	5.5	-	-	-
RC_RigidFrame_20Storeys_08	20	2	-	5.5	-	-	-
RC_RigidFrame_25Storeys_08	25	2	-	5.5	-	-	-
RC_RigidFrame_30Storeys_08	30	2	-	5.5	-	-	-
RC_RigidFrame_50Storeys_01	50	2	-	3.5	-	-	-
RC_ShearWall_50Storeys_01	50	2	-	3.5	✓	-	✓

853 Note: EQ = Earthquake

Appendix B Calculating wind loads according to AS1170.2

The following figure illustrates the adopted process of calculating quasi-static wind loads as prescribed by the Australian standard *AS1170.2:2011*.

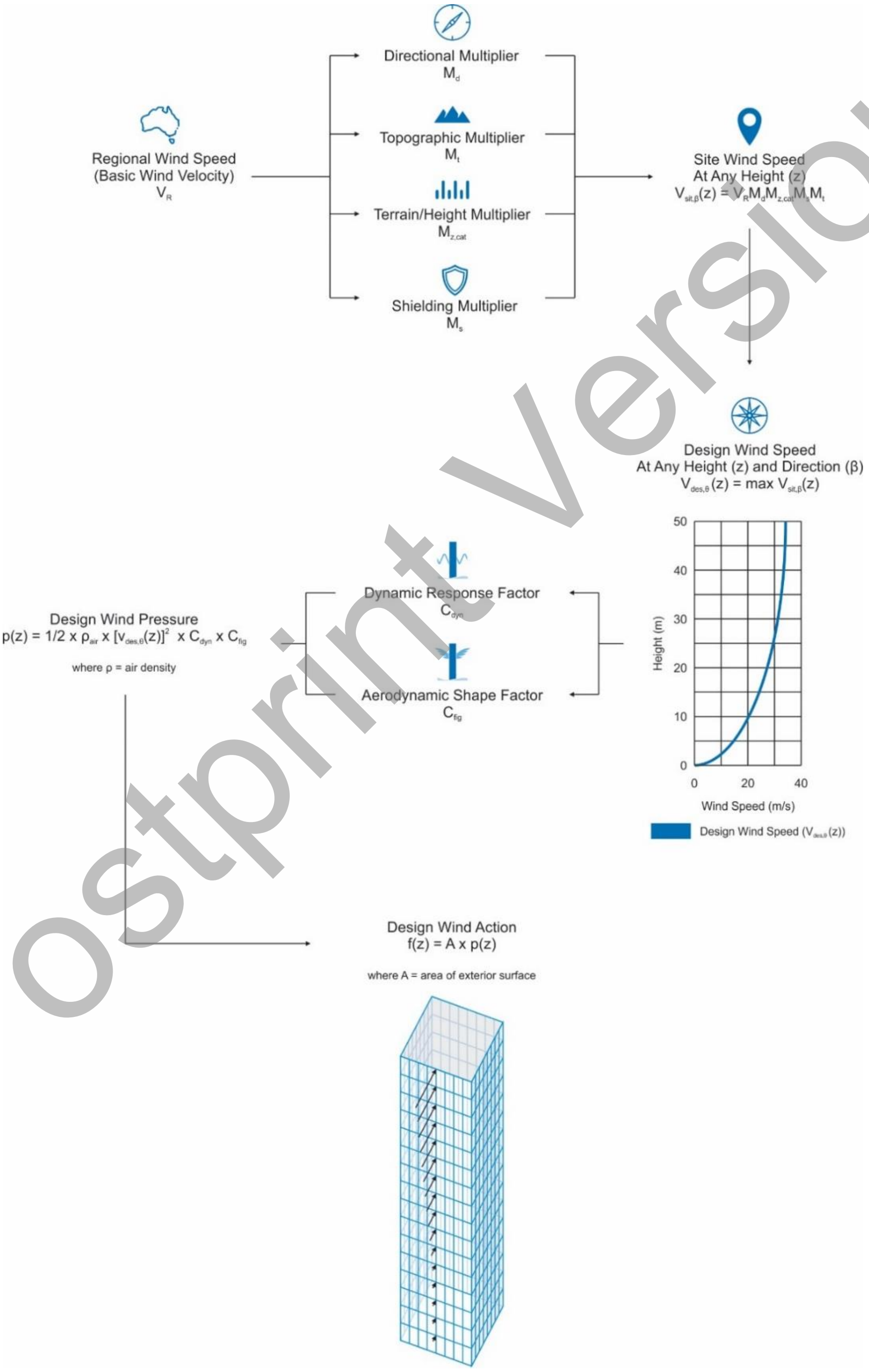

Figure B.1 - Process of calculating wind loads as prescribed by Australian standard AS1170.2:2011

Appendix C Calculating earthquake loads using Equivalent Static Method according to AS1170.4

The following figure illustrates the adopted process of calculating static earthquake loads as prescribed by the Australian standard *AS1170.4:2007*.

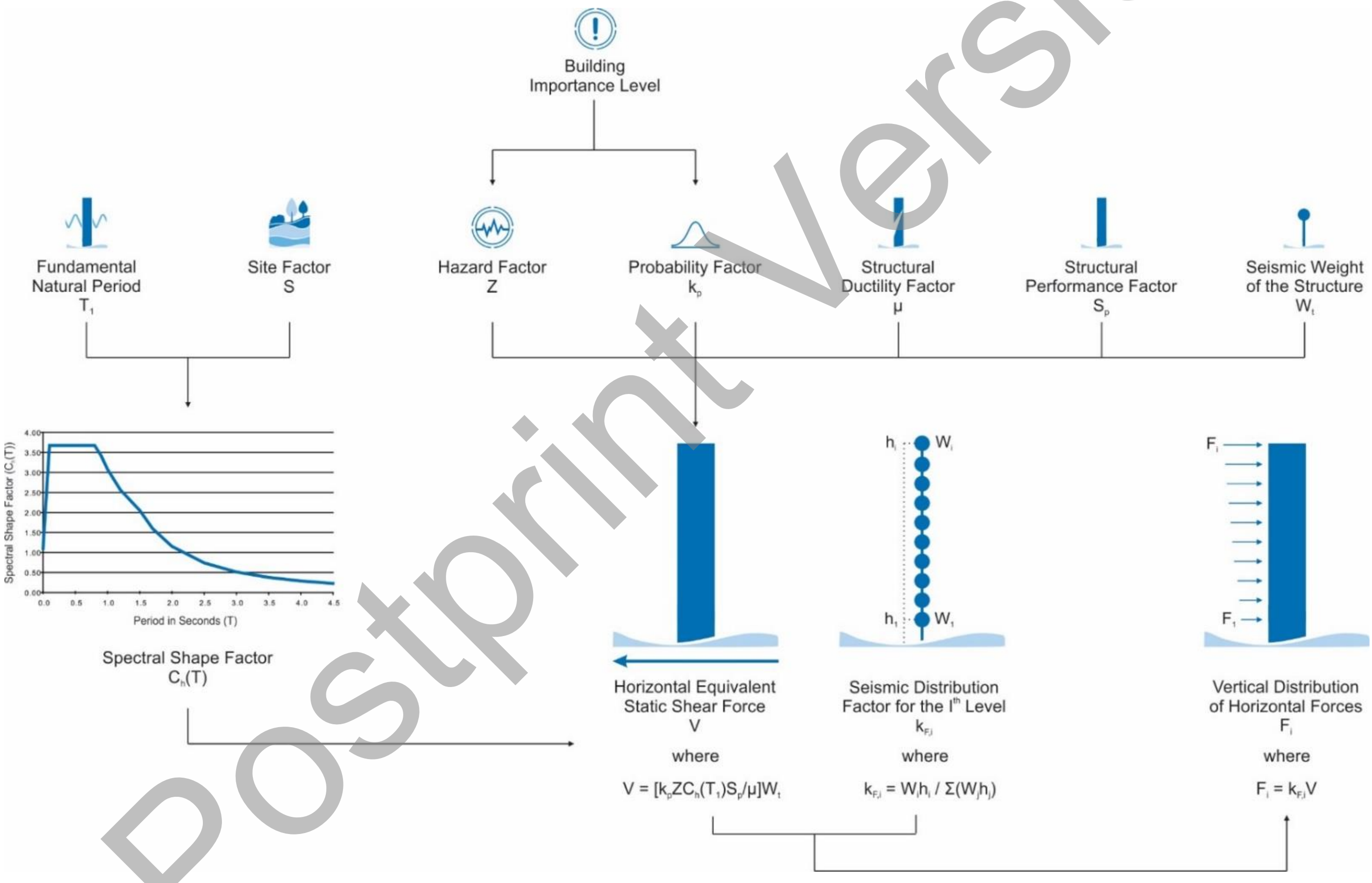

Figure C.0.1 - Process of calculating equivalent static earthquake loads as prescribed by Australian standard AS1170.4:2007

Appendix D Calculating earthquake loads according to Response Spectrum Analysis method.

The following figure illustrates the adopted process of calculating dynamic earthquake loads according to the Response Spectrum Analysis method.

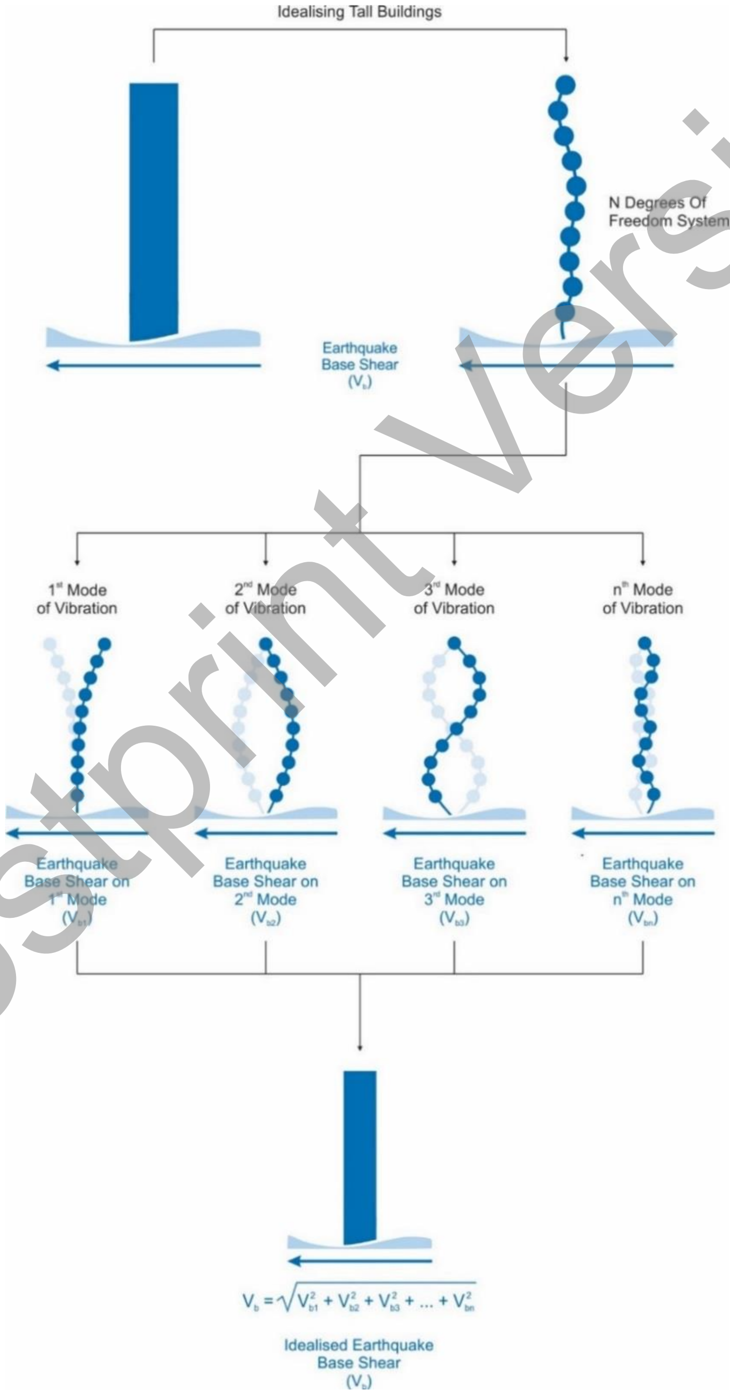

Figure D.1 - Response-Spectrum Analysis for calculating earthquake loads

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