University of Southern Queensland

Faculty of Health, Engineering and Sciences

Analysis of Wall Formwork in the Australian Multi-storey Construction Industry

A dissertation submitted by

Bradley Carson

in fulfilment of the requirements of

ENG4111 and 4112 Research Project

towards the degree of

Bachelor of Engineering (Honours) (Civil)

Submitted October, 2016

Abstract

This research paper has two primary objectives. Firstly, to research and evaluate the relevant Australian standards and regulations for vertical wall formwork. Secondly to evaluate and analyse the wall formwork used in multi-storey formwork construction. The primary objectives are established to expand the general understanding of vertical wall formwork use within the Australian high-rise construction industry, as well as the associated regulations.

A research case study of 77 Australian high-rise construction sites was deemed the most suitable initial method for gathering data for this study. A combination of research and consultation with representatives from building and formwork contractors involved in the respective construction projects was employed to gather said data. Limit State Analysis and Finite Element Analysis was then used to evaluate the structural capacity of some the types of wall formwork identified as being used in the high-rise construction industry.

The project case study was very useful in obtaining information pertaining to formwork use as well as identifying a specific range of concrete pressures that wall formwork is subjected to on a high-rise construction site. Because wall formwork systems are predominately pre-engineered and prefabricated for re-use over and over again, this data is particularly useful for formwork designers. There is currently a gap in appropriate literature for formwork designers in the Australian formwork industry. It is hoped that the outputs of this study can serve as a guide to help cover this gap in regards to wall formwork

University of Southern Queensland

Faculty of Health, Engineering and Sciences

ENG4111/ENG4112 Research Project

Limitations of Use

University of Southern Queensland

Faculty of Health, Engineering and Sciences

ENG4111/ENG4112 Research Project

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Bradley Carson

0050078297

Contents

LIST OF FIGURES

LIST OF TABLES

1 Introduction

1.1 BACKGROUND

Concrete formwork is a temporary structure used on construction projects. Formwork provides temporary support to freshly cast concrete until the concrete cures enough so that the imposed loads can be carried by the concrete structure itself. Formwork is basically a mould for concrete. Formwork can either be incorporated as a permanent part of the design or be removed after the concrete has reached a desired strength. Formwork can represent up to 60 percent of the overall cost of the concrete structure (Hurd, 2005). Savings can be achieved through the continual reuse of the formwork throughout the construction of a project.

There are many types of formwork available in the market for use depending on the application and location of use. The two most common types of vertical wall formwork used in the Australian high rise construction industry are traditional timber LVL (Laminated Veneer Lumber) wall forms and steel RHS (Rectangular Hollow Section) wall forms. Timber formwork typically consists of plywood sheathing, with timber members placed as studs and wales on the back of the formwork connected with bolts and screws to form a frame. Steel RHS formwork consist of plywood or metal sheathing on a welded steel RHS frame. Both types of wall forms are prefabricated offsite with the steel RHS alternative the most labour intensive and costly.

The wall form work used in high-rise construction is cycled and used over and over again during the construction of a project. The wall forms can often remain onsite in the weather for up to 12 months over the construction phase of a high-rise tower. Because of this the more expensive steel RHS wall forms are favoured on larger scale projects because of their longer life cycle over the traditional timber LVL alternative.

1.2 OBJECTIVES

In this study, there are two primary objectives and five secondary objectives. The primary objectives are established to expand the general understanding of vertical formwork use within the Australian high-rise construction industry, as well as the associated regulations. The primary objectives established are:

1. Research and evaluate the relevant Australian standards and regulations for vertical wall formwork
2. Evaluate the wall formwork used in the Australian high-rise construction industry.

The secondary objectives established in support of the primary objectives are:

1. Establish the typical use cycle of vertical wall forms
2. Identify the types of wall formwork used in the Australian high-rise construction industry
3. Develop a greater understanding of the lateral concrete pressures that occur in wall formwork within the Australian high-rise construction industry.
4. Evaluate the structural capacity of the different types of wall formwork used in the Australian high-rise construction industry.
5. Compare the different types of wall formwork used in multistorey formwork construction in Australia.

Due to the delay in the release of an update of Australian Standard AS3610 covering formwork design and the issues stopping the release of the proposed Formwork Designers Handbook by the Concrete Institute of Australia there is currently a gap in appropriate literature for formwork designers in the Australian formwork industry. It is hoped that the outputs of this study can serve as a guide to help cover this gap in regards to vertical wall formwork.

2 Literature Review

2.1 HIGH RISE FORMWORK CONSTRUCTION

Reinforced concrete construction is by far the most popular method of constructing high-rise buildings in Australia today. Over eighty percent of tall buildings over twenty stories tall are constructed in this way. Modern concrete technology has provided concrete mixes with properties which can be pumped with ease to the uppermost floors of tall buildings without clogging hoses and yet still give the properties required for strong, serviceable and durable building structures (SRIA, 2016). Modern concreting methods including the use of prefabricated reinforcement cages and precast concrete elements have enabled high rise structures to be built with increasing speed. The 47-storey Telecom Corporate building in Melbourne was constructed in record time with an average floor to floor cycle in its office areas of only 3 days (SRIA, 2016).

“Reinforced concrete framing systems have been proven to be the most economical form of construction for medium- to high-rise buildings, in Australia” (SRIA, 2016). This can be attributed to the following:

- The fluid nature of reinforced concrete makes changes in structural dimension, shape and direction straightforward. Service penetrations through floor slabs, beams, walls and columns can be easily accommodated.

- It allows follow-up work from other trades such as building fit out to begin the minute formwork is removed.

- Reinforced concrete is fire-resistant, so there are no delays waiting for the structure to be fire-proofed.

- The Steel Reinforcement Institute of Australia’s research has shown that reinforced concrete buildings will usually have a significantly reduced floor-to-floor height in comparison to structural steel buildings averaging 420mm less per floor.

Vertical forming systems are those used to form the vertical supporting elements of the structure (i.e. columns, walls). There are a number of different vertical forming systems used in the Australian high rise construction industry. These include: conventional, crane lifted platforms, slip forms, and jump forms (Peurifoy & Oberlender, 2011).

Conventional forming systems rely on the site tower crane to lift prefabricated vertical wall forms into their pouring position on top of the concrete slab. The slab intern acts as a platform so that the wall form can be accessed by workers to align, secure the forms in place and fit reinforcing steel prior to the concrete pour. The most common procedure is to fasten a base plate to the slab with fasteners or concrete nails (ACI, 2005).

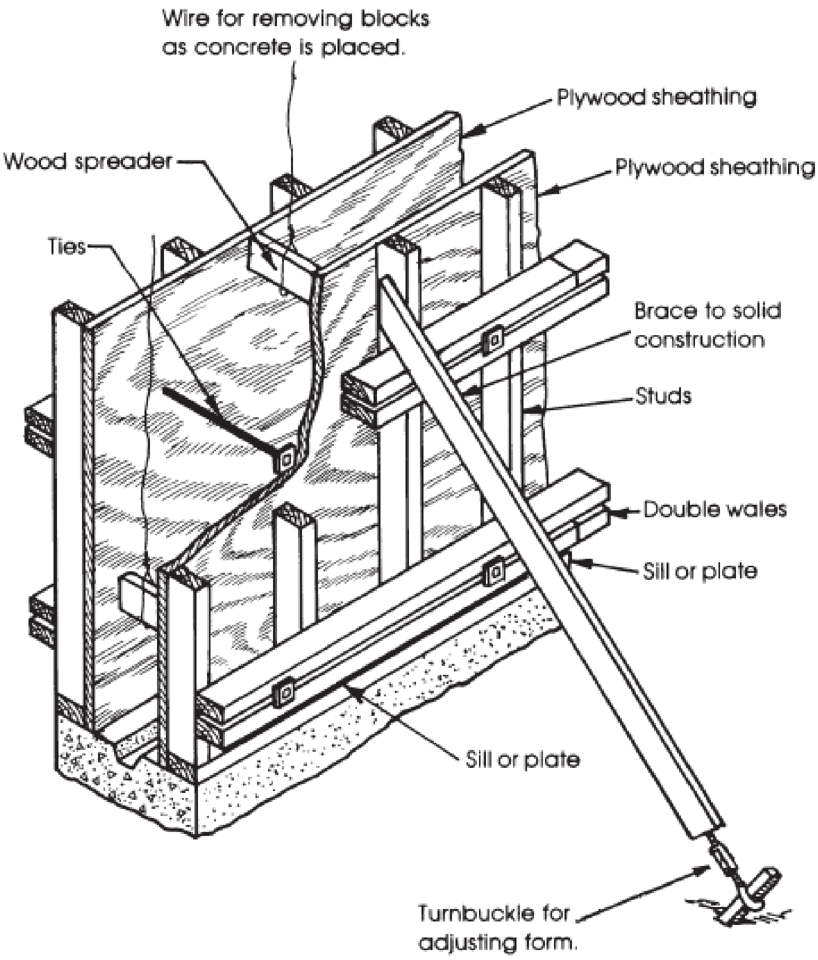

Figure 2-1 Conventional Wall Forming System (ACI, 2005)

Slip forms place concrete by extrusion. The concrete is placed in the forms, which at the same time is being jacked vertically, extruding the concrete, in the shape of the form. The movement of the forms is slow enough for concrete to gain the strength to keep its shape and support its weight. Vertical slip forms are usually moved by jacks riding on smooth steel rods in the concrete. The continuous process is carried on, filling and moving the forms upward, often 24 hours a day until the structure is complete. The working deck, concrete supply hoppers, and finishers platforms are carried by the moving formwork (ACI, 2005).

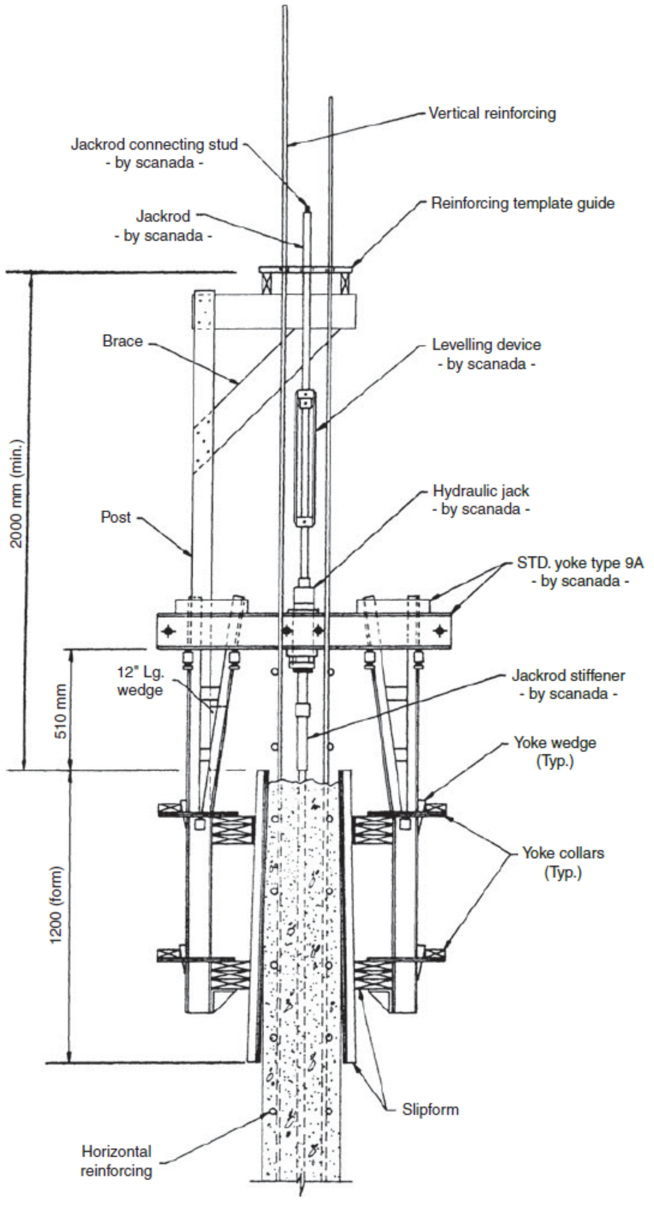

Figure 2-2 Typical Slip Form (Peurifoy & Oberlender, 2011)

Jump forms are used where no floor is available on which to support the wall formwork, or most commonly in high-rise construction where the wall and columns proceed ahead of the floor slab. Jump forms use the same prefabricated vertical wall forms as a conventional system. The form is “cycled” that is, filled with concrete, stripped, and then jumped to the next level after the concrete is set (ACI, 2005). The jump forms provide built in working platforms to allow workers to access the forms, place reinforcing steel, pour the concrete and concrete finishing. Jump forms are electrically or hydraulically self-climbing. Used correctly they minimise the number of pieces to be handled by the site tower crane and simplify the task of resetting the wall forms which in turn saves considerable time.
Crane lifted platforms are essentially the same as jump forms in that they proceed ahead of the floor slab and provide working platforms which simplify the task of resetting the forms. However, as the name suggests instead of being self-climbing like jump forms they are lifted in between cycles by the site tower crane.

Figure 2-3 Crane Lifted Forming Platform System

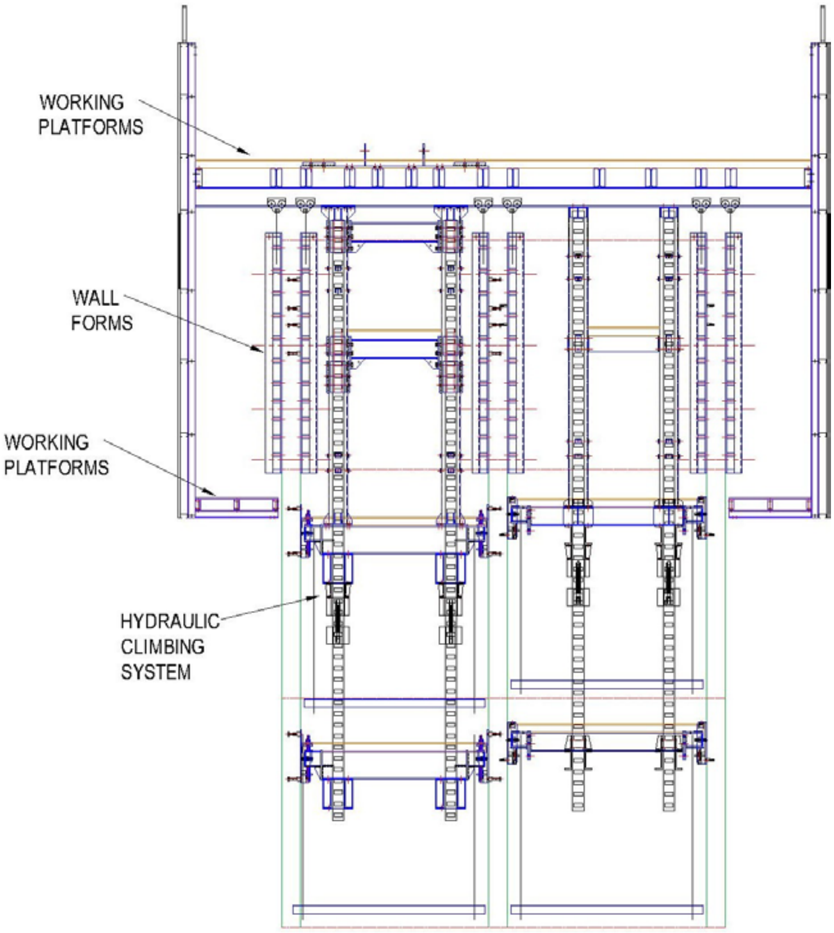

Figure 2-4 Section Through & Image of a Typical Jump Form System

2.2 VERTICAL FORMWORK DESIGN

Size, shape, and alignment of concrete walls and columns depend on accurate construction of the vertical forms. Vertical formwork needs to be strong enough to handle construction loads safely and stiff enough to maintain its shape under full load. Forms need to be constructed to withstand handling and reuse without losing their dimensional integrity (Nemati, 2007). Formwork must be rigid enough under construction loads to maintain the designed shape and alignment of the concrete element. If the forms deflect excessively, deformations in the concrete surface may require expensive chipping and grinding. If the forms move out of place, the misalignment can destroy the integrity of the structure or affect installation of the structural frame or the building's facade (ACI, 2005). The quality of the surface finish of the concrete is directly affected by the forms and form material. Poor formwork design or workmanship will lead to form concrete leakage and rough finishes. If the forms do not produce the specified finish, considerable corrective work such as grinding, patching, rubbing, or coating may be required (ACI, 2005).

Forms and forming systems usually fall into one of four categories (ACI, 2005):

- Conventional job-built forms for one-time use. Form components are assembled piece by piece on the jobsite.
- Prefabricated conventional forms that can be reused.
- Manufactured modular panel forms, provided by a formwork supplier as a total system.
- Special form systems for specific situations or structures.

Prefabricated, reusable form panels have become standard items of construction. Ready-made or contractor-built prefabricated forms are commonly used for wall forming where multiple floors are being erected. For wall forms, the frame work and sheathing are preassembled in units small enough to be handled by crane or machinery conveniently (ACI, 2005). Conventional vertical wall forms are made up of the following components: sheathing, studs, wales and tie rods. Sheathing retains the concrete and is supported by studs. Studs are supported by wales. The wales are held in place by tension members such as tie rods (Nemati, 2007).

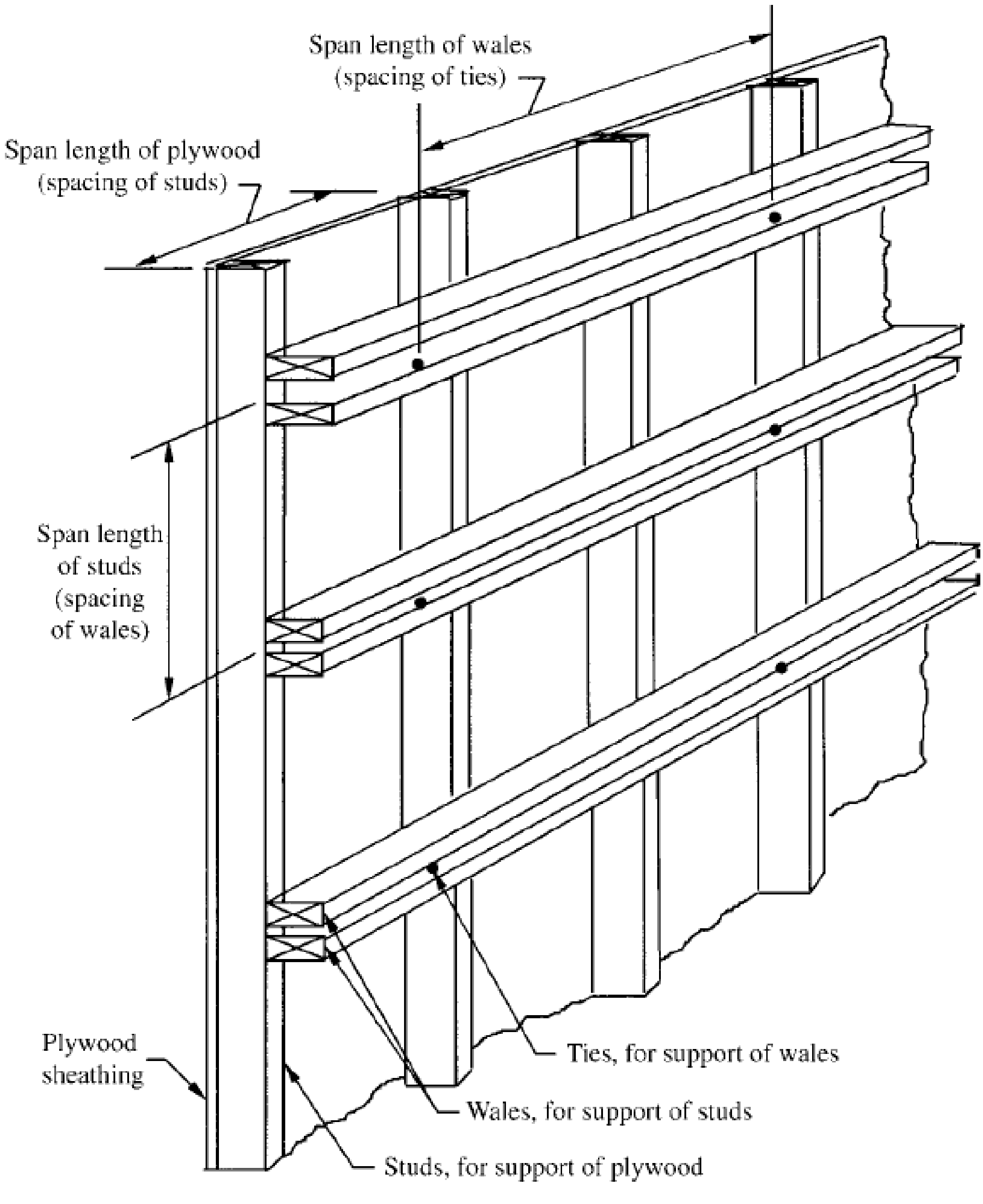

Figure 2-5 Typical Vertical Wall Form with Components Identified (Peurifoy & Oberlender, 2011)

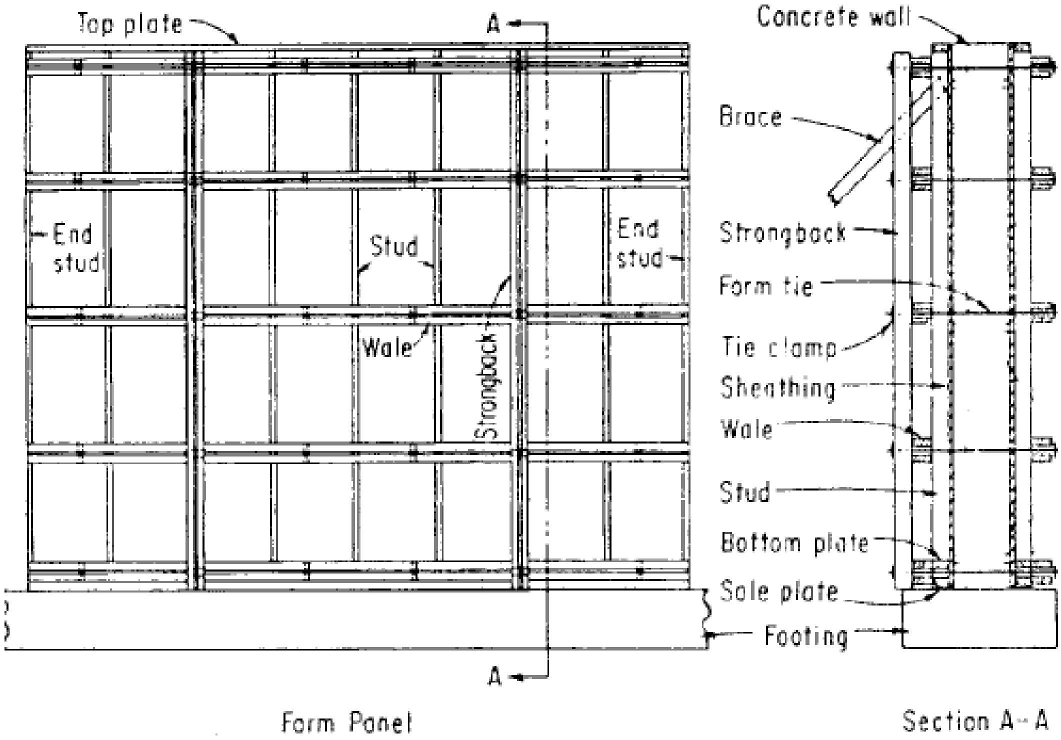

Figure 2-6 Elevation and Section on Typical Vertical Wall Form (Peurifoy & Oberlender, 2011)

Sheathing is the form face on each side of the wall against which the fresh concrete is placed. It is typically made up of plywood or steel plate within the Australian formwork industry. The sheathing provides resistance to the pressure of the freshly placed concrete (Peurifoy & Oberlender, 2011).

Studs are the members to which the sheathing is attached. They can either be installed vertically or horizontally. Studs provide support for the sheathing (Peurifoy & Oberlender, 2011). In the Australian form work industry, they are usually made up of 95mm x 47mm timber LVL's or 100mm x 50mm steel RHS.

Wales, are usually made up of double 95mm x 47mm timber LVL's or 100mm x 50mm steel RHS with a 50mm gap in-between. They are installed on opposite sides of wall forms, perpendicular to the studs, to hold the studs in position, to ensure good alignment for the forms, and to receive the form ties. The wales provide support for the studs (Peurifoy & Oberlender, 2011).

In order to secure concrete forms against the lateral pressure of unhardened concrete, a tensile unit called a concrete form tie is used (Nemati, 2007). Form ties, with a clamping device on each end, are installed through the forms to resist the bursting pressure exerted by the concrete. Some are equipped with devices which enable them to serve as form spreaders or spacers such as a PVC sleeve which also keep concrete out of the ties thread to make tie removal easier. Many types and sizes are available, with allowable working strengths varying from 750kg to 25000kg. Form ties provide support for the wales (Peurifoy & Oberlender, 2011).

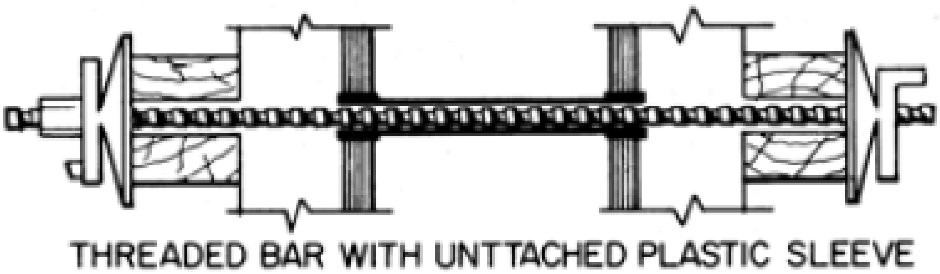

Figure 2-7 Typical Form Tie (Nemati, 2007)

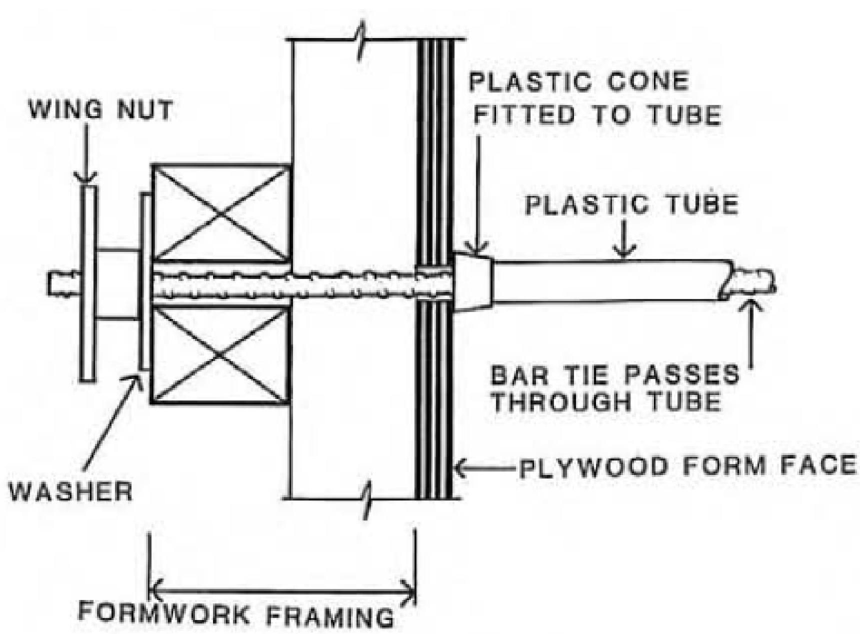

Figure 2-8 Typical Form Tie with Components Identified (McAdam, 1991)

The two most common types of conventional vertical wall formwork used in the Australian high rise construction industry are traditional timber LVL (Laminated Veneer Lumber) wall forms and steel RHS (Rectangular Hollow Section) wall forms. Timber formwork typically consists of plywood sheathing, with timber members placed as studs and wales on the back of the formwork connected with bolts and screws to form a frame. Steel RHS formwork consist of plywood or metal sheathing on a welded steel RHS frame. Both types of wall forms are prefabricated offsite with the steel RHS alternative the most labour intensive and costly. The frame work of conventional steel RHS wall forms used in the Australian high-rise construction industry are often designed and configured exactly the same way as the alternative timber LVL wall forms which are based on design guides provided by the timber companies such as Carter Holt Harvey Wood Products Australia (see Figure 2-10). As well as adopting the same frame work design and member spacing the steel forms also adopt steel member sizes similar to their timber counterpart. Truform specify the use of 95mm x 47mm LVL in their design guides for their two different vertical wall form assemblies (see Figures 2-9 & 2-10) and the formwork industry adopt a 100mm x 50mm in the steel equivalent wall form (see Figure 2-12).

Because of their greater expense steel wall forms are mostly used in large construction projects or in situations where large number of re-uses of the same form is possible. Advantages of steel forms over timber forms include (Civil Resources, 2010):

- They are stronger, more durable & have a longer life
- Reuses can be assumed to vary from 100 to 120 compared to timber which varies from 10 to 12
- Because of bolt able connections steel forms can be installed & dismantled with greater ease & speed resulting in a saving in labour cost.
- When steel sheathing is used steel forms produce a higher quality exposed concrete surface. Thus saving in the cost of finishing the concrete surface.

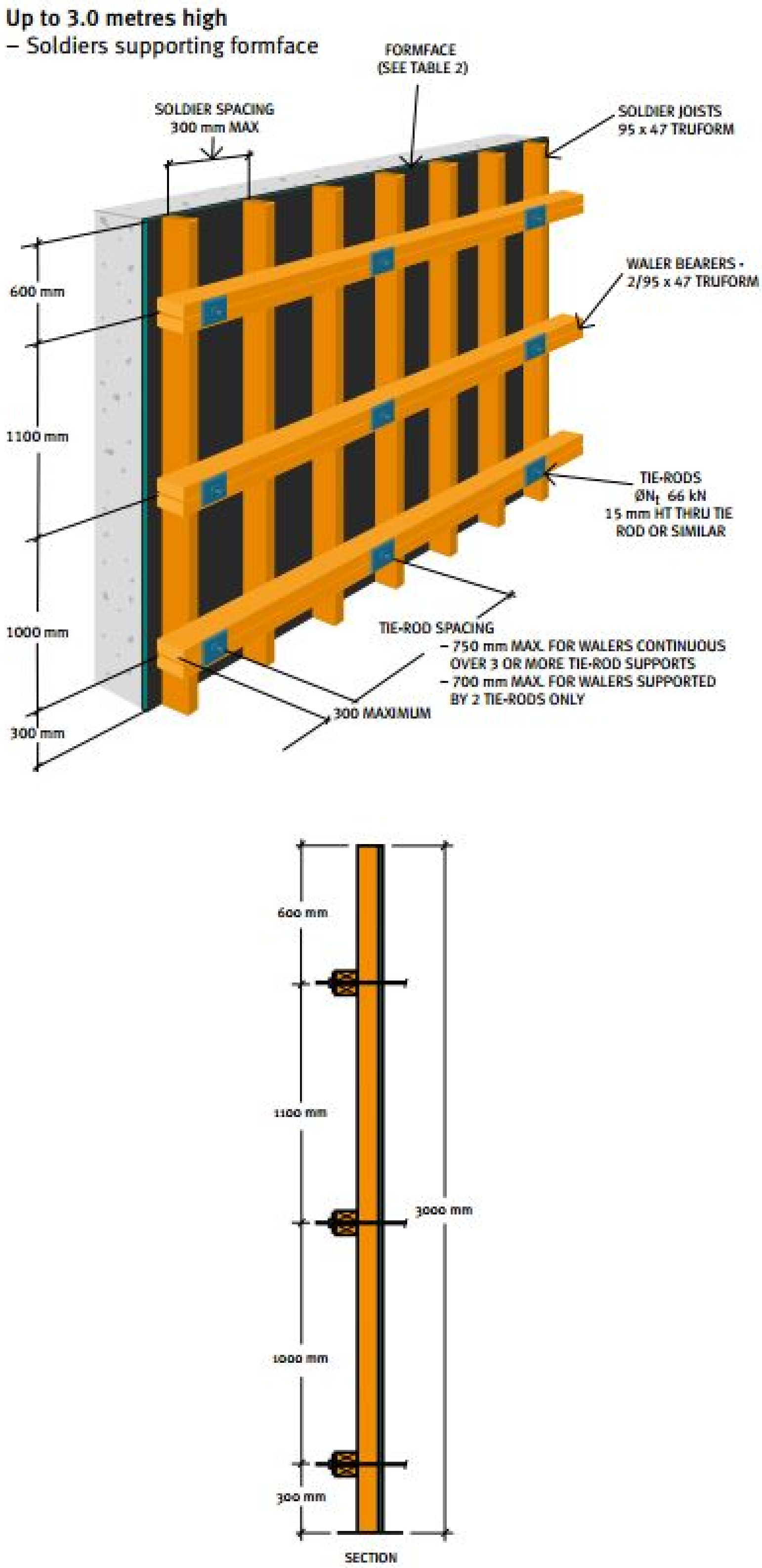

Figure 2-9 Timber LVL Wall Forms with Studs Supporting Form Face (Carter Holt Harvey Wood Products Australia, 2012)

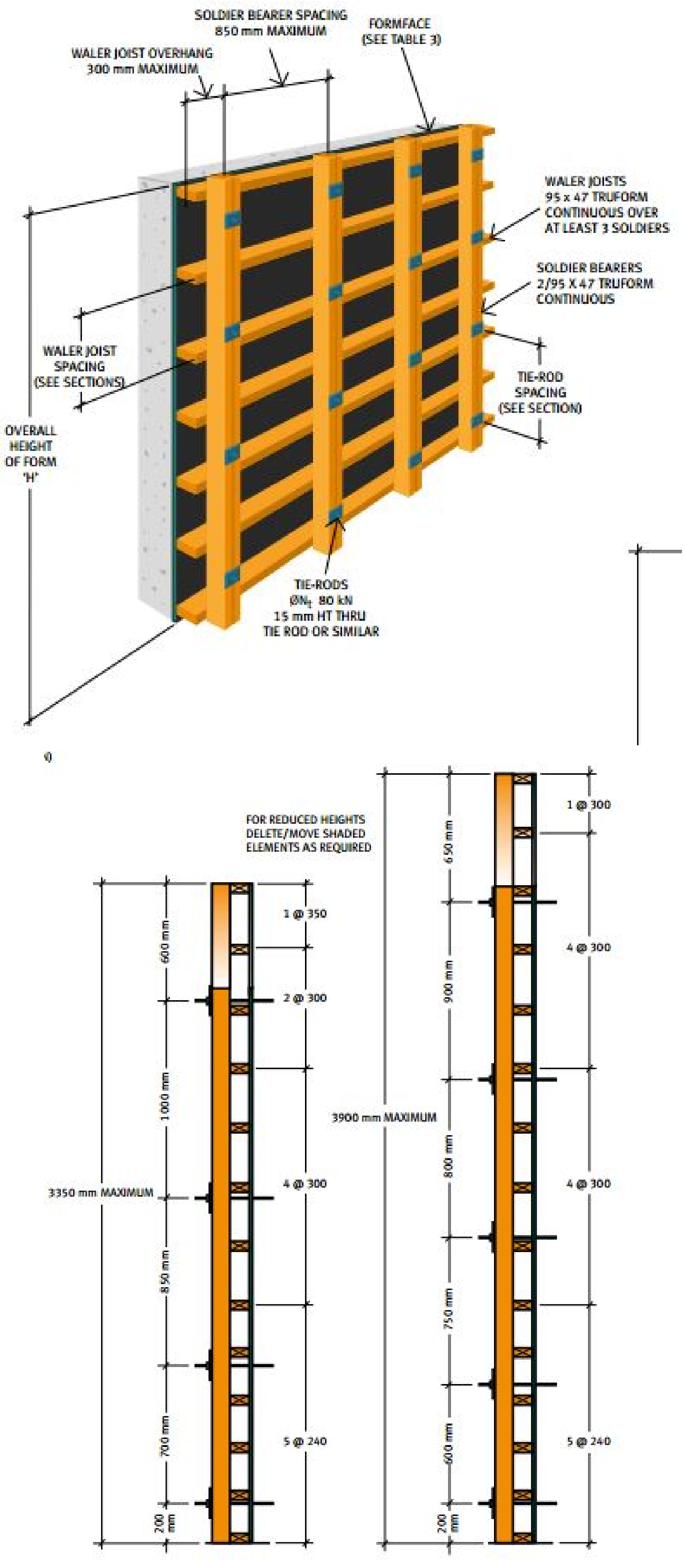

Figure 2-10 Timber LVL Vertical Forms with Wales Supporting Form Face (Carter Holt Harvey Wood Products Australia, 2012)

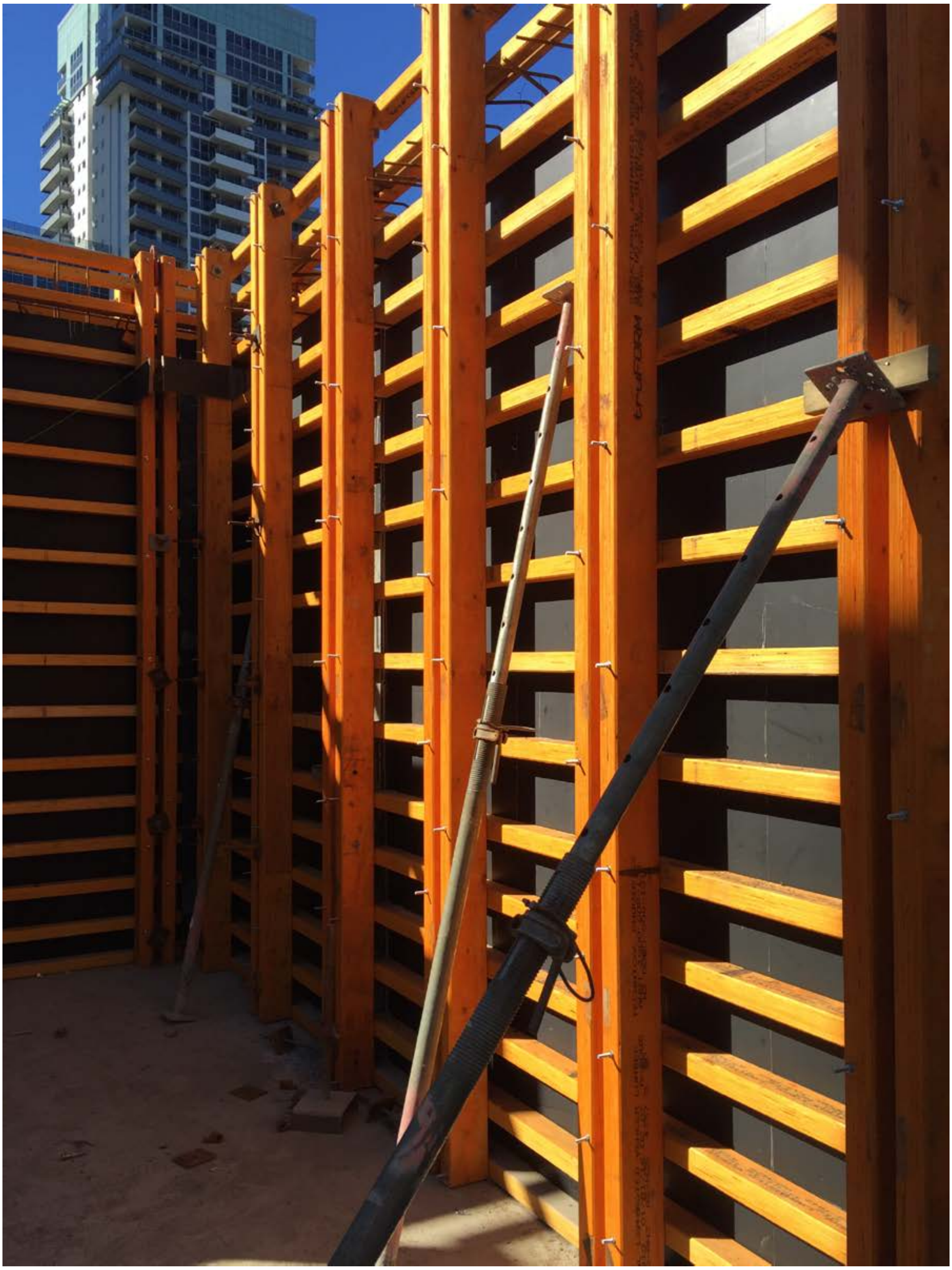

Figure 2-11 Timber LVL Vertical Forms onsite 300 George St Brisbane

Figure 2-12 Steel Frame RHS wall forms within jump form at 300 George St Brisbane

There are now a number of specialty, manufactured forms available that reduce the time and labour of conventional forming systems. These systems and panels are durable enough for many reuses. Manufactured modular panel forms are built by assembling a number of smaller prefabricated panels into one large form (ACI, 2005). They offer three distinct advantages (ACI, 2005):

- Components can be assembled for almost any size or shape.
- There is less need for skilled labour since almost all cutting, trimming, and fitting are eliminated
- The same forms can be used and reused as part of a large section and another time as individual units.

Many accessory panels are available, including small filler and corner units of varying size. Hardware and ties supplied with form panels vary with different manufacturers. Specialised patented hardware is a major component of all the panel systems. Three basic types of panel systems are (ACI, 2005):

- Unframed plywood panels, backed by steel braces with special locking and tying hardware.
- All-metal panels of plates supported by matching frames. These panels are produced in both steel and Aluminium. Aluminium panels have the advantage of being extremely light making them easier to handle with machinery.
- Plywood panels set in a metal frame with metal bracing on the back.

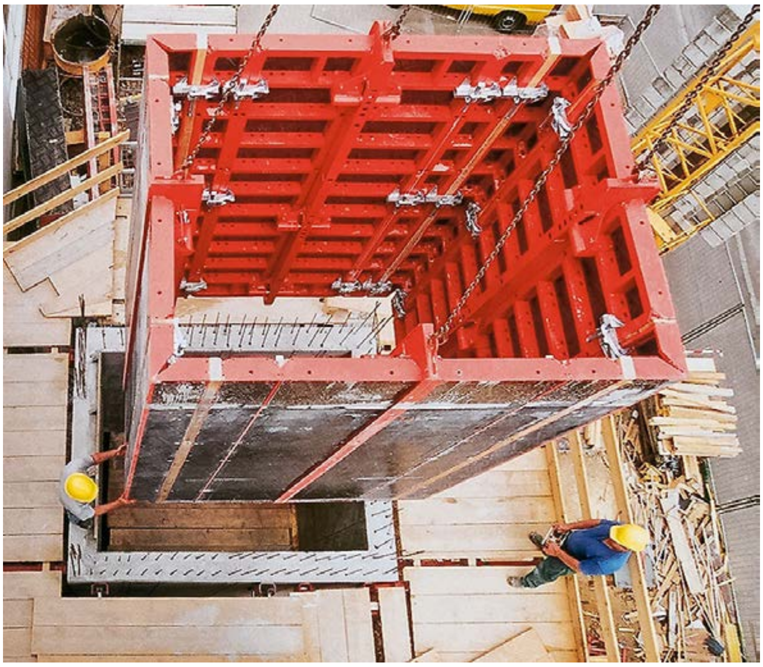

Figure 2-13 Peri Modular Panel Wall Formwork (Peri, 2016)

Figure 2-14 Aluminium modular panel form onsite at Abian Towers Brisbane

Figure 2-15 Manufactured Modular Panel Forms onsite at 320 Hay St Perth

Special forms often referred to as stay-in-place forms become a part of the completed structure. They are often used for inaccessible locations where it is impractical and expensive to remove forms (ACI, 2005), or in places where a one off form is required and it’s too expensive or time consuming to manufacture a conventional form. In some cases, the stay-in-place form is designed to carry some of the loads for which the structure is designed (ACI, 2005). These forms are often steel, plastic, laminated fibre or thin precast, pre-stressed concrete units that are placed on supporting formwork or atop concrete slabs and bonded to become part of the concrete element. Insulating Concrete Forms (ICF) are stay-in place forms that are assembled as interlocking blocks or sheets. The ICF units then provide an insulation to the finished walls (ACI, 2005).

Figure 2-16 Stay in Place Forms – Precast Concrete Panels serving as Column Forms (ACI, 2005)

During the forming of a high-rise building construction joints are needed to divide the total structure into a number of portions, each of which can be practically formed and poured in one operation (McAdam, 1991). Usually each floor of a high-rise building dictates the position of a construction joint with each floor representing a pour. Therefore, pour and shutter heights vary from one job to another, typically pour heights range from 2.8m up to 4.2m on a high-rise construction project. At the construction joint the wall forms lap onto the previously poured wall and are clamped with a form tie to create a seal as shown in the figure below. At the base of a vertical wall form at the junction to a kicker or the previous wall pour concrete pressures are highest.

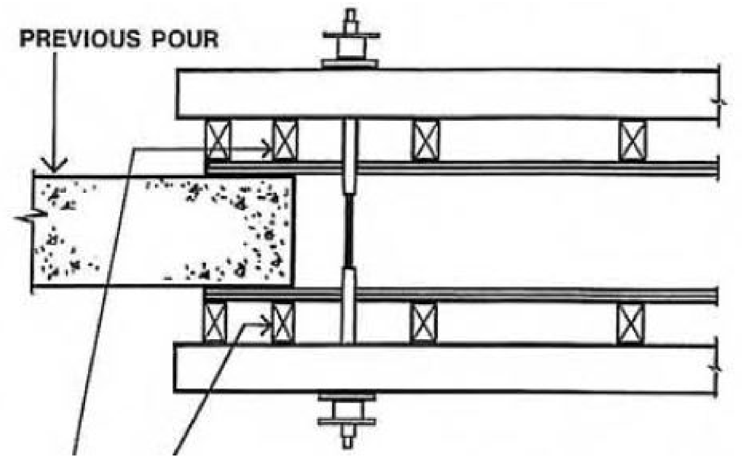

Figure 2-17 Typical Construction joint (McAdam, 1991)

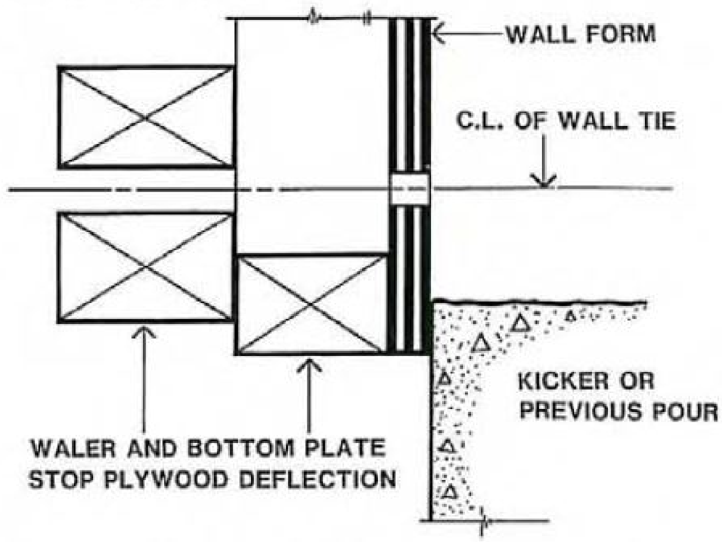

Figure 2-18 Typical Construction Joint with Components Identified (McAdam, 1991)

Wall formwork systems are predominately prefabricated for re-use over and over again. The design guides provided by timber companies such as Truform adopt a one design suits all approach. As can be seen in the figures 2-10 and 2-11 the spacing of the horizontal wales are the same for all pour heights with simply more wales added to the top of the wall form to extend the form for a higher pour. This is also evident with modular panel forming systems, with more standardised panels added to a form to suit the required poor height. No extra strength is added to the base of these standardised forming systems where concrete pressure is at its highest. Because formwork companies adopt this one design suits all jobs approach for their wall formwork it is important that this design can suit the highest lateral formwork pressures encountered within the industry. Whyte and Brandis (2010) suggests that assumptions made concerning fit-for-purpose formwork systems are often inadequately communicated between relevant parties, with a willingness to make gains from re-use somewhat skewing the balance between quality, cost saving and time saving. Whyte and Brandis (2010) also suggest that project cost-saving measures such as reuses of inadequate wall formwork that leads to formwork failure is self-defeating as the cost saving is inevitably cancelled out.

2.3 CONCRETE PRESSURE ON WALL FORMWORK

Knowledge of concrete pressure is critical for the economical and safe design of formwork for concrete construction (Barnes & Johnstone, 2004). Up to 60 percent of the cost of a completed concrete structure is the cost of the formwork. In order to minimise this cost and maintain safety, an accurate method of estimating concrete lateral pressures is needed for the design of vertical concrete formwork such as for walls and columns (Barnes & Johnstone, 2004).

Concrete is a mixture of sand and aggregate that is bonded together by a paste of cement and water. Admixtures are commonly used in concrete mixes. Additives include liquids, solids, powders, or chemicals that are added to a concrete mix to change properties of the basic concrete mixture. They can accelerate or retard setting times, decrease water permeability, or increase strength, air content, and workability. Admixtures include pozzolans such as silica flume, blast-furnace slag, and fly ash (Peurifoy & Oberlender, 2011).

The pressure exerted by concrete on formwork is determined primarily by several or all of the following factors (Peurifoy & Oberlender, 2011):

- Rate of placing concrete in forms
- Temperature of concrete
- Weight or density of concrete
- Cement type or blend used in the concrete
- Method of consolidating the concrete
- Method of placement of the concrete
- Depth of placement
- Height of form

Wet concrete is like water it exerts a lateral pressure which increases with depth. During placement concrete imposes lateral pressure on the form face of the vertical wall formwork. Initially the pressure is purely hydrostatic with the pressure increasing with the depth of fluid concrete (McAdam, 1991). The freshly placed concrete behaves temporarily like a fluid, producing a hydrostatic pressure that acts laterally on the vertical forms. This lateral pressure is comparable to full liquid head when concrete is placed full height within the period required for the concrete to initially set (Nemati, 2007).

With slower rate of placing, concrete at the bottom of the form begins to harden and lateral pressure is reduced to less than full fluid pressure by the time concreting is completed in the upper parts of the form. The effective lateral pressure has been found to be influenced by the weight, rate of placement, temperature of concrete mix, use of retardant admixtures, and vibration (Nemati, 2007).

As this relaxation in pressure is related to the time for the initial set of the particular concrete to occur it follows that the faster the concrete is poured the less the pressure will relax. With a very fast pour which is now quite common, the pressure may remain hydrostatic throughout the pour (McAdam, 1991). Figure 2-19 below shows this progressive reduction in pressure as the concrete at the bottom of the form sets.

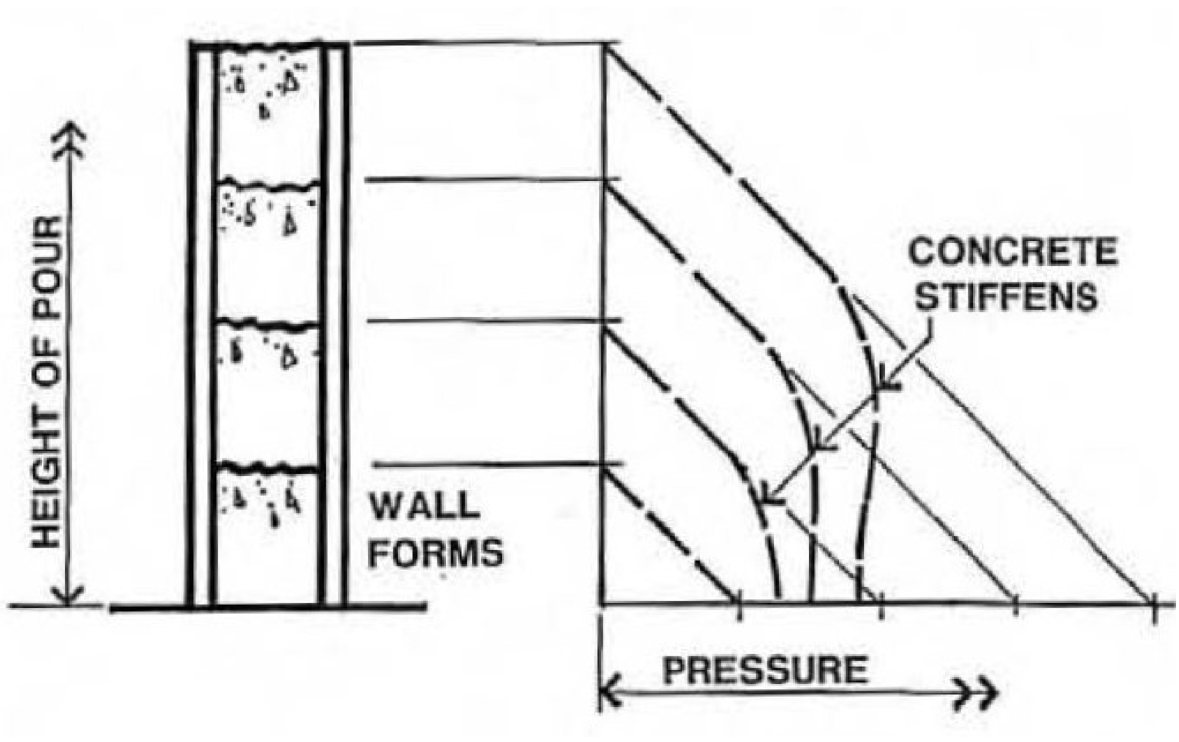

Figure 2-19 Progressive Reduction in Lateral Concrete Pressure (McAdam, 1991)

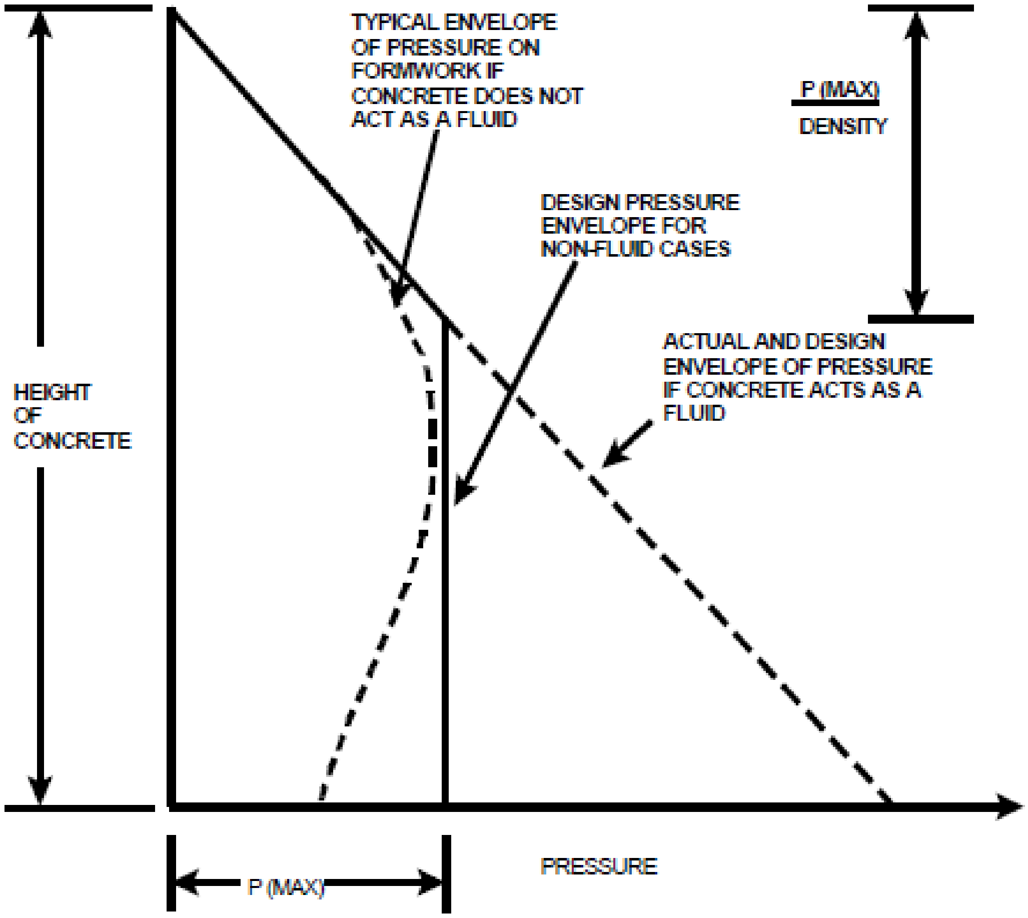

Figure 2-20 Concrete Pressure Envelope (Barnes & Johnstone, 2004)

Lateral pressures of fresh concrete impose loads against wall or column forms. As a result of various studies, several recommended and proposed procedures for empirically estimating pressures have been developed. Each method assumes that concrete pressure increases linearly with depth to a maximum value and remains constant thereafter (Barnes & Johnstone, 2004). These empirical formulas are presented and discussed further in section 2.4. Pressure exerted on formwork can be less than a liquid head as shown in Figure 2-20. The lower pressure is due to factors including stiffening of the concrete as placement is proceeding and internal friction of the granular constituents (Barnes & Johnstone, 2004). The ability to change from a semi-liquid or plastic to a solid state appears to be the result of two actions within the fresh concrete. The first action is the result of the setting of the cement paste, which can take a few minutes to a few hours according to concrete properties and conditions. The second action is the development of internal friction between the particles of aggregate in the concrete, which restrain them from moving freely past each other. The magnitude of that friction increases with the loss of water from the concrete (Peurifoy & Oberlender, 2011). The pressure distribution proposed by most design methods follows the hydrostatic line to a calculated estimate of the maximum pressure then remains at this same pressure to the base of the form. The limitations on the use of these equations has increased as concrete mixtures became more complex through the addition of a variety of mineral and chemical admixtures. When concrete mix designs or concrete placement rates do not meet the requirements of these pressure limiting equations, the pressure for full liquid head should be used in the design of vertical wall formwork (Barnes & Johnstone, 2004).

2.4 PREVIOUS RESEARHES ON CONCRETE PRESSURE ON WALL FORMWORK

(Rodin, 1952) collected and reviewed the published experimental data on the lateral pressures of concrete against vertical formwork. (Rodin, 1952) presented a rational explanation of the types of pressure distribution found in practice, and explained why this pressure is not hydrostatic, except in special circumstances. He also discussed the factors affecting the lateral pressure such as the rate of concrete placement, the method of placing the concrete, the consistency and proportions of the mix, the temperature of the concrete, the rate of setting of the concrete, and the size and shape of the formwork. Rodin concluded that where external vibrators are used, the full depth of concrete would be fluidized and the formwork should be designed for full hydrostatic pressure. For internal vibration, he proposed some formulas and curves to determine the lateral concrete pressures. These formulas were based on a concrete mix having proportions of 1:2:4 by weight with a slump of 150 mm at a temperature of 21°C.

(Rodin, 1952) formulas are:

$H_{max} = 1.63R^{1/3}$

$P_{max} = 23.5\ H_{max}$

Where concrete density is assumed to be 2400 kg/m^3; H_{max} = head at which maximum pressure occurs (m); P_{max} = maximum lateral pressure (kN/m^2); and R = rate of placing (m/hr).

The American Concrete Institute (ACI) publishes a document called ACI 347 – Guide to Formwork for Concrete (Civil Engineering, 2016). The ACI collected and analysed the existing literature and test reports, and then developed design recommendations and formulas for determining the magnitude and distribution of lateral pressure on concrete formwork. It was proposed that for design purposes, the lateral pressure envelope should be hydrostatic up to some limiting value and then constant at the limiting value. The objective of the ACI Committee 347 was to keep the determination of pressure straightforward with a minimum of variables and assumptions. The Committee concluded that placement rate, concrete mix temperature and the effect of vibration are the most important variables to be considered for wall form pressures (Hurd, 2005). It also introduced weight and chemistry coefficients, CW and CC, which make it possible to apply the formulas to a variety of mixes and concrete weights (Hurd, 2005).

“ACI 347 – Guide to Formwork for Concrete” provides formulas for calculating pressure on wall forms due to the placement of fresh concrete. For concrete mixes with a slump of 7 inches or less, and for a depth of internal vibration of 4 feet or less the following two equations are provided (Civil Engineering, 2016):

- For forms with a rate of placement of less than 7ft/h and a placement height not exceeding 14ft the following formula can be used:

$$P = C_W\, C_C\, [150 + 9000R/T]$$

- For forms with a placement rate less than 7ft/h where placement height exceeds 14 ft, and for all walls with a placement rate of 7 to 15ft/h the following formula can be used:

$$P = C_W\, C_C\, [150 + 43400/T + 2800R/T]$$

For any conditions that exceed those specified above, the design pressure is calculated by using the equation for full hydrostatic head:

$$P = \gamma H.$$

where:

P = Pressure

γ = Unit weight of the concrete mix

H = Height of concrete placement

C_C = Chemistry coefficient, values can be found in Figure ###

C_W = Unit weight coefficient, values can be found in Figure ###

R = Rate of placement of concrete measured in feet/hour

T = Temperature in degrees Fahrenheit

Table 2-1 ACI Chemistry Coefficients, CC (Hurd, 2005)

Cement type or blend	**Chemistry coefficient C_C**
Types I, II, and III cements without retarders	1.0
Types I, II, and III cements with a retarder	1.2
Other types or blends containing less than 70%slag or 40% fly ash without retarders	1.2
Other types or blends containing less than 70% slag or 40% fly ash with a retarder	1.4
Blends containing more than 70% slag or 40% fly ash	1.4

Table 2-2 ACI Unit Weight Coefficients, CW (Hurd, 2005)

Unit Weight of Concrete	**C_W**
Less than 140 lb/ft^3	$C_W = 0.5[1 + (w/145\ lb/ft^3)]$
140 to 150 lb/ft^3	1.0
More than 150 lb/ft^3	$C_W = w/145\ lb/ft^3$

The Construction Industry Research Information Association (CIRIA), produced CIRIA Report 108 as a research study to predict concrete lateral pressure. CIRIA Report 108 extended and improved the method originally provided by CIRIA Report 1 first published in 1965 to cover concrete using admixtures and blended cements (Clear & Harrison, 1985). Based on onsite studies conducted on concrete lateral pressure on formwork, CIRIA recommended an equation for the maximum concrete pressure on formwork. This equation considered some influencing variables such as vertical form height, rate of rise, concrete temperature at placing, and the use of admixture and blends or blended cements. The shape of concrete pressure envelope is the same as that one described by AC1 347. The CIRIA recommended formulas for maximum concrete pressure on formwork are the following (Clear & Harrison, 1985):

(a) $P_{max} = \frac{\rho}{100}\left[C_1\sqrt{R} + C_2K\sqrt{H - C_1\sqrt{R}}\right]$

(b) $P_{max} = \frac{\rho h}{100}$

where

C1 = coefficient (1.0 or 1.5) dependent on the size and shape of formwork;

C2 = coefficient (0.3, 0.45, or 0.6) dependent on the constituent materials of concrete;

y = weight density of concrete;

H = vertical form height (m);

h = vertical pour height (m);

K = temperature coefficient;

R = rate of concrete rise (m/hr);

T = temperature of concrete at placing.

2.5 AUSTRALIAN CODES AND STANDARDS

Australia formwork practice is governed by a state-based regulatory scheme. It has a legislative approach to governing formwork practice that varies from state-to-state (Whyte & Brandis, 2010). Queensland, Victoria, South Australia and New South Wales all have independent codes of practice for formwork. However, all the state based legislation stipulate that the design of all formwork systems, both traditional and modular must satisfy Australian Standards:

- AS3610 – Formwork for concrete (1995)
- AS3600 – Concrete structures (2009)

A comparison between AS3610 and the New South Wales and Queensland codes of practice indicates differences regulating form workers. Whilst Australian Standard AS3610 is performance based and describes outcomes, the state codes seek to give practical guidance on suitable process (Whyte & Brandis, 2010).

Whilst legislative development in formwork practice over the years has been carried out, Whyte and Brandis (2010) argue that corresponding safety levels might be argued not to have kept pace. The Australian Formwork Standard, AS3610, was last revised in 1995. In 1997 the Standards Development Committee for Formwork started reviewing AS3610 in an attempt to keep up with developments and innovation in the industry. In February 2010 the Development Committee partially republished the standard with the introduction of AS3610.1-2010 covering 'Documentation and Surface Finish. Despite draft revisions of AS3610 focusing on enhancing design guidance of formwork, further amendments to the standard have yet to be released. While part two of the standard remains undeveloped Whyte and Brandis (2010) suggests continued development of AS3610 will bring the standard up to date with current construction practice and ensure suitable guidance and accountability.

As part of the review into AS3610 a Formwork Design Handbook was drafted by some members of the Standards Development Committee (Whyte & Brandis, 2010). The Handbook is intended to overcome the short comings of AS3610, and to introduce and explain procedures, requirements and methods for the design and construction of formwork that minimise frequency of formwork failure (Concrete Institute of Australia, 2016). However, changes in the conditions of contract for Handbook development have stalled production and the handbook has yet to be released.

Due to the delay in the release of an update of Australian Standard AS3610 covering formwork design and the issues stopping the release of the proposed Formwork Designers Handbook there is currently a gap in appropriate literature for formwork designers in the Australian formwork industry.

The Queensland Formwork Code of Practice (2016) specifies qualification requirements for vertical formwork design and certification, these can be seen in table 2-3. The code stipulates that an engineer, such as a suitably qualified civil engineer experienced in structural design, is responsible for overseeing the safe design and certification of the complete formwork structure. While this code requires that overseeing the safe design and certification of formwork systems may only be performed by an engineer, it is recognised that some design work may be performed by appropriate personnel such as a 'competent person' experienced in formwork design and documentation. Once formwork is in place onsite verification that the formwork structure complies with the design of the formwork system must be documented and provided. Table 2-4 provides a list of circumstances and the required level of qualification required of the person carrying out the formwork structure inspection.

Table 2-3 Formwork Design & Certification Requirements (Workplace Health and Safety Queensland, 2016)

Formwork design and certification	
Vertical formwork (Columns and walls)	
Less than 2.4 m high	Competent person
2.4 to 3.5 m high	Engineer
More than 3.5 m high (single arrangement)	Engineer
More than 3.5 m high (repetitive arrangement)	Engineer
Single-sided less than 2.4 m	Competent person
Single-sided more than 2.4 m	Engineer
Self-climbing or crane assisted formwork systems	Engineer
Soffit formwork	
Less than 3 m high and less than 250 mm thick	Competent person
More than 3 m high or more than 250 mm thick	Engineer
Infill slabs less than 4.5 m high, 20 m^2 and 300 mm thick	Competent person
Stair and landing formwork more than 3 m high or more than 200 mm thick	Engineer
Multistorey formwork and backpropping	Engineer

Table 2-4 Formwork Inspection Requirements (Workplace Health and Safety Queensland, 2016)

	Inspection	
	Access for trades	**Pre-pour**
Vertical formwork (columns and walls)		
Less than 2.4 m high	Competent person	Competent person
2.4 to 3.5 m high	Competent person	Competent person
More than 3.5 m high (single arrangement)	Competent person	Engineer
More than 3.5 m high (repetitive arrangement)	Initial pre-pour inspection by engineer on first arrangement only and then competent person thereafter	
Single-sided less than 2.4 m	Competent person	Competent person
Single-sided more than 2.4 m	Competent person	Engineer
Self-climbing or crane assisted formwork systems	Initial pre-pour inspection by engineer and then competent person thereafter	
Soffit formwork		
Less than 3m high and less than 250mm thick	Competent person	Competent person
More than 3m high or more than 250mm thick	Competent person	Engineer
Infill slabs more than 4.5m high, $20m^2$ and 300mm thick	Competent person	Engineer
Stair and landing formwork more than 3m high or more than 200mm thick	Initial pre-pour inspection by engineer and then competent person thereafter	
Multistorey formwork and backpropping	Competent person	Engineer

2.6 AS3610 FORMWORK FOR CONCRETE

The Standards Association of Australia publish Formwork for Concrete AS3610. This standard with its commentary present design and construction requirements for falsework and formwork of all structure types. It sets out obligations for the design, fabrication, erection and stripping of formwork, as well as the specification, evaluation and repair of the quality of the formed concrete surface and the influence of this activity on the design and construction of an in situ concrete structure (Standards Australia, 1995).

AS3610 stipulates 3 stages of design loads during the construction cycle that need to be considered when designing formwork:

- Stage 1 – prior to the placement of concrete.
- Stage 2 – during the placement of concrete.
- Stage 3 – after the placement of concrete, until the concrete is able to support the applied loads.

However, stages 1 and 3 are not quantified in the standard for vertical formwork as they usually only comprise the loading effects of hoisting, alignment, stripping and storage (McAdam, 1991). Stage 2 during concrete placement is the critical stage in wall form design as the concrete placement imposes significant lateral pressure on the form face. Although some work has been done on the theoretical determination of lateral concrete pressure from fluid concrete, more accurate results have been obtained from data collected on sites at actual pours. AS3610 uses the work from an onsite study, CIRIA Report 108 to provide two formulae for the determination of a design value for maximum lateral concrete pressure on vertical wall forms (McAdam, 1991).

AS3610 stipulates the maximum lateral pressure exerted by the plastic concrete during stage 2 shall be the smaller of the following two formulae:

(a) $$P_{max} = \frac{\rho}{100}\left[C_1\sqrt{R} + C_2 K\sqrt{H - C_1\sqrt{R}}\right]$$

(b) $$P_{max} = \frac{\rho h}{100}$$

where

P_{max} = maximum lateral concrete pressure, in kilopascals

ρ = wet density of concrete, in kilograms per cubic metre

C1 is a coefficient dependent on the size and shape of formwork

C1 = 1.5 where both plan width and breadth of the section are less than 2 m

C1 = 1.0 for all other cases

R = rate at which the concrete rises vertically up the form, in metres per hour

C2 = coefficient given for the constituent materials of the concrete (see figure####)

K = temperature coefficient

H = vertical form or concrete discharge height, whichever is the greater, in metres

h = vertical pour height, in metres

T = concrete temperature at placement, in degrees Celsius

Table 2-5 Values for Concrete Coefficient C2 (AS3610 1995)

VALUES OF COEFFICIENT C_2

Cementitious materials and admixtures	C_2
Type GP, HE cement	0.30
Type LH, SR, SL cement	0.45
Type GB cement	0.45
Blends containing > 40% flyash or > 70% slag	0.60

For all cementitious types the value of C_2 shall be increased by 0.15 where one or both of the following apply:
(a) A retarding admixture is used in the concrete.
(b) A superplasticizing admixture is used in the concrete.

NOTES:

1 Retarding admixtures include retarders, retarding water reducers, retarding superplasticizers and any admixture which is used such that it effectively acts as a retarder.

2 Products which have become commercially available since the publication of CIRIA Report 108 in 1985 should be investigated to determine whether they should be classified as retarders.

3 This Table is based on CIRIA Report 108 and the appropriate types of cement given in AS 3972 have been substituted for those tested. Note that in AS 3972, Type SR cement is defined on a performance basis and may contain a high percentage of slag necessitating the use of a higher value of coefficient C_2.

4 Silica fume has a marked effect on the properties of fresh concrete and is frequently used in conjunction with superplasticizers. Concrete with this ingredient falls outside the test parameters of the CIRIA Report and no guidance can be provided.

The formulae stipulated by AS3610 are only accurate where the parameters of the pour can be stringently controlled. This is because slight changes in concrete temperature and pour rate can have a significant effect on the maximum lateral pressure exerted on the wall form. Formwork designers know how little control they have over the method, rate of placement and temperature of the concrete onsite so in most cases the practice of designing for full hydrostatic pressure is adopted (McAdam, 1991). However, there are still occurrences where full fluid pressure on the wall form can be exceeded, these include:

- When the concrete pump nozzle is immersed in the fluid concrete
- Grout injected concrete
- Pumping the concrete into the formwork from the base
- Deep vibration of the concrete
- External vibration of the concrete

To account for these factors it is recommended that the calculated full hydrostatic head be increased by 50% (McAdam, 1991).

AS3610 stipulates that formwork components or assemblies shall be analysed and designed with one of the following procedures:

- Limit state procedures, in accordance with the appropriate material structural design code.
- Permissible stress procedures, in accordance with the appropriate material structural design code.

Clause 3.3.4 of AS3610.1 2010 stipulates the allowable deflection of formwork. There are five classes of concrete surface finish prescribed in AS3610.1, with each class of finish designated a maximum limit respectively. The permitted deflection is related to the specific span with a maximum of 2mm or 3mm for classes 1 and 2 concrete finish respectively. Table 2-6 species the tolerances for form face deflection for the 5 classes of concrete surface finish. The total formwork system deformation comprises three factors which may be cumulative: form face deflection, deflection of the formwork framing, and errors in formwork fabrication or construction (McAdam, 1991).

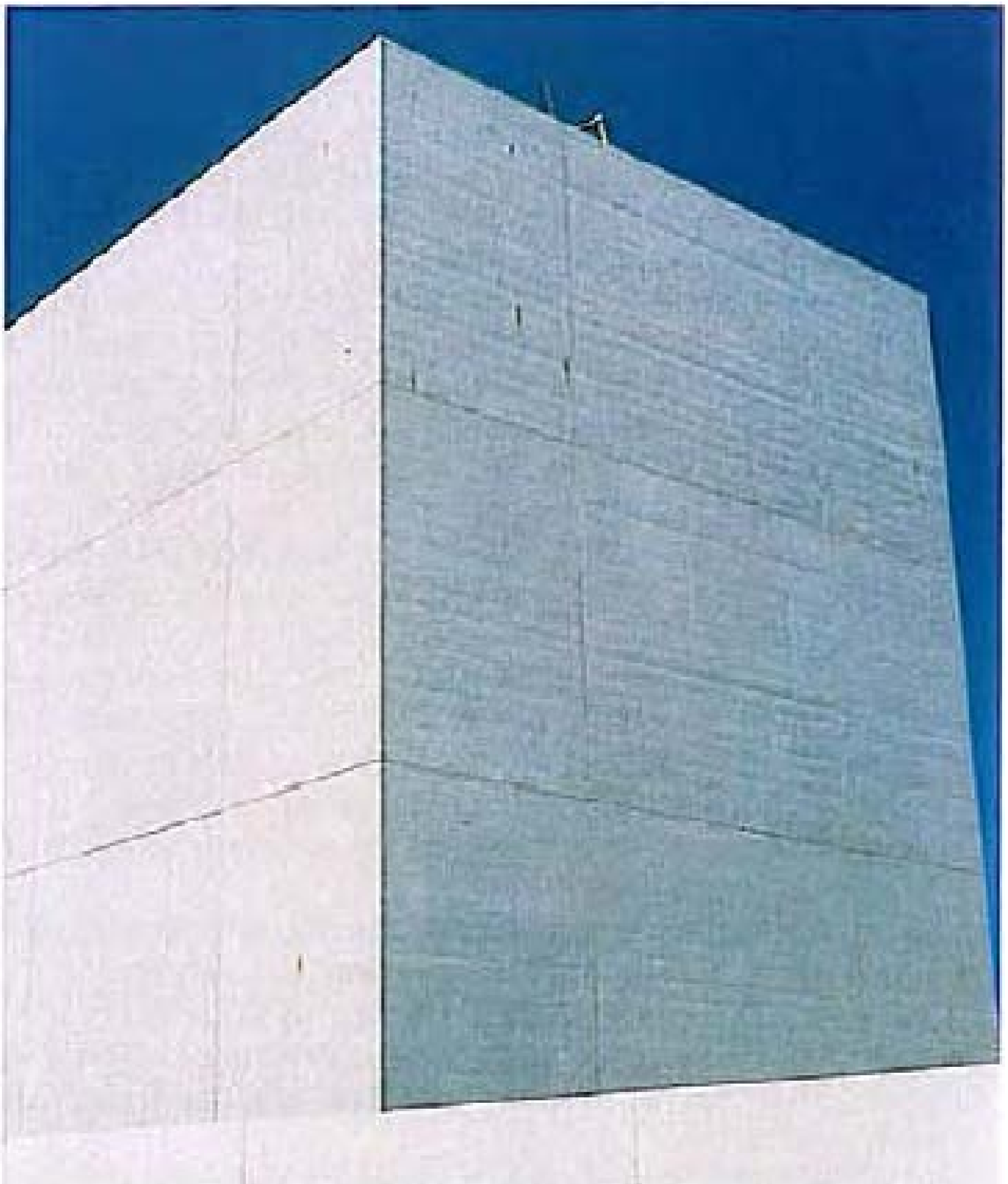

Figure 2-21 Corrugations Due to Over Deflection of Formwork (McAdam, 1991)

Table 2-6 Vertical formwork deflection limits (AS3610.1 2010)

ACCEPTABLE QUALITY OF SURFACE FINISH

	Quality of surface finish	Class 1		Class 2		Class 3		Class 4		Class 5		Ref. Clause
1	Blowholes (see Appendix A) (visual quality at least equivalent to)	Photo 1(a), 1(b)		Photo 2(a), 2(b)		Photo 3(a), 3(b)		N/A		N/A		5.2.1(a)
2	Form face deflection (not greater than)	Lesser of 2 mm or span/360		Lesser of 3 mm or span/270		Span/270		Span/270		N/A		5.2.2(b)
		Maximum tolerance for straight elements with smooth surface, in mm										
	Percentage of readings	95	100	90	100	80	100	70	100	70	100	
3	Face step:											5.2.2(d)
	(a) Within the element	1	2	2	3	3	5	5	8	*	*	
	(b) At in situ construction joint	2	3	2	3	3	5	5	8	*	*	
4	Surface undulations											
	(a) l = 300											
	(a – b) ≤	1	2	2	4	3	4	5	7	*	*	5.2.2(c)
	(b) l = 1500											
	(a – b) ≤	2	4	3	6	5	7	8	10			
5	Flatness:											5.2.2(e)
	(a) 1.25 m grid	4	5	6	7	7	10	*	*	*	*	
	(b) at 5 m over 10 m (not applicable to precast concrete)	5	7	7	10	10	15	*	*	*	*	
6	Out-of-plumb:											5.2.2(f)
	(a) height <3 m	3	5	4	6	5	7	*	*	*	*	
	(b) 3 ≤ height <8 m (not applicable to precast concrete)	6	8	8	10	10	12	*	*	*	*	

2.7 ALLOWABLE CAPACITY OF FORMWORK

The allowable capacity of formwork for the purpose of this study was carried out using the limit state procedures in accordance with the appropriate material structural design code (Standards Australia, 1995). (Gorenko, et al., 2012) defines the 'limit state of a structure' as a term that describes the state of a loaded structure on the verge of becoming unfit for use. This may occur as a result of failure of one or more members, overturning instability, excessive deformations, or the structure in any way ceasing to fulfil the purpose for which it was intended. The first step in verifying the limit state capacity of a structure is to determine the most adverse combination of actions that may occur in the lifetime of the structure. With actions determined, the next stage in the design procedure is to determine the internal action effects in the structure. With regard to the strength limit state used in Australian material design codes, the following inequality must be satisfied: Design action effect ≤ Design capacity or resistance (Gorenko, et al., 2012).

After calculating the lateral concrete pressure using the appropriate formula, as stipulated by AS3610 Formwork for Concrete the next step is to check the suitability of a formwork system under the calculated design load. For any given vertical formwork system, the allowable bending stress, shear and deflection are checked to ensure that the design load on the formwork, as calculated using the pressure formulae, is below the allowable capacity of the wall formwork assembly and its individual components.

Wall formwork needs to be strong enough to handle the calculated loads safely and stiff enough to maintain its shape under full load. Vertical wall forms are made up of the following components: sheathing, studs, wales and tie rods. Sheathing retains the concrete and is supported by studs. Studs are supported by wales. The wales are held in place by tension members such as tie rods. Other than tie rods, the other components of the formwork structurally behave like beams. Beam formulas are used to analyse the formwork components (Nemati, 2007).

The allowable capacity of formwork, i.e., the allowable maximum bending stress, shear stress, and deflection, is calculated using the relevant Australian material structural design code for each individual component in the formwork frame. Timber components are governed by AS1720.1 Timber Structures (2010). Steel components are governed by As4100 Steel Structures (1998).

AS1720.1 Timber Structures Clause 5.4.2 states that the design capacity of plywood in bending ($M_{d,p}$) for strength limit state, shall satisfy the following:

$M_{d,p} \geq M_p^*$

where

$M_{d,p} = \phi\ k_1\ k_{19}\ g_{19}\ f'_b\ Z_p$

M_p^* = design action effect for flatwise bending of plywood (see Figure 2-22)

ϕ = capacity factor of plywood (see Table 2-7)

k_1 = modification factor for duration of load (see Table 2-8)

k_{19} = modification factor for moisture condition (see Table 2-9)

g_{19} = modification factor for plywood assembly (see Table 2-11)

f'_b = characteristic value in bending (see Table 2-10)

Z_p = section modulus of plywood = I_p/y_p

I_p = second moment of area of parallel plies whose grain direction is parallel to the span

y_p = distance from the neutral axis to the extreme fibre of the outermost parallel ply

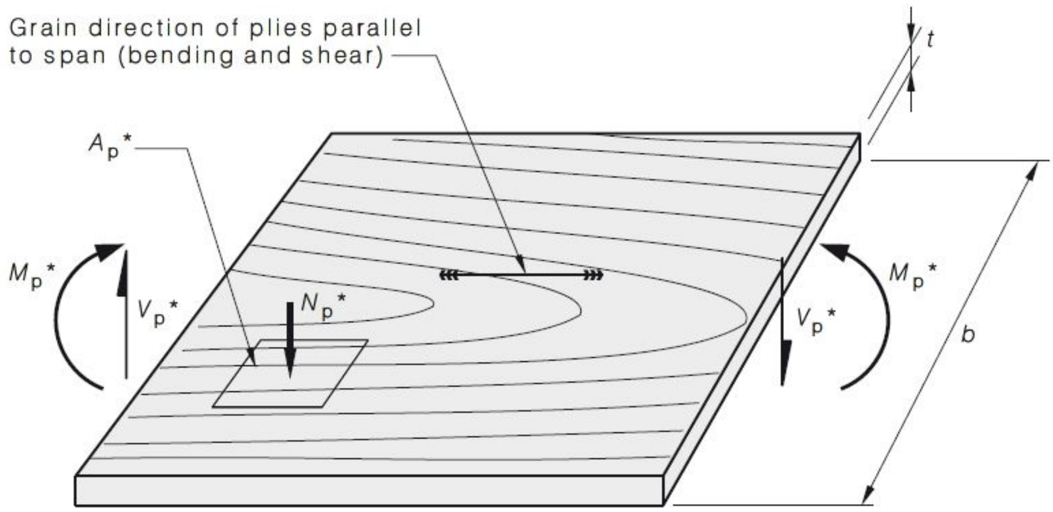

Figure 2-22 Notation for Analysis of Plywood (AS1170.1)

Table 2-7 Capacity Factor for Structural Timber (AS1170.1)

VALUES OF CAPACITY FACTOR (ϕ) FOR CALCULATING THE DESIGN CAPACITY (R_d) OF STRUCTURAL MEMBERS

Structural timber material	Application of structural member		
	Category 1	Category 2	Category 3
	Structural members for houses for which failure would be unlikely to affect an area* greater than 25 m^2; OR secondary members in structures other than houses	Primary structural members in structures other than houses; OR elements in houses for which failure would be likely to affect an area* greater than 25 m^2	Primary structural members in structures intended to fufill an essential service or post disaster function
	Values of capacity factor (ϕ)		
Sawn timber—AS 2082, AS 2858, AS/NZS 1748, AS 3519:			
—Stress grades: MGP 15, A17, F17 and higher F-grades	0.95	0.85	0.75
—All other timber† and stress grades	0.90	0.70	0.60
Round timber— AS 3818.3 or AS 3818.11, as appropriate	0.90	0.70	0.60
Glue-laminated timber—AS/NZS 1328.1	0.95	0.85	0.75
Structural plywood—AS/NZS 2269.0	0.95	0.85	0.75
Structural laminated veneer lumber—AS/NZS 4357.0	0.95	0.90	0.80

Table 2-8 Modification Factor k_1 for Duration of Load (AS1170.1)

DURATION OF LOAD FACTOR FOR STRENGTH

Effective duration of peak action	Modification factor (k_1)*	
	For the strength of timber	For the strength of joints using laterally loaded fasteners†
5 seconds	1.00	1.14
5 minutes	1.00	1.00
5 hours	0.97	0.86
5 days	0.94	0.77
5 months	0.80	0.69
50+ years	0.57	0.57

Table 2-9 Moisture Content Factor k_{19} (AS1170.1)

MOISTURE CONTENT FACTORS FOR PLYWOOD—STRENGTH FACTOR k_{19}

Type of stress	Factor k_{19}	
	Moisture content* 15% or less	Moisture content* 25% or more
Bending	1.0	0.6
Tension in plane of sheet	1.0	0.7
Shear	1.0	0.6
Compression in plane of sheet	1.0	0.4
Compression normal to plane of sheet	1.0	0.45

Table 2-10 Characteristic Values for Structural Plywood (AS1170.1)

STRUCTURAL PLYWOOD—CHARACTERISTIC VALUES FOR F-GRADES (Moisture content 15% or less)

Stress grade	Characteristic values, MPa						
	Bending (f'_b)	Tension (f'_t)	Panel shear (f'_s)	Compression in the plane of the sheet (f'_c)	Bearing normal to the plane of the sheet (f'_p)	Short duration average modulus of elasticity (*E*)	Short duration average modulus of rigidity (*G*)
F34	90	54	6.0	68	31	21 500	1 075
F27	70	45	6.0	55	27	18 500	925
F22	60	36	5.5	45	23	16 000	800
F17	45	27	5.1	36	20	14 000	700
F14	36	22	4.8	27	15	12 000	625
F11	31	18	4.5	22	12	10 500	525
F8	25	15	4.2	20	9.7	9 100	455
F7	20	12	3.9	15	7.7	7 900	395

Table 2-11 Assembly Factor g19 for Structural Plywood (AS1170.1)

ASSEMBLY FACTORS g_{19} FOR BEARING AND SHEAR NORMAL TO THE FACE OF THE PLYWOOD PANEL AND IN FLATWISE BENDING

Property	Direction of face plies	Assembly factor (g_{19})
Bending strength	Perpendicular to span	
	—3 ply	1.2
	—5 ply or more	1.0
	Parallel to span	1.0
Shear strength	Any orientation	0.4
Bearing strength	Any orientation	1.0
Bending deflection	Parallel or perpendicular to span	1.0
Shear deformation	Parallel or perpendicular to span	1.0

AS1720.1 Timber Structures Clause 5.4.3 states the design capacity of plywood in beam shear ($V_{d,p}$) for strength limit state shall satisfy the following:

$V_{d,p} \geq V_p*$

where

$V_{d,p} = \phi\ k_1\ k_{19}\ g_{19}\ f'_s\ A_s$

V_p*= design action effect for shear normal to the face of the plywood panel (see Figure 2-22)

f'_s = characteristic value in panel shear (see Table 2-10)

A_s = 2/3 (b t); (where b = breadth of plywood, t = full thickness of plywood)

AS1720.1 Timber Structures Clause 5.4.4 states the design capacity of plywood in bearing ($N_{d,p}$) for strength limit state shall satisfy the following:

$N_{d,p} \geq N_p*$

where

$N_{d,p} = \phi\ k_1\ k_{19}\ g_{19}\ f'_p\ A_p$

N_p* = design action effect for bearing normal to the face of the plywood panel (see Figure 2-22)

f'_p = characteristic value in compression normal to the plane of the panel (see Table 2-10)

A_p = bearing area under the design loads

When structural LVL's are designed with the grain of the veneers orientated in the longitudinal direction AS1720.1 Timber Structures Clause 8.2 stipulates that structural design with structural LVL shall be the same as sawn timber. To analyse the capacity of LVL timber studs and wales used in timber wall forms AS1720.1 Timber Structures Clause 3.2 is to be followed.

AS1720.1 Timber Structures Clause 3.2.1 denotes the design capacity in bending (M_d) of un-notched timber LVL beams, for the strength limit state, shall satisfy the following:

$M_d \geq M^*$

where

$M_d = \phi\ k_1\ k_4\ k_6\ k_9\ k_{12}\ f'_b\ Z$

M^* = design action effect in bending

ϕ = capacity factor (see Table 2-7)

f'_b= characteristic value in bending for the section size

Z = section modulus of beam about the axis of bending (for rectangular beams $Z_x = bd^2/6$ and $Z_y = db^2/6$, where b equals the breadth and d equals the depth of the beam).

k_1 = modification factor for duration of load (see Table 2-8)

k_4= partial seasoning factor (see Table 2-12)

k_6= temperature (adopt k_6=0.9, conservative)

k_9 = modification factor for strength sharing (adopt k_9=1, conservative)

k_{12} = stability factor

Table 2-12 Partial Seasoning Factor k_4 for Timber (AS1170.1)

PARTIAL SEASONING FACTOR (k_4)

Least dimension of member	38 mm or less	50 mm	75 mm	100 mm or more
Value of k_4	1.15	1.10	1.05	1.00

AS1720.1 Clause 3.2.3.2 indicates the stability factor k_{12} for modification of the characteristic value in bending shall be given by the following:

- For ρ_b S1 ≤ 10; k_{12} = 1.0
- For 10 ≤ ρ_b S1 ≤ 20; k_{12} = 1.5 − 0.05 ρ_b S1
- For ρ_b S1 ≥ 20; $k_{12} = \frac{200}{(\rho b\ S1)^2}$

Where slenderness coefficient S1 is calculated:

- a beam that is loaded along its compression edge and has discrete lateral restraints at points L_{ay} apart, along the compression edge of the beam

$$S1 = 1.25\ \frac{d}{b}\left(\frac{L_{ay}}{d}\right)^2$$

- a beam that is loaded along its compression edge and has a continuous lateral restraint system along the compression edge of the beam:

$$S1 = 2.25\ \frac{d}{b};\ satisfying\ \ \frac{L_{ay}}{d} \le 64\left(\frac{b}{\rho b\ d}\right)^2$$

AS1720.1 Timber Structures Clause 3.2.5 denotes the design capacity in shear (V_d) of un-notched timber LVL beams, for the strength limit state, shall satisfy the following:

$V_d \ge V^*$

where

$V_d = \phi\ k1\ k4\ k6\ f'_s\ A_s$

V^* = design action effect in shear

f'_s = characteristic value in shear

A_s = shear plane area (for a rectangular beam, A_s= 2/3(bd), where b equals the breadth and d equals the depth of the beam).

AS4100 Steel Structures (1998) denotes the two bending moment capacities to be considered in design as the nominal section moment capacity, and the nominal member moment capacity. The nominal section moment capacity M_s, refers to the flexural strength of a cross section. Whilst the member moment capacity refers to the flexural-torsional capacity of the beam as a whole (Gorenko, et al., 2012).

AS4100 Clause 5.1 specifies that at all sections of the beam bending about the major principle x axis must satisfy:

M_x*≤ ϕM_{sx}, and

M_x* ≤ ϕM_{bx}

where

M_x*= the design bending moment about the x-axis

ϕ = the capacity factor (see Table 2-13)

$M_{sx} = f_y Z_{ex}$ (the nominal section moment capacity)

$M_{bx} = \alpha_s \alpha_m M_{sx} \leq M_{sx}$ (the nominal member moment capacity)

f_y = yield stress of steel

Z_{ex} = the effective section moduli

$$\alpha_s = 0.6\left\{\sqrt{\left[\left(\frac{M_{sx}}{M_o}\right)^2 + 3\right]} - \left(\frac{M_{sx}}{M_o}\right)\right\}$$

$$M_o = \sqrt{\left(\frac{\pi^2 EI_y}{l_e^2}\right)}\sqrt{GJ + \left(\frac{\pi^2 EI_w}{l_e^2}\right)}$$

- For CHS, SHS and RHS sections

$$M_o = \sqrt{\left(\frac{\pi^2 EI_y GJ}{l_e^2}\right)}$$

AS4100 Clause 5.3.1 stipulates that the member moment capacity M_{bx} of a beam segment with full lateral restraint shall be taken as the nominal section moment capacity M_{sx} of the critical section. Full lateral restraint may be achieved for a beam by: (a) continuous lateral restraint (Clause 5.3.2.2of AS 4100), or (b) full, partial or lateral restraint provided at sufficient locations along the beam (Clauses 5.3.2.3 and 5.3.2.4 of AS 4100). The distance between the locations in (b) is termed the segment length.

Australian standards give guidance not figures for determining deflection limits to satisfy serviceability limit state. The desirable deflection limit in the members of a vertical wall form depends on the job specific concrete finish required.

For calculating deflection in simply supported timber members subject to a uniformly distributed load (Boughton & Crews, 2013) gives the following equation:

$$\delta = \sum \left[J2 \ \frac{5}{384} \ \frac{w \ L^4}{EI} \right]$$

For calculating deflection in simply supported steel members subject to a uniformly distributed load (Hibbeler, 2012) gives the following equation:

$$\Delta_{max} = \frac{5wL^4}{384EI}$$

For calculating deflection in simply supported steel members subject to a point loads (Gorenko, et al., 2012) gives the following equation:

$$\Delta_{max} = \frac{PL^3}{6EI} \left[\left(\frac{3a}{4L} \right) - \left(\frac{a}{L} \right)^3 \right]$$

Table 2-13 Capacity Factor for Structural Steel (AS4100 1998)

CAPACITY FACTORS (ϕ) FOR STRENGTH LIMIT STATES

Design capacity for	Clauses	Capacity factor (ϕ)	
Member subject to bending			
—full lateral support	5.1, 5.2 & 5.3	0.90	
—segment without full lateral support	5.1 & 5.6	0.90	
—web in shear	5.11 & 5.12	0.90	
—web in bearing	5.13	0.90	
—stiffener	5.14, 5.15 & 5.16	0.90	
Member subject to axial compression			
—section capacity	6.1 & 6.2	0.90	
—member capacity	6.1 & 6.3	0.90	
Member subject to axial tension	7.1 & 7.2	0.90	
Member subject to combined actions			
—section capacity	8.3	0.90	
—member capacity	8.4	0.90	
Connection component other than a bolt, pin or weld	9.1.9(a), (b), (c), and (d) 9.1.9(e)	0.90 0.75	
Bolted connection			
—bolt in shear	9.3.2.1	0.80	
—bolt in tension	9.3.2.2	0.80	
—bolt subject to combined shear and tension	9.3.2.3	0.80	
—ply in bearing	9.3.2.4	0.90	
—bolt group	9.4	0.80	
Pin connection			
—pin in shear	9.5.1	0.80	
—pin in bearing	9.5.2	0.80	
—pin in bending	9.5.3	0.80	
—ply in bearing	9.5.4	0.90	
Welded connection		SP Category	GP Category
—complete penetration butt weld	9.7.2.7	0.90	0.60
—longitudinal fillet weld in RHS ($t < 3$ mm)	9.7.3.10	0.70	—
—other fillet weld and incomplete penetration butt weld	9.7.3.10	0.80	0.60
—plug or slot weld	9.7.4	0.80	0.60
—weld group	9.8	0.80	0.60

2.8 WALL FORMWORK USE AND REUSE

Concrete wall formwork is re-used in projects to facilitate and economise the concrete construction process, as re-use can reduce the costs associated with formwork, as well as provide for a more sustainable solution. It is worth noting that there is limited availability of literature that provides guidance on how to quantitatively assess factors that have direct impact on the re-use of formwork. Most literature, related to formwork use describe engineering judgment as the main factor used for determining whether a piece of formwork can be used again or not (Hurd, 2005).

A study conducted in Singapore describes various factors that contribute to the re-use of traditional timber formwork (Ling & Leo, 2000), and identifies five main factors that affect the re-use of traditional timber formwork. These five main factors are:

1. Materials used to fabricate the formwork;
2. Workmen who work with the formwork;
3. Design of the completed structure;
4. Design, fabrication, and stripping of the formwork; and
5. Site management issues.

After examining the effects of fifteen sub-factors that fall under the main factors, the study concludes that only three sub-factors have any impact on the reusability of formwork. These are:

(i) the working attitudes of workers,
(ii) the efficiency of the crew, and
(iii) the formwork stripping or formwork striking process.

Of these, all three sub-factors belong to the workmen who work with formwork; hence, it can be concluded that the most important factor that affects formwork re-use is the workmen who handle formwork on-site (Ling & Leo, 2000).

To identify and assess factors that impact the reuse of formwork, it is necessary to define the activities that represent one use cycle of formwork. The typical use of traditional timber formwork on a construction project has been assumed to consist of assembling and erecting forms, setting rebar, pouring and curing concrete, and stripping the forms from the cured member (Hurd, 2005). The activities that a construction worker has to execute in the process of forming concrete have been defined as (Hallowell & Gambatese, 2009):

1. Transport materials and equipment without motorised assistance;
2. Transport materials using construction vehicle or other motorised assistance;
3. Lift or lower materials, form components or equipment;
4. Hold materials or components in place (static lift);
5. Accept/load/connect materials or forms from crane;
6. Cut materials using skill or table saw;
7. Nail/screw/drill form components or other materials;
8. Hammer using sledgehammer or other equipment;
9. Plumb and/or level forms using body weight, pry bar or other equipment;
10. Ascend or descend ladder;
11. Work below grade or in confined space;
12. Work above grade (>5 feet) or near uncontrolled opening;
13. Inspect forms and construction planning; and
14. Excavation.

This list identifies all activities that can be performed during the formwork process, they may or may not be carried out every formwork cycle if at all and are not in any particular sequence.

3 Methodology

3.1 INTRODUCTION

In this study, there are two primary objectives and five secondary objectives. The primary objectives are established to expand the general understanding of vertical formwork use within the Australian high-rise construction industry, as well as the associated regulations. The primary objectives established are:

1. Research and evaluate the relevant Australian standards and regulations for vertical wall formwork
2. Evaluate the wall formwork used in the Australian high-rise construction industry.

The secondary objectives established in support of the primary objectives are:

1. Establish the typical use cycle of vertical wall forms
2. Identify the types of wall formwork used in the Australian high-rise construction industry
3. Develop a greater understanding of the lateral concrete pressures that occur in wall formwork within the Australian high-rise construction industry.
4. Evaluate the structural capacity of the different types of wall formwork used in the Australian high-rise construction industry.
5. Compare the different types of wall formwork used in multistorey formwork construction in Australia.

Due to the nature of the objectives established, it is necessary to carry out research using multiple methods. The relationship between the different objectives and associated research methods is represented in Figure 3-1.

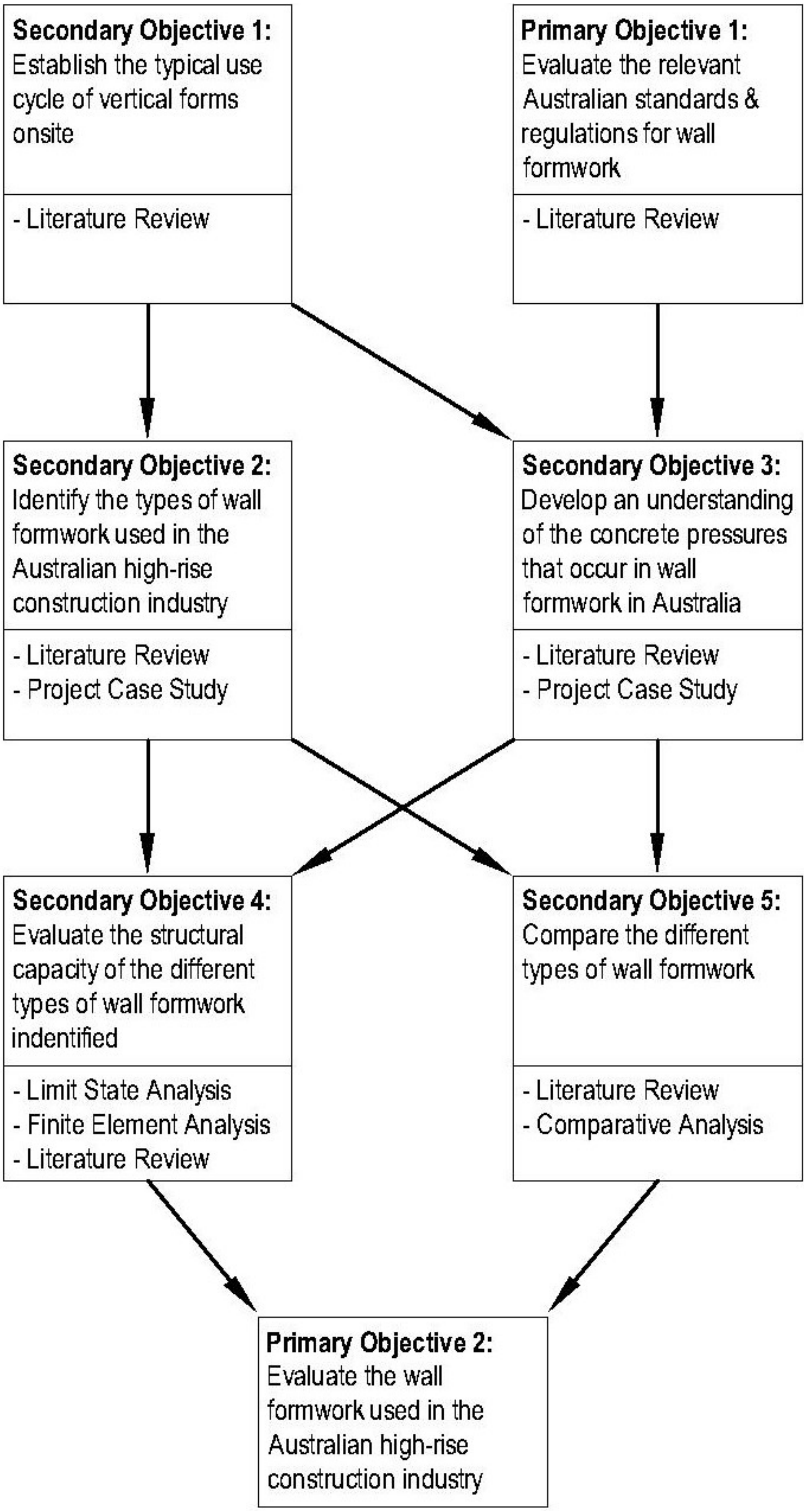

Figure 3-1 Research Scheme

In order to meet primary objective 1 an evaluation of the relevant Australian standards and regulations for vertical formwork, a literature review was deemed the most appropriate method. Australian standards and regulations were gathered and reviewed as well as other research reports that evaluate current legislation of the high-rise formwork industry.

A literature review was also deemed the most appropriate method to form an understanding for secondary objective 1, an establishment of the typical use cycle of vertical wall forms.

To find answers for secondary objectives 2 and 3, Identifying the types of wall forms used in the Australian high-rise construction industry as well as developing a greater understanding of the types of concrete pressures that occur within them, a research case study of Australian high-rise construction sites was deemed the most suitable method. A combination of research and consultation with representatives from building and formwork contractors involved in the respective construction projects was employed to gather the data within this case study.

Limit State Analysis and Finite Element Analysis (FEA) was employed in order to satisfy secondary objective 4, an evaluation of the structural adequacy of the different types of wall formwork used in multistorey formwork construction. The types of wall formwork for analysis were previously identified in the project case study.

A combination of literature research review and a comparative analysis was used to compare the different types of wall formwork used within the Australian high-rise construction industry in order to satisfy secondary objective 5.

An Evaluation of the wall formwork used in the Australian high-rise construction industry (primary objective 1) was able to be completed using the information gathered meeting secondary objectives 1 to 5.

3.2 PROJECT CASE STUDY

In order to identify the types of wall forms used in the Australian high-rise construction as well as develop a greater understanding of the magnitude of concrete pressures that occur within them, a research case study of Australian high-rise construction projects was deemed the most suitable method. The purpose of the project case study was to obtain information and record data pertaining to formwork use as well as to identify concrete pressures on wall formwork in real world projects. For the purpose of this study a high-rise construction site was deemed to be a building project with 10 storeys above ground level or more.

A combination of research and consultation with representatives from building and formwork contractors involved in the respective construction projects was employed to gather the data within this case study. The case study required 8 pieces of information to be gathered from each building project for analysis.

The first 5 pieces of information were for classification purposes:

1. Project name
2. Project location
3. Building type
4. Number of floors/storeys
5. Formwork contractor

The type of vertical wall formwork used on each particular project was the 6th piece of information gathered for each project. As some of these projects are large and there may have been several different types of wall formwork used at different stages of the project, the wall formwork used to form the lift core of each particular project was the information extracted. The justification for this being that the lift core walls are usually the largest vertical walls formed on a high-rise building project and they are most commonly present on every floor of a high-rise building from the basement to the roof top.

The concrete pour height for the lift core wall formwork of each building is the 7th piece of information gathered from each project. During the forming of a high-rise building construction joints are needed to divide the total structure into a number of portions, each of which can be practically formed and poured in one operation (McAdam, 1991). Usually each floor of a high-rise building dictates the position of a construction joint with each floor representing a pour. Vertical wall forms are then produced to suit this job specific pour height. The pour height is an important piece of information as it is needed to calculate concrete pressure within wall formwork.

In order to form a greater understanding of the lateral concrete pressures that occur in wall formwork within the Australian high-rise construction industry. The case study was used to determine the maximum hydrostatic pressure that wall formwork was or will be subjected at each the 77 building sites as the 8th piece of information gathered. An understanding of the concrete pressures within the Australian high rise construction is important as most formwork companies adopt a one design suits all jobs approach with vertical formwork. Wall formwork systems are predominately prefabricated for re-use over and over again on different construction projects. For higher pour heights wall formwork is generally just extended at the top with no extra strength added to the base of standardised forming systems where concrete pressure is at its highest. The concrete pressure data collected in this study will be useful for future wall formwork designs to ensure that the design is suitable for the range of pressures the form will be subjected to when re-used across different projects in the multistorey formwork industry.

The formulae for full hydrostatic head presented in AS3610 (1995) was used to calculate lateral concrete pressure in the wall forms across all 77 constructions projects.

$$P_{max} = \frac{\rho h}{100}$$

where

P_{max} = maximum lateral concrete pressure, in kilopascals

ρ = wet density of concrete, in kilograms per cubic metre

h = vertical pour height, in metres

The justification for using full hydrostatic head rather than the pressure reducing formulae presented by ACI and CRIA to calculate lateral concrete pressure is that the pressure reducing formulae are only accurate when the parameters of the pour can be stringently controlled. This is because slight changes in concrete temperature and pour rate can have a significant effect on the maximum lateral pressure exerted on the wall form (McAdam, 1991). When concrete mix designs or concrete placement rates do not meet the requirements of these pressure limiting equations, the pressure for full liquid head should be used in the design of vertical wall formwork (Barnes & Johnstone, 2004). Formwork designers have limited control over the method, rate of placement and temperature of the concrete onsite so the formulae for full hydrostatic pressure was adopted.

After and during concrete placement into wall and column forms it is vibrated to consolidate the concrete. Consolidation is achieved by removing the air from the fresh concrete in place. The purpose of vibration is to fluidise the concrete, destroying its shear strength capability and any friction between the concrete and the form, entrapped air will float to the surface of the concrete and escape (ACI, 2005). Because deep vibration of vertical wall forms to consolidate the concrete is common practice within the Australian construction industry full fluid pressure on the wall forms can be exceeded. To account for deep vibration McAdam(1995) recommends that the calculated full hydrostatic head be increased by 50%. A concrete pressure allowing for deep vibration will be the 9th piece of information gathered from the 77 construction projects.

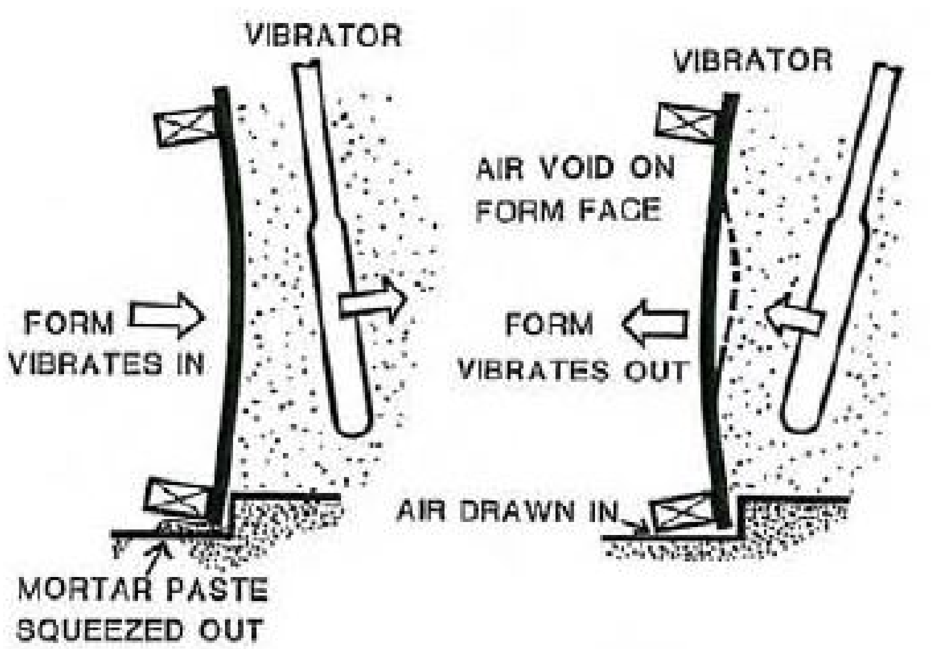

Figure 3-2 Immersion Concrete Vibration (McAdam, 1991)

3.3 WALL FORMWORK EVALUATION

In order to meet secondary objective 4 an evaluation of the structural capacity of the different types of wall formwork used in the Australian high-rise construction industry a combination of comparison and structural analysis techniques were used.

Formwork systems used within the Australian high-rise construction are largely pre-engineered and prefabricated, towards economies of scale. Prefabricated, reusable form panels have become standard items of construction. Ready-made or contractor-built prefabricated forms are ideal for wall forming where multiple floors are being erected, as this allows a large number of re-uses of the same form. However, Whyte and Brandis (2010) suggest that assumptions made concerning fit-for-purpose wall formwork systems are often inadequately communicated between relevant parties, with a willingness to make gains from 're-use' somewhat skewing the balance between quality, cost and time. This miscommunication can often lead to formwork failure.

Because formwork companies generally like to adopt a one design suits all jobs approach for their wall formwork systems it is important that these fit for purpose systems suit the range of lateral formwork pressures encountered across the industry. The first reason for this is to avoid formwork failure in case of miscommunication between relevant parties and secondly so that the one system can be safely and cost effectively re-used by the formwork contractor across all of their projects.

To understand the structural safety associated with formwork use in high-rise construction the concrete pressure data obtained from the project case study was used to evaluate the structural capacity of the types of formwork found to be used in the Australian high rise construction industry. The aim of this evaluation was to assess whether the current wall form designs being used are adequate for the range of concrete pressures that are occurring on high-rise construction sites. The results also indicate which wall formwork systems are at risk of causing a formwork failure if a miscommunication occurs and they adopted for blanket use across the industry.

3.3.1 Vertical Wall Forms for Analysis

The following wall form assemblies were analysed as part of this research paper as they were found in the project case study to be used in the Australian high-rise construction industry:

- Conventional Steel RHS Frame / 17mm Form Plywood Sheathing (Figure 3-3)
  - Form configured based the on Truform timber design guide (see Figure 2-10)

Figure 3-3 Steel Frame RHS Wall Forms within Jump Form at 300 George St Brisbane

- Conventional Timber LVL Frame / 17mm Form Plywood Sheathing (Figure 3-4)
    - Forms configured based the on Truform timber design guide (see Figure 2-10)

Figure 3-4 Timber LVL Wall Forms onsite 300 George St Brisbane

- Peri Modular Panel Formwork (Figure 3-5)
    - Manufacturer designed and supplied panel forms. Panels are bolted together using patented components to create a larger section.

Figure 3-5 Peri Modular Panel Forms within Jump Form at Crown Towers Project Perth WA

- Ischebeck Titan Aluminium Wall Formwork System (Figure 3-6)
    - Manufacturer designed and supplied aluminium forms.

Figure 3-6 Ischebeck Aluminium Panel Forms (Ischebeck Titan, 2016)

3.3.2 Limit State Analysis

The frame work of steel RHS conventional wall forms used in the Australian high-rise construction industry were found during the research for the project case study to be based on timber design guides with steel RHS members substituted in instead of timber because they are stronger, more durable and have a longer life. The adaptation has been developed out of necessity due to the amount of re-uses the forms are subjected to in multistorey construction. As well as adopting the same frame work design and member spacing the steel forms also adopt steel member sizes similar to their timber counterpart, 95mm x 47mm timber LVL's are replaced by 100mm x 50mm steel RHS. As the structural members being used in these wall forms differ from the original timber LVL design the structural capacity of this formwork system should be different. Because this style of formwork system has become a common building tool in Australian high-rise construction it was deemed appropriate that a thorough structural analysis be carried out to assess the actual capacities of these steel frame wall forms. The outcomes of this analysis could serve as a guide for formwork designers wishing to use this style of wall formwork in the future because at present there is no published literature or design information pertaining to this formwork system. The analysis may also lead to a fine tuning of the steel wall form design and ultimately lead to a cost saving in their production.

A Limit State Analysis was carried out on the individual components in the formwork assembly using the relevant material structural design code. Individual components were checked for maximum allowable bending moment, shear stress and deflection. From this limit state analysis, a theoretical maximum concrete pressure capacity was attributed to the RHS conventional vertical wall form system.

3.3.2.1 Analytical Model

Figure 3-7 shows the basic model, which idealises the fresh constructed concrete wall. Because of symmetry of the wall and to simplify the analysis, half section of the wall is considered in the analytical model. Wall forms are firstly installed and then the concrete is placed into wall forms, which is vibrated to consolidate the concrete. The cast concrete is assumed to be placed at the same time and considered to be homogenous over the entire length. Fresh concrete imposes loads on the wall form structure in the form of an initial pressure envelope which is represented in the model by a distributed load.

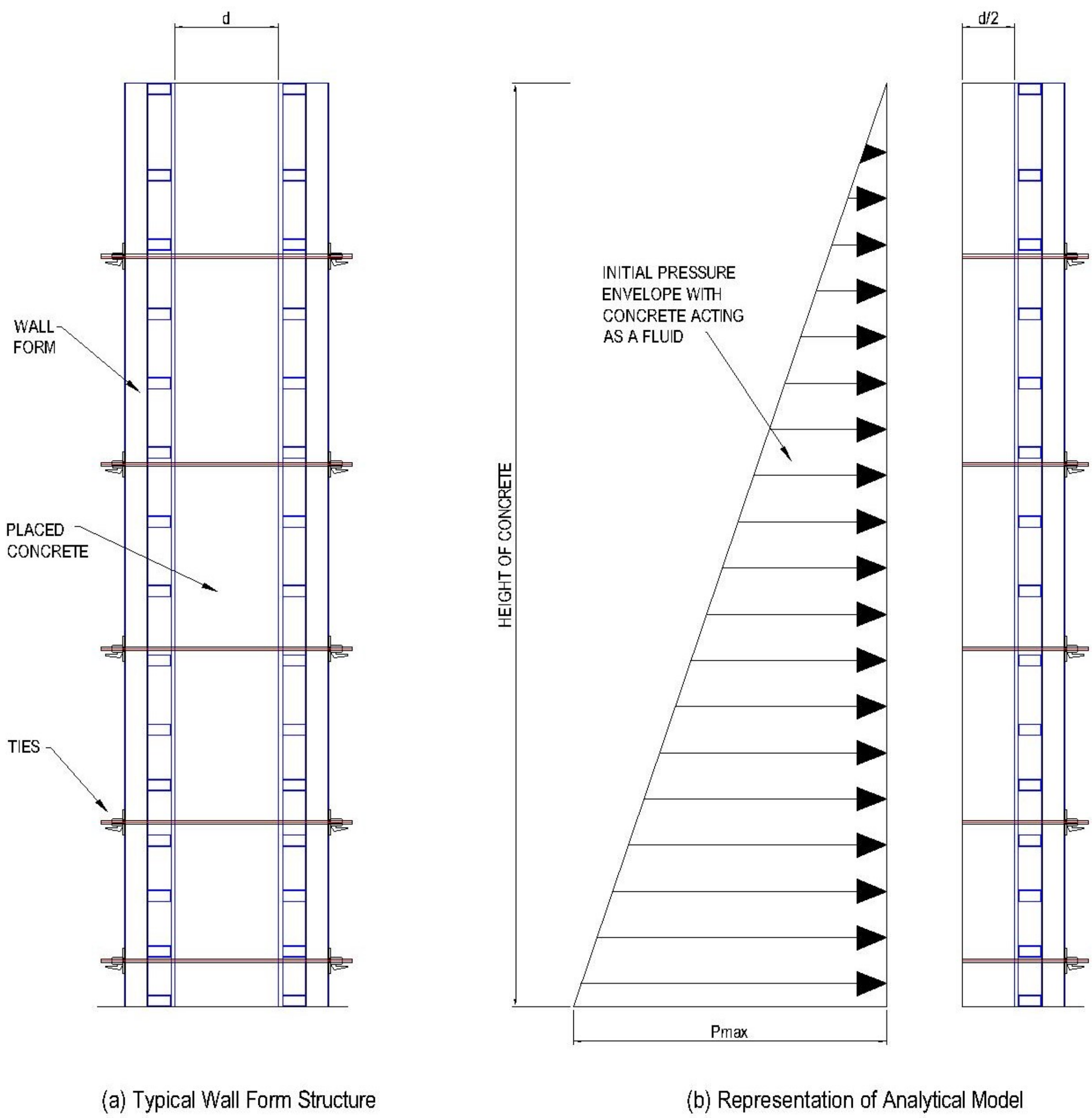

Figure 3-7 Analytical Model

3.3.2.2 Wall Formwork Arrangement

Figure 3-8 shows the steel RHS conventional wall formwork system being analysed. The arrangement is based on the wall forms used by the form work contractor Heinrich Constructions at the 44 storey high-rise construction project 1 William St in Brisbane to form the buildings lift core during 2015.

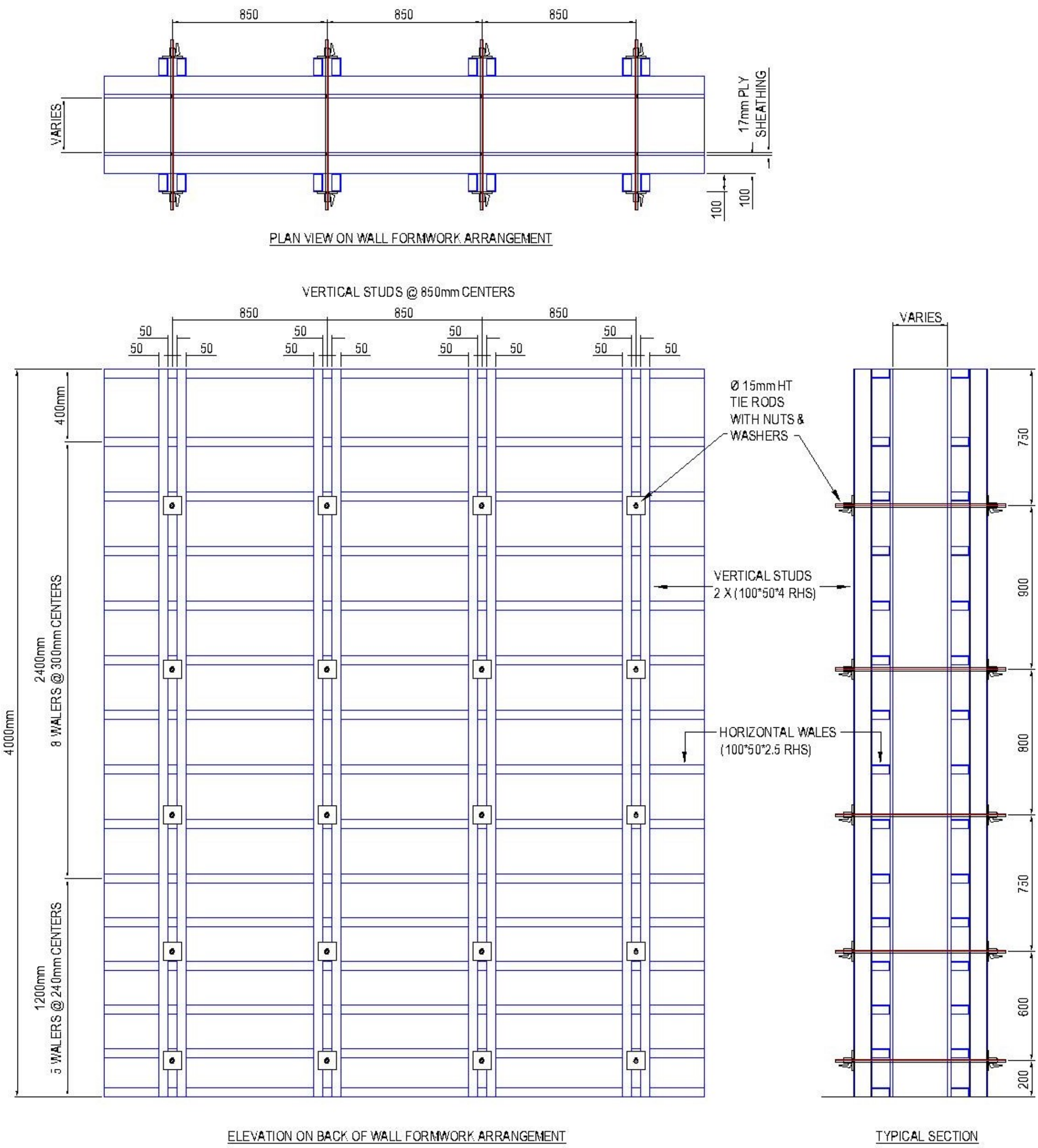

Figure 3-8 Wall Formwork Arrangement for Analysis

3.3.2.3 Analysis Formulas

Other than tie rods all the other components of the formwork structure behave like beams. The beam formulas for bending, shear and deflection were used to analyse these components of the wall formwork system.

- Maximum bending moment due to a Uniform Distributed Load (w) for beams supported over 3 or more spans (Structx, 2016):

$$M_{max} = 0.1\ wL^2$$

- Maximum shear force due to a Uniform Distributed Load (w) for beams supported over 3 or more spans (Structx, 2016):

$$V_{max} = 0.6\ wL^2$$

- Maximum deflection due to a Uniform Distributed load (w) for beams supported over 3 or more spans (Structx, 2016):

$$\Delta_{max} = \frac{0.0069wL^4}{EI}$$

The formulas were re-arranged to make the Distributed Load (w) the subject, from this the safe distributed working load was calculated for each structural component of the wall form.

- Bending Moment: $w = \frac{M_{max}}{0.1\ L^2}$
- Shear Force: $w = \frac{V_{max}}{0.6\ L^2}$
- Deflection: $w = \frac{\Delta_{max}\ (EI)}{0.0069\ L^4}$

The component in the structure with the lowest safe working load became the limiting factor for the structure. The value for this distributed load was then designated the theoretical maximum permissible concrete pressure for the wall formwork system.

3.3.2.4 Model Design Data and Assumptions

The following design simplifications and assumptions have been made:

- All loads are assumed to be uniformly distributed
- Beam formulas are used to analyse the formwork components
- Beams that are supported over three or more spans are considered to be continuous

Formwork deflection criteria as stipulated by AS3610.1 Formwork for Concrete 2010:

- The allowable deflection for the formwork structure elements shall be the lesser of span/360 or 2mm for a Class 1 concrete finish.
- The allowable deflection for the formwork structure elements shall be the lesser of span/270 or 3mm for a Class 2 concrete finish.

Material properties of the structural elements:

Properties of Plywood Sheathing as per the (Carter Holt Harvey Wood Products Australia, 2012) manufacturer guide:

- Identification Code, 17-24-7
- Nominal Thickness, t = 17mm
- Stress Grade, F17
- grain direction of plies is parallel to the span
- Section Modulus of Plywood, Z_p = 33.5 mm^3/mm
- Second Moment of Area, I = 285 mm^4/mm

All structural steel shall be 450 grade complying with AS4100 Steel Structures 1998.
Properties of steel RHS as per One Steel Design Capacity Tables for Structural Steel Hollow Sections:

- Yield Stress, fy = 450 MPa
- Tensile Strength, fu = 500 MPa
- Young's Modulus of Elasticity, E = 200 x 10^3 MPa
- Shear Modulus of Elasticity, G = 80 x 10^3 MPa
- Density, ρ = 7850 kg/m3
- Poisson's Ratio, v = 0.25

Properties of steel RHS Horizontal Waling:

- Size of RHS: 100 x 50 x 2.5 mm
- Section is Compact about its x axis
- Second Moment of Area, $I_x = 2.54 \times 10^6$ mm^4
- Elastic Modulus, $Z_x = 33.9 \times 10^3$ mm^3
- Gross Area of Section, $A_g = 959$ mm^2
- Section Moment Capacity, $\phi M_{sx} = 9.18$ kNm
- Section Shear Capacity, $\phi V_v = 110$ kN
- Maximum segment length for full lateral restraint, FLR = 1.74 m

Properties of steel RHS Vertical Studs:

- Size of RHS: 100 x 50 x 4 mm
- Section is Compact about its x axis
- Second Moment of Area, $I_x = 3.74 \times 10^6$ mm^4
- Elastic Modulus, $Z_x = 49.8 \times 10^3$ mm^3
- Gross Area of Section, $A_g = 1480$ mm^2
- Section Moment Capacity, $\phi M_{sx} = 13.5$ kNm
- Section Shear Capacity, $\phi V_v = 170$ kN
- Maximum segment length for full lateral restraint, FLR = 1.68 m

3.3.3 3D Finite Element Analysis

The theoretical capacity calculated in the limit state analysis for the RHS conventional wall form arrangement was verified using 3D Finite Element Analysis. The wall form assembly was modelled in 3D using the drafting software package AutoCAD Inventor. The 3D model was then analysed using the Finite Element Analysis tools within the AutoCAD Inventor programme.

A 3D model is a representation of a real life system or process by some mathematical or numerical expression, which can be used as a substitute for the real thing, and allows to predict what would happen in a real system by changing the input data parameters of the model. Finite Element Analysis (FEA) is a computerised method for predicting how an item reacts to real-world forces, vibration, heat, fluid flow, and other physical effects. It is called analysis, but in the development process, it is used to predict what is going to happen when the item is used (Autodesk Inc, 2016). FEA works by breaking down a real object into a large number of finite elements, such as little cubes. Mathematical equations help predict the behaviour of each element. The software then adds up all the individual behaviours to predict the behaviour of the actual object (Autodesk Inc, 2016).

The wall form assembly was modelled in 3D using the drafting package AutoCAD Inventor as shown in Figure 3-9. Autodesk Inventor is a 3D mechanical solid modelling design software. The wall form system was modelled to scale using the software's in built materials library. The individual components were able to be assigned their material specific properties including: Yield Stress, Tensile Strength, Modulus of Elasticity and Density.

The 3D model was then analysed using the Finite Element Analysis (FEA) tools within the AutoCAD Inventor programme. The FEA tools were used to give instantaneous and time-dependent changes in the displacements, in the support reactions and in the statically indeterminate internal forces, along with the corresponding changes in stress and strain in individual sections. In this particular circumstance the FEA was particularly useful in giving accurate deflection results for the individual structural members of the wall form system.

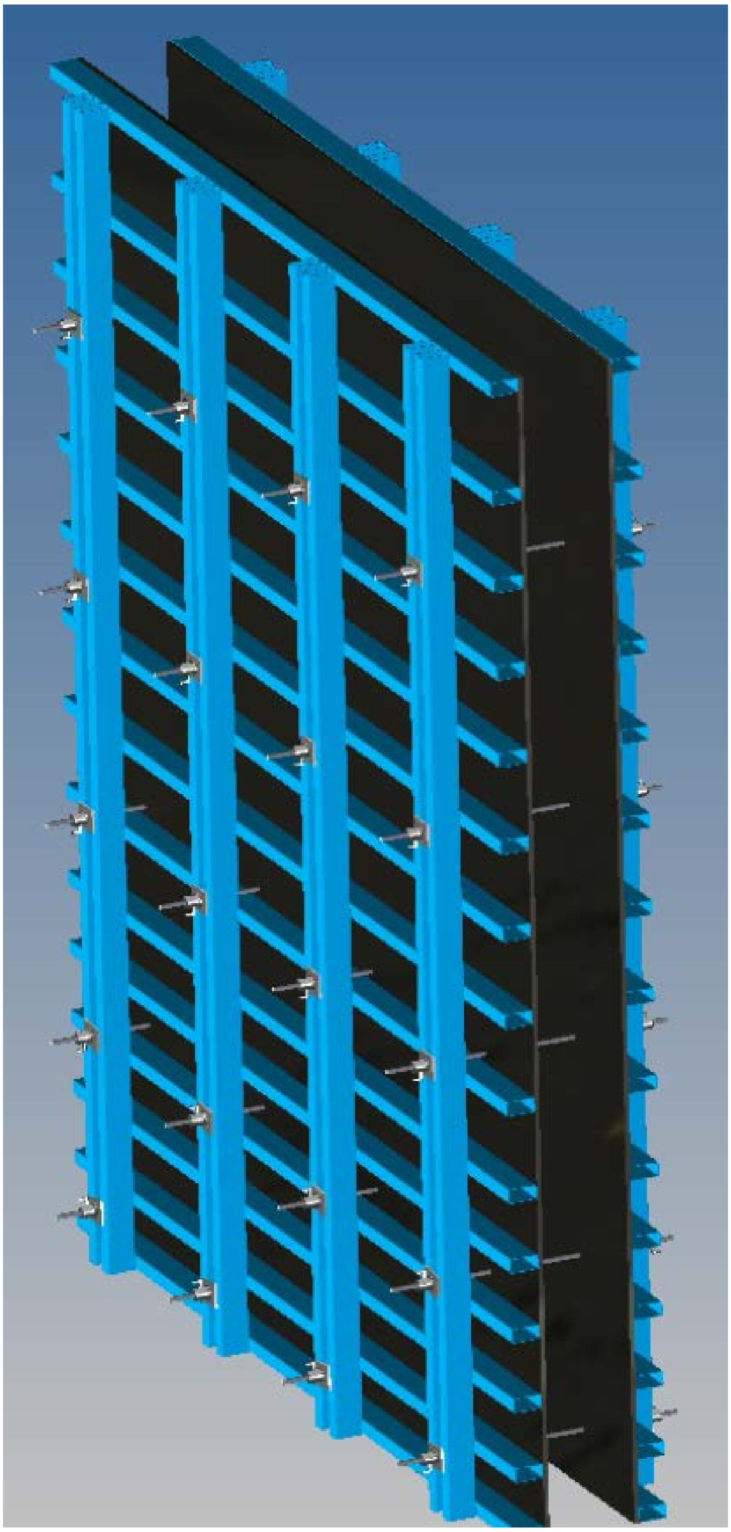

Figure 3-9 Steel RHS Conventional Wall Form modelled in AutoCAD Inventor

3.3.4 Comparative Analysis

Because formwork companies within the Australian high-rise construction industry adopt a one design suits all jobs approach for their wall formwork systems it is important that these fit for purpose systems suit the lateral formwork pressures encountered across the industry. As pour heights and concrete pressures within formwork differ between projects the pre-engineered and prefabricated wall formwork needs to have the capacity to cover this varying range.

To understand the structural safety associated with formwork use in high-rise construction the concrete pressure data obtained from the project case study was used to evaluate the structural capacity of the 4 formwork varieties identified. The aim of this analysis was to evaluate whether current wall form designs being used are adequate for the varying range of concrete pressures that are occurring on Australian construction sites.

The theoretical capacity calculated in the limit state analysis for the RHS conventional wall form arrangement was used to assess its suitability. The 3 manufacturer designed formwork systems supplied by Truform, Peri and Ishebeck come with product specific design information including maximum concrete pressure. The specification information provided by the manufacturers was compared with the concrete pressure data from the project case study to assess whether these panels are adequate for blanket use across high-rise construction in Australia.

The justification for this evaluation is that assumptions made concerning fit-for-purpose wall formwork systems are often inadequately communicated between relevant parties, with a willingness to make gains from re-use somewhat skewing the balance between quality, cost and time (Whyte & Brandis, 2010). A number of formwork systems are designed as modular systems that are intended to be erected in specific configurations as prescribed by the designer and manufacturer. While modular systems require engineer design certification, this certification can be done once and used as evidence of design compliance. The design certification can be provided as part of the brochure prepared by the manufacturer of the system (Workplace Health and Safety Queensland, 2016), thus when formwork is re-used on future projects there is a danger that formwork will be inadequate for the concrete pressures encountered and formwork failure may occur.

4 Results

This chapter discusses the outcomes of the various methods/approaches put forward by the research to address the main objectives of this study. The literature review was used to present and then evaluate the national and state based regulations that govern formwork practice in Australia. The data obtained in the project case study from the 77 high-rise construction sites was analysed and discussed to map the use of vertical formwork and to present information pertaining to the concrete pressures that they are subjected to during construction. The limit state and finite element analysis results are put forward and discussed to help determine a maximum permissible design load for steel RHS conventional wall formwork. Design information for the relevant formwork systems being used in the Australian high-rise construction industry were obtained from the manufacturers or determined. This information was then cross checked next to concrete pressure data obtained in the project case study to evaluate and discuss the respective wall formwork systems suitability for use in Australian multistorey construction.

4.1 EVALUATION OF THE RELEVANT AUSTRALIAN STANDARDS AND REGULATIONS FOR VERTICAL WALL FORMWORK

Australia formwork practice is governed by a State-based regulatory scheme. It has a legislative approach to governing formwork practice that varies from state-to-state (A. Whyte, 2010). Queensland, Victoria, South Australia and New South Wales all have independent codes of practice for formwork. However, all the state based legislation stipulate that the design of all formwork systems, both traditional and modular must satisfy Australian Standards:

- AS3610 – Formwork for concrete (1995)
- AS3600 – Concrete structures (2009)

The Standards Association of Australia publish Formwork for Concrete AS3610 (1995). This standard with its commentary present design and construction requirements for falsework and formwork of all structure types. It sets out obligations for the design, fabrication, erection and stripping of formwork, as well as the specification, evaluation and repair of the quality of the formed concrete surface and the influence of this activity on the design and construction of an in situ concrete structure (Standards Australia, 1995). A comparison between AS3610 and the New South Wales and Queensland codes of practice indicates differences regulating form workers. Australian Standard AS3610 (1995) is performance based and describes outcomes, the state codes seek to give practical guidance on suitable formwork process and practice.

In regards to wall and column formwork AS3610 (1995) presents formulas for calculating the maximum lateral pressure exerted by the fresh concrete on formwork during placement. The formulae stipulated by AS3610 are only accurate where the parameters of the pour can be stringently controlled. This is because slight changes in concrete temperature and pour rate can have a significant effect on the maximum lateral pressure exerted on the wall form. Formwork designers know how little control they have over the method, rate of placement and temperature of the concrete onsite so in most cases the formulae presented by AS3610 (1995) are disregarded and the more conservative practice of designing for full hydrostatic pressure is adopted.

AS3610 stipulates that formwork components or assemblies shall be analysed and designed with either limit state procedures or permissible stress procedures in accordance with the appropriate material structural design code. AS3610 was last revised in 1995, as a result guidance governing Australian formwork design practice is over two decades old. In 1997 the Standards Development Committee for Formwork started reviewing AS3610 in an attempt to keep up with developments and innovation in the industry. In February 2010 the Development Committee partially republished the standard with the introduction of AS3610.1-2010 covering 'Documentation and Surface Finish' (Whyte & Brandis, 2010). Despite draft revisions of AS3610 focusing on enhancing design guidance of formwork, further amendments to the standard have yet to be released. While part two of the standard remains undeveloped Whyte and Brandis (2010) suggests continued development of AS3610 will bring the standard up to date with current construction practice and ensure suitable guidance and accountability.

As part of the review into AS3610 (1995) a Formwork Design Handbook was drafted by some members of the Standards Development Committee (Whyte & Brandis, 2010). The Handbook is intended to overcome the short comings of AS3610, and to introduce and explain procedures, requirements and methods for the design and construction of formwork that minimise frequency of formwork failure (Concrete Institute of Australia, 2016). However, changes in the conditions of contract for Handbook development have stalled production and the handbook has yet to be released.

Although legislative development in formwork practice over the years has been carried out, it can be argued that it has not kept pace with innovation and practice within the industry. This is most notably evident in AS3610 the Australian standard governing formwork being over two decades old. Due to the delay in the release of an update of Australian Standard AS3610 Formwork for Concrete (1995) covering formwork design and the issues stopping the release of the proposed Formwork Designers Handbook there is currently a gap in appropriate literature for formwork designers in the Australian formwork industry.

4.2 CASE STUDY SUMMARY

Data obtained in the project case study was collected from 77 high-rise construction sites. For the purpose of this study a high-rise construction site was deemed to be a building project with 10 storeys above ground level or more. The 77 projects were carried out by nine different formwork contractors and the projects were located in Queensland, New South Wales and Western Australia. Table 4.1 displays the data extracted during the case study. The projects are listed in chronological order of construction commencement date, with the earliest sites commencing construction in 2005 and the later sites surveyed commencing in 2016. Consultation with representatives from building and formwork contractors involved in the respective construction projects was employed to gather the data within this case study. The respondents belonged to the posts of company director, project manager and project engineer. As part of the study, the projects name, location, building type, number of storeys and the formwork contractor supplying and working the formwork were collected as identifiers.

The 77 sites were a mixture of apartment, hotel and office buildings. A distribution of the building types can be seen in Figure 4-1. Apartment buildings made up more than half of the construction sites in the study. The distribution of building types in the study is an accurate representation of high-rise buildings being constructed in the industry. Appendix B summarises the case study data collected from each of the 77 construction sites.

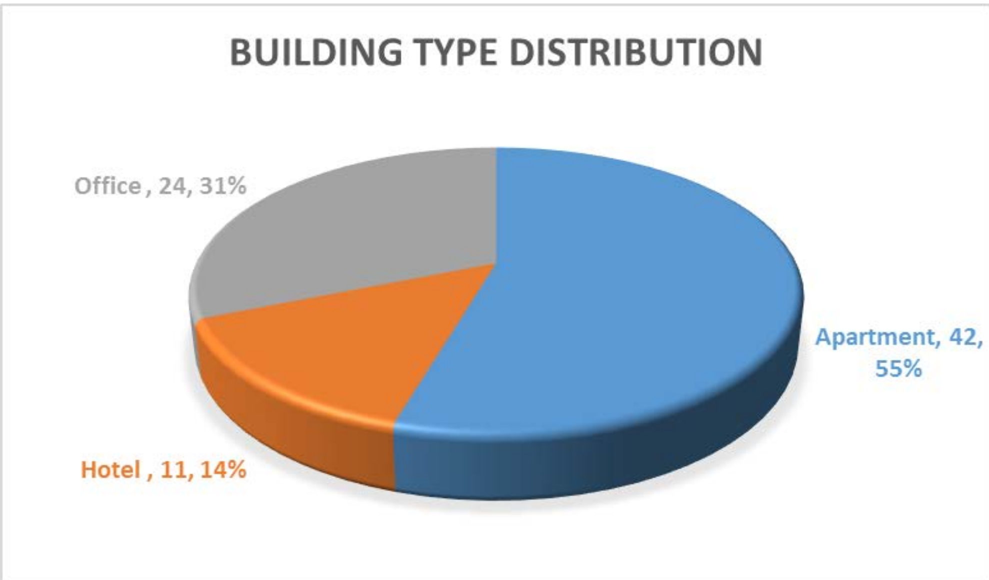

Figure 4-1 Distribution of Buildings Types in Case Study

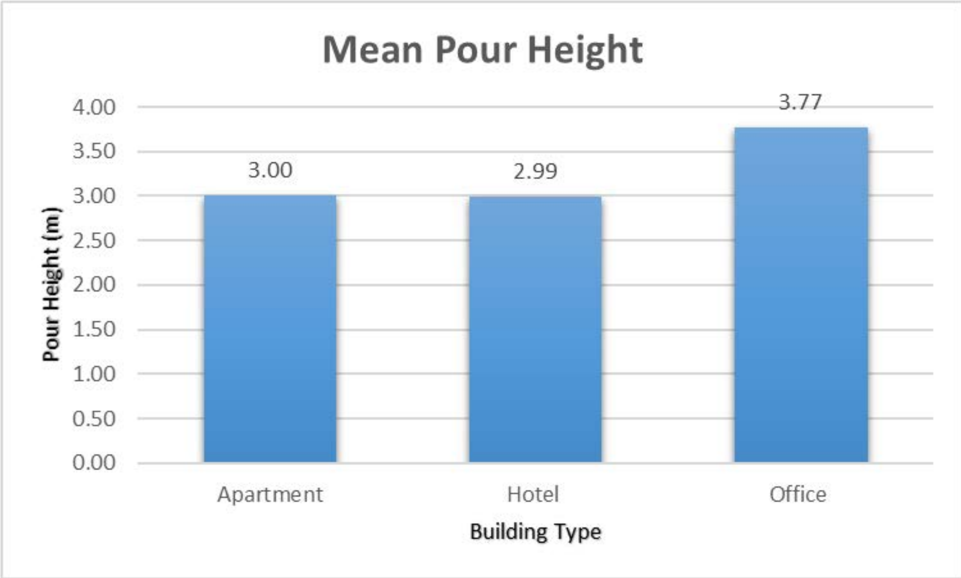

Figure 4-2 Mean Pour Height for Building Type

Figure 4-2 shows the mean pour height used in the construction of each building type. It can be seen in general that office buildings with on average 3.77m have a much higher concrete pour height then apartment and hotel buildings with an average of 3m and 2.99m respectively. This is indicative of formwork companies simplifying work onsite by matching the concrete pour height to the floor to floor height of a building. Figure 4-3 represents the effect this higher pour height has on the concrete pressures applied to wall formwork.

Figure 4-3 Average Maximum Concrete Pressure for Building Type

The formulae for full hydrostatic head presented in AS3610 (1995) was used to calculate lateral concrete pressure in the wall forms across all 77 constructions projects. A concrete pressure allowing for deep immersion vibration to consolidate the concrete was also calculated for each site at 1.5 times full hydrostatic pressure. Figure 4-3 shows the average maximum concrete pressures for each building type. Because of the higher pour heights used in the construction of high-rise office buildings, wall formwork on average is subjected to a 20 kNm^2 concrete pressure higher than that at an apartment or hotel high-rise construction site. Office buildings average a maximum hydrostatic concrete pressure of 90.54 kNm^2, whilst on apartment and hotel construction sites formwork is subjected to an average maximum lateral pressure of 72 kNm^2.

Table 4-1 Statistical Analysis of Concrete Pressure Data

Concrete Pressure Data	
Mean	77.77 kNm^2
Standard Error	1.07
Median	73.20 kNm2
Mode	69.60 kNm^2
Standard Deviation	9.38
Sample Variance	88.03 kNm^2
Kurtosis	-0.75
Skewness	0.79
Range	37.20
Minimum	67.20 kNm^2
Maximum	104.40 kNm^2
Count	77

The mean maximum concrete pressure across the 77 construction sites was 77.77 kNm^2, however this average pressure was increased significantly by the extremely high concrete pressures that occur on office building projects. Perhaps a better indicator for this data set is the median concrete pressure which was calculated as 73.20 kNm^2. The mode or most occurring concrete pressure across the sites surveyed was 69.60 kNm^2. The concrete pressure data collected highlighted the vast range of pressure that wall formwork is subjected to in multi-storey formwork construction. The maximum hydrostatic pressure was found to be 104.40 kNm^2 and the minimum was 67.20 kNm^2 giving a wide range of 37.20 kNm^2.

Figure 4-4 provides a graphical representation of the spread and distribution of the maximum concrete pressures experienced across the 77 construction sites.

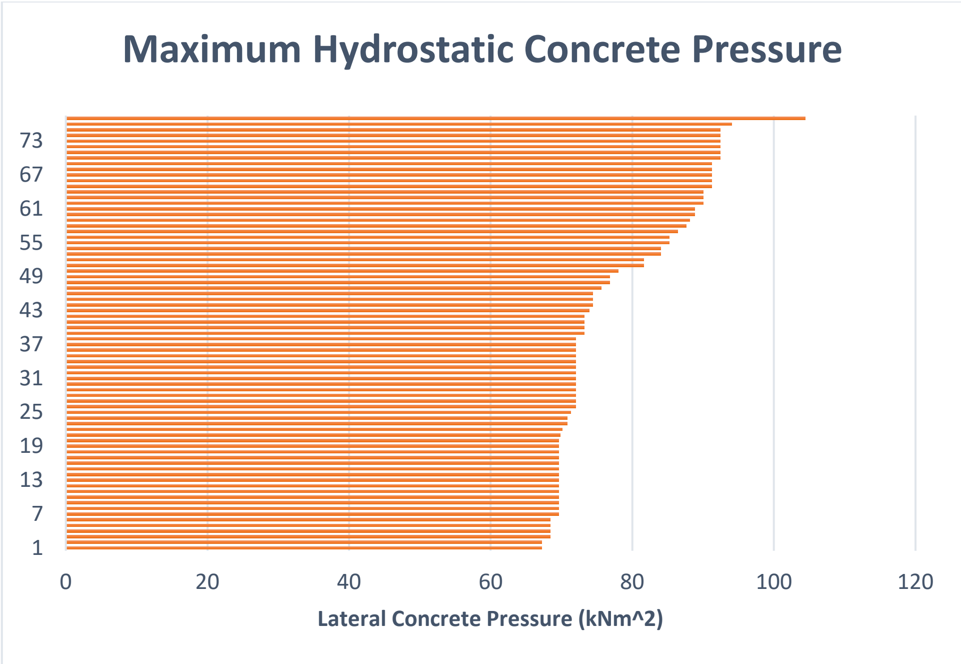

Figure 4-4 Maximum Hydrostatic Concrete Pressure at each High-rise Project

The type of vertical wall formwork used on each of the 77 projects by the 9 different formwork contractors was collected as part of the project case study analysis. As most of these projects are large and there may have been several different types of formwork used at different stages of construction, the wall formwork used to form the buildings lift core was identified. The justification for this being that the lift core walls are usually the largest vertical walls formed on a high-rise building project and they are most commonly present on every floor of a high-rise building from the basement to the roof top.

There were 4 different wall formwork systems identified by the project case study to be used to form the lift cores of the 77 sites surveyed. These systems included:

- Conventional RHS Wall Forms (62 sites, 81%)
- Conventional LVL Wall Forms (4 sites, 5%)
- Peri Modular Panel Forms (8 sites, 10%)
- Ishebeck Modular Aluminium Forms (3 sites, 4%)

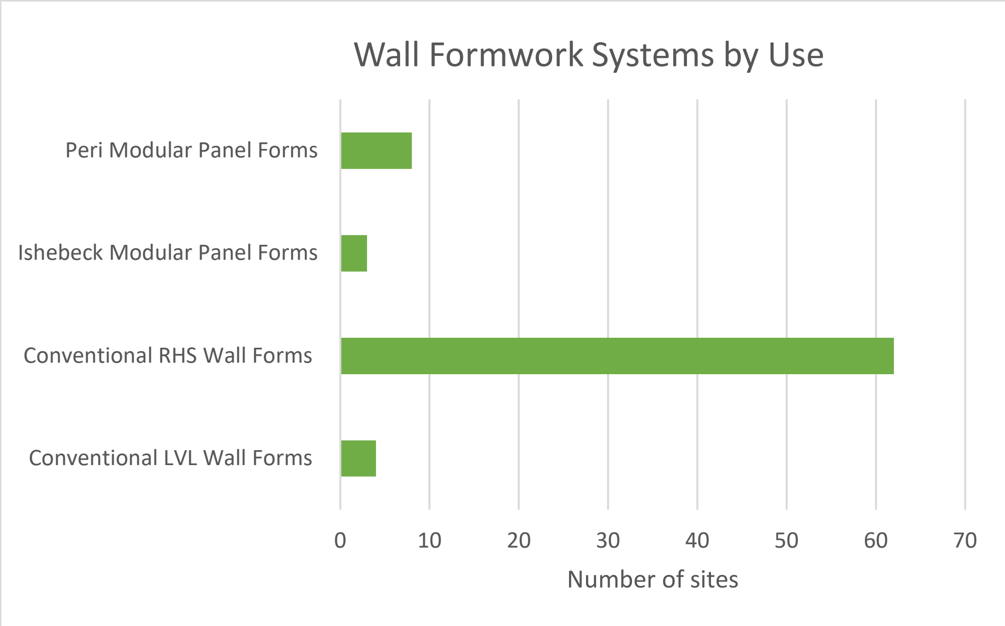

Figure 4-5 Wall Formwork Systems used across High-rise Construction Sites Surveyed

As can be seen in Figure 4-5 Wall Formwork Systems used across High-rise Construction Sites Surveyed most formwork contractors preferred the use of Conventional style wall formwork with a steel Rectangular Hollow Section (RHS) frame and a ply sheathing form face in there high-rise building projects. Conventional wall formwork with a Laminated Veneer Lumber (LVL) frame and ply form face were used on 4 projects, it is worth noting that these projects were buildings with only 10 to 12 floors. Peri Modular Panel Forms and Ishebeck Modular Panel Forms were used sparingly across the sites surveyed with their use limited to 2 particular formwork contractors. These manufactured systems consist of steel or aluminium frames with plywood faces. Formwork panels of desired dimensions are formed by putting together several smaller panels, and connecting them together using metal clamps or brackets.

The project case study data also allows for the extraction of the number of re-uses a wall form-system is subjected to at each multistorey construction site. A statistical analysis of this re-use data can be seen in Table 4.3. The mean re-uses across the 77 construction sites was 27.19 cycles. Because of outliers in the data set such as the 82 storey George St residential tower a better depiction of formwork re-use per site maybe the median cycle which was calculated as 25. The mode or most occurring re-use across the sites surveyed was 15 cycles. The variance in the number of floors between the highest building site surveyed and the smallest was depicted in the range of wall formwork re-uses of 72 cycles.

Table 4-2 Statistical Analysis of Formwork Re-use data

Formwork Re-uses per Project	
Mean	27.19
Standard Error	1.49
Median	25.00
Mode	15.00
Standard Deviation	13.04
Sample Variance	170.03
Kurtosis	2.78
Skewness	1.21
Range	72.00
Minimum	10.00
Maximum	82.00
Count	77.00

4.3 LIMIT STATE ANALYSIS RESULTS

A Limit State Analysis was carried out on the individual components in the RHS conventional vertical wall form system assembly using the relevant material structural design code. Individual components were checked for maximum allowable bending moment, shear stress and deflection. From this limit state analysis, a theoretical maximum concrete pressure capacity was attributed to the RHS conventional vertical wall form system.

Calculations for Plywood sheathing

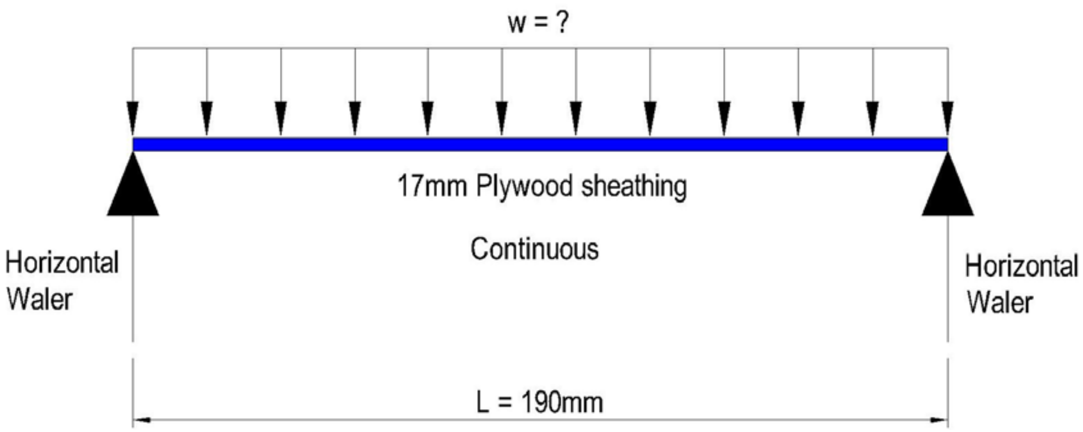

Figure 4-6 Line Load Diagram on 17mm Plywood Sheathing

Span L = 240mm – 50mm

Span L = 190mm (Clear span) (at the critical bottom of the wall form)

Bending Moment

Bending capacity of Plywood:

ϕ = 0.85 (AS1720.1, Table 2.1)

k_1 = 0.97 (AS1720.1, Table 2.1) (up to 5-hour duration)

k_{19} = 1 (AS1720.1, Table 5.2)

g_{19} = 1 (AS1720.1, Table 5.3)

f'_b = 45 MPa (AS1720.1, Table 5.3)

Z_p (for an 1800mm x 1200mm sheet) = 33.5 mm^3 x 1200 = 40.2 x 10^3 mm^3

$M_{d,p} = \phi\ k_1\ k_{19}\ g_{19}\ f'_b\ Z_p$ (AS1720.1, CL 5.4.2)

$M_{d,p} = (0.85) * (0.97) * (1) * (1) * (45) * (40.2 \times 10^3\ mm^3) = 1.49 \times 10^6$ Nmm

Bending Capacity of 17mm Form Ply = 1.49 kNm^2

UDL up to Max Bending Moment:

$$w = \frac{M_{max}}{0.1\ L^2}$$

$$w = \frac{1.49}{0.1\ (0.19)^2}$$

w = 412.74 kNm

Shear Force

Shear capacity of Plywood:

$V_{d,p} = \phi\ k_1\ k_{19}\ g_{19}\ f'_s\ A_s$ (AS1720.1, CL 5.4.3)

f'_s = 6 MPa (AS1720.1, Table 5.1)

$A_s = 2/3\ (b\ t) = (2/3) * (1200*17) = 13600 mm^2$

$V_{d,p} = (0.85) * (0.97) * (1) * (1) * (6) * (13600) = 67.28$ kN

Shear Capacity of 17mm Form Ply = 67.28 kN

UDL up to Max Shear Force:

$$w = \frac{V_{max}}{0.6\ L^2}$$

$$w = \frac{67.28}{0.6\ (0.19)^2}$$

w = 3106.19 kNm^2

Deflection for Class 1 finish

Maximum deflection = L/360 (AS3610.1, Table 3.3.2)

L/360 = 190mm/360 = 0.53mm

I (for an 1800mm x 1200mm sheet) = 285 x 1200 = 34.2 x 10^4 mm^4

UDL up to Max Deflection:

$$w = \frac{\Delta_{\max}\ (\mathrm{EI})}{0.0069\ \mathrm{L}^4}$$

$$w = \frac{(0.53mm)*(14000MPa)*(34.2\times10^4 mm^4)}{0.0069*(190\mathrm{mm})^4}$$

w = 282.21 kNm^2

Deflection for Class 2 finish

Maximum deflection = L/270 (AS3610.1, Table 3.3.2)

L/270 = 190mm/270 = 0.7mm

I(for an 1800mm x 1200mm sheet) = 285 x 1200 = 34.2 x 10^4 mm^4

UDL up to Max Deflection:

$$w = \frac{\Delta_{\max}\ (\mathrm{EI})}{0.0069\ \mathrm{L}^4}$$

$$w = \frac{(0.7mm)*(14000MPa)*(34.2\times10^4 mm^4)}{0.0069*(190\mathrm{mm})^4}$$

w = 372.73 kNm^2

Calculations for Horizontal Waling (100 x 50 x 2.5 RHS)

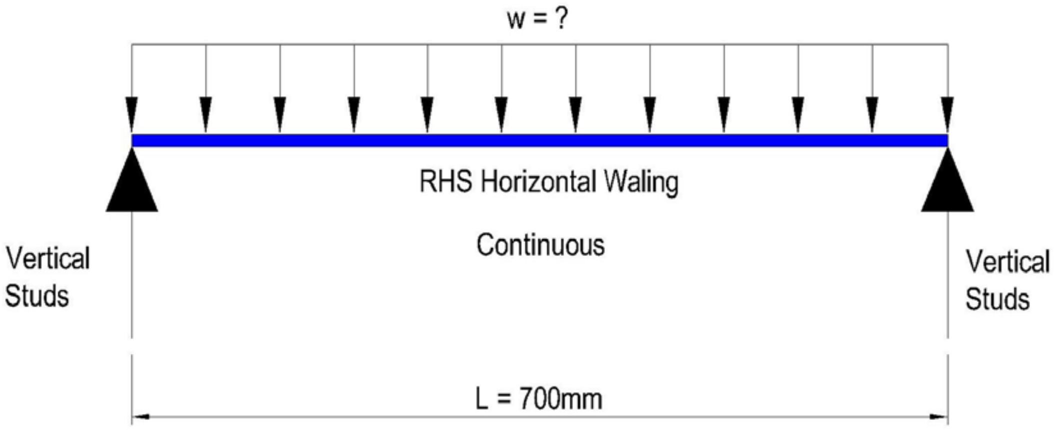

Figure 4-7 Line Load Diagram on RHS Horizontal Waling

Span L = 850mm – 150mm

Span L = 700mm (Clear span)

Each wale supports a 240mm strip

Bending Moment

Bending capacity of RHS Horizontal Waling:

ϕM_{sx} = 9.18 kNm

Maximum segment length for full lateral restraint, FLR = 1.74 m

Therefore, beam has full lateral restraint, member capacity = section capacity (ϕM_{sx})

Bending Capacity of RHS Horizontal Waling = 9.18 kNm

UDL up to Max Bending Moment:

$$w = \frac{M_{max}}{0.1\ L^2}$$

$$w = \frac{9.18}{0.1\ (0.7)^2}$$ = 187.35 kNm^2

Equivalent UDL = 187.35 kNm^2 / 0.24m = 780.61 kNm^2

A wale spanning 700mm, spaced at 240mm centres could support a concrete pressure of 780.61 kNm^2 in Bending for strength limit state

Shear Force

Shear capacity of RHS Horizontal Waling:

ϕV_v = 110kN

UDL up to Max Shear Force:

$$w = \frac{V_{max}}{0.6\ L^2}$$

$$w = \frac{110}{0.6\ (0.7)^2}$$

w = 374.15 kNm^2

As each wale supports a 240mm strip

Equivalent UDL = 374.15 kNm / 0.24m = 1558.96 kNm^2

A wale spanning 700mm, spaced at 240mm centres could support a concrete pressure of 1558.96 kNm^2 in Shear for strength limit state

Deflection for Class 1 finish

Maximum deflection = L/360 (AS3610.1, Table 3.3.2)

L/360 = 700mm/360 = 1.94mm

UDL up to Max Deflection:

$$w = \frac{\Delta_{max}\ (EI)}{0.0069\ L^4}$$

$$w = \frac{(1.94mm)(200000MPa)(2.54\times10^6 mm^4)}{0.0069\ (700)^4}$$

w = 594.87 kNm^2

As each wale supports a 240mm strip

Equivalent UDL = 594.87kNm / 0.24m = 2478.64 kNm^2

A wale spanning 700mm, spaced at 240mm centres could support a concrete pressure of 2478.64 kNm^2 in deflection to produce a Class 1 concrete finish

Deflection for Class 2 finish

Maximum deflection = L/270 (AS3610.1, Table 3.3.2)

L/270 = 700mm/270 = 2.6mm

UDL up to Max Deflection:

$$\mathrm{w} = \frac{\Delta_{\max}\,(\mathrm{EI})}{0.0069\ \mathrm{L}^4}$$

$$\mathrm{w} = \frac{(2.6mm)(200000MPa)(2.54\times10^6 mm^4)}{0.0069\ (700)^4}$$

w = 767.25 kNm^2

As each wale supports a 240mm strip

Equivalent UDL = 767.25kNm / 0.24m = 3321.88 kNm^2

A wale spanning 700mm, spaced at 240mm centres could support a concrete pressure of 2478.64 kNm^2 in deflection to produce a Class 2 concrete finish

Calculations for Vertical Studs (100 x 50 x 4 RHS)

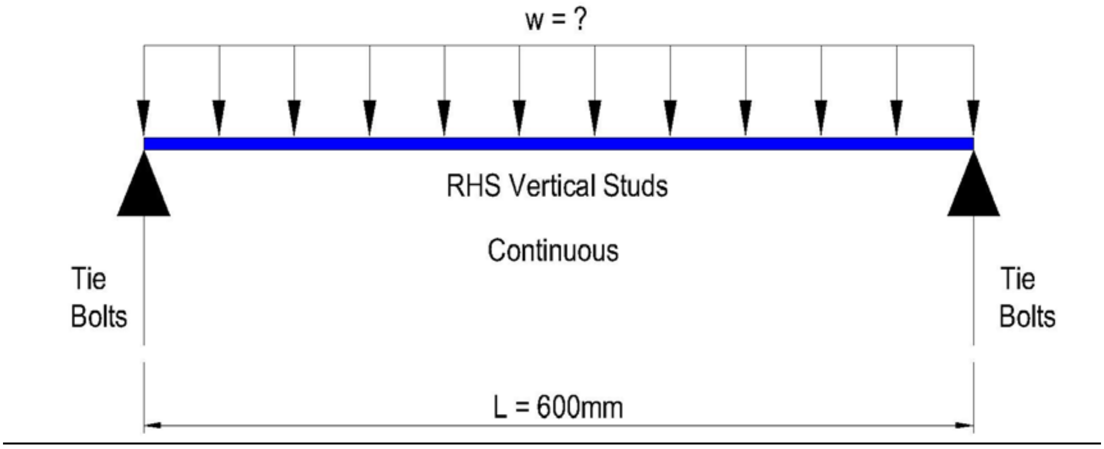

Figure 4-8 Line Load Diagram on RHS Vertical Studs

Span L = 600mm (at the critical bottom of the wall form)

Each stud supports an 850mm strip

Bending Moment

Bending capacity of RHS Vertical Studs:

ϕM_{sx} = 2 x 13.5 kNm = 27 kNm (2 RHS members per stud)

Maximum segment length for full lateral restraint, FLR = 1.68 m

Therefore, beam has full lateral restraint, member capacity = section capacity (ϕM_{sx})

Bending Capacity of RHS Horizontal Waling = 27 kNm

UDL up to Max Bending Moment:

$$w = \frac{M_{max}}{0.1\ L^2}$$

$w = \frac{27}{0.1\ (0.6)^2}$ = 750 kNm^2

Equivalent UDL = 750 kNm / 0.85m = 882.35 kNm^2

A stud spanning 600mm, spaced at 850mm centres could support a concrete pressure of 882.35 kNm^2 in Bending for strength limit state

Shear Force

Shear capacity of RHS Horizontal Waling:

ϕV_v = 2 x 170 kN = 340 kN (2 RHS members per stud)

UDL up to Max Shear Force:

$$w = \frac{V_{max}}{0.6\ L^2}$$

$$w = \frac{340}{0.6\ (0.6)^2}$$

w = 1574.07 kNm^2

Equivalent UDL = 1574.07 kNm^2 / 0.85m = 1851.85 kNm^2

A stud spanning 600mm, spaced at 850mm centres could support a concrete pressure of 1851.85 kNm^2 in Shear for strength limit state

Deflection for Class 1 finish

Maximum deflection = L/360 (AS3610.1, Table 3.3.2)

L/360 = 600mm/360 = 1.67mm

I = 2 x (3.74 x 10^6) = 7.48 x 10^6 mm^4 (2 RHS members per stud)

UDL up to Max Deflection:

$$w = \frac{\Delta_{max}\ (EI)}{0.0069\ L^4}$$

$$w = \frac{(1.67mm)(200000MPa)(7.48\times10^6 mm^4)}{0.0069\ (600)^4}$$

w = 2793.79 kNm^2

As each stud supports an 850mm strip

Equivalent UDL = 2793.79kNm^2 / 0.85m = 3286.81 kNm^2

A stud spanning 600mm, spaced at 850mm centres could support a concrete pressure of 3286.81 kNm^2 in deflection to produce a class 1 concrete finish

Deflection for Class 2 finish

Maximum deflection = L/270 (AS3610.1, Table 3.3.2)

L/270 = 600mm/270 = 2.22mm

UDL up to Max Deflection:

$$\mathrm{w} = \frac{\Delta_{\max}\ (\mathrm{EI})}{0.0069\ \mathrm{L}^4}$$

$$\mathrm{w} = \frac{(2.22mm)(200000MPa)(7.48\times10^6 mm^4)}{0.0069\ (600)^4}$$

w = 3713.90 kNm^2

As each stud supports an 850mm strip

Equivalent UDL = 3713.90kNm^2 / 0.85m = 4369.3 kNm^2

A stud spanning 600mm, spaced at 850mm centres could support a concrete pressure of 4369.3 kNm^2 in deflection to produce a Class 1 concrete finish

From the limit state analysis calculations, it can be concluded that the plywood sheathing is the component in the structure with the lowest allowable working load and thus the limiting factor for the structure. To maintain a class 1 concrete finish with deflection of the plywood sheathing form face limited to span/360 the maximum un-factored permissible concrete pressure for the wall formwork system is 282.21 kNm^2. To maintain a class 2 concrete finish with deflection of the plywood sheathing form face limited to span/270 the maximum un-factored permissible concrete pressure for the wall formwork system is 372.73 kNm^2.

4.4 FINITE ELEMENT ANALYSIS RESULTS

The theoretical capacities calculated in the limit state analysis for the RHS conventional wall form arrangement of a 280 kNm^2 un-factored hydrostatic pressure envelope for a class 1 concrete finish was verified using 3D Finite Element Analysis.

The 280 kNm^2 concrete pressure envelope was applied to the RHS wall form assembly by splitting the face of the wall form into 8 500mm horizontal bands. A different uniform pressure distribution was applied to each of these 8 horizontal bands with pressure increasing moving towards the bottom of the wall form. Figure 4-9 shows these pressure distributions.

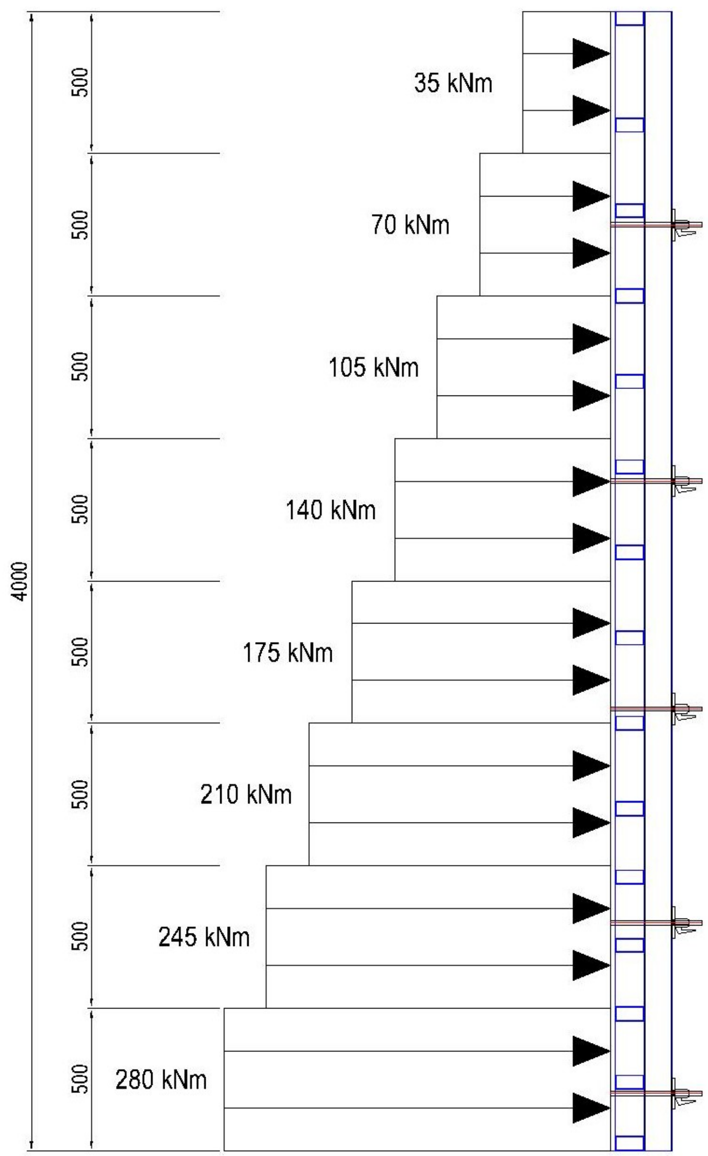

Figure 4-9 280 kNm Hydrostatic Pressure Envelope used in FEA

Figure 4-10 & 4-11 shows the Principal stress contour; it indicates maximum stress of 743.514 MPa which occurs in the RHS around the 3rd form tie up from the bottom of the wall form.

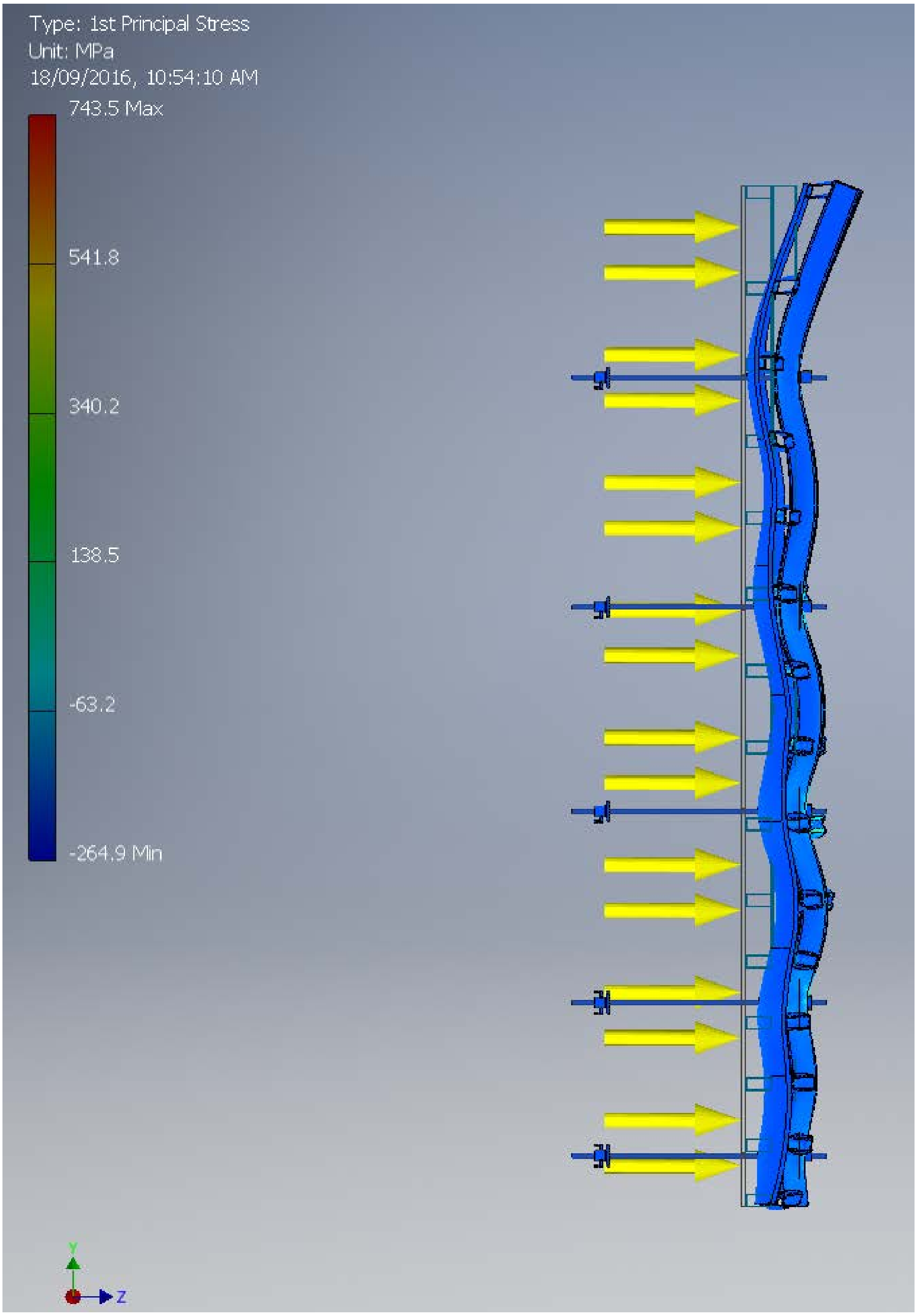

Figure 4-10 RHS Wall Form Principal Stress Contour from FEA

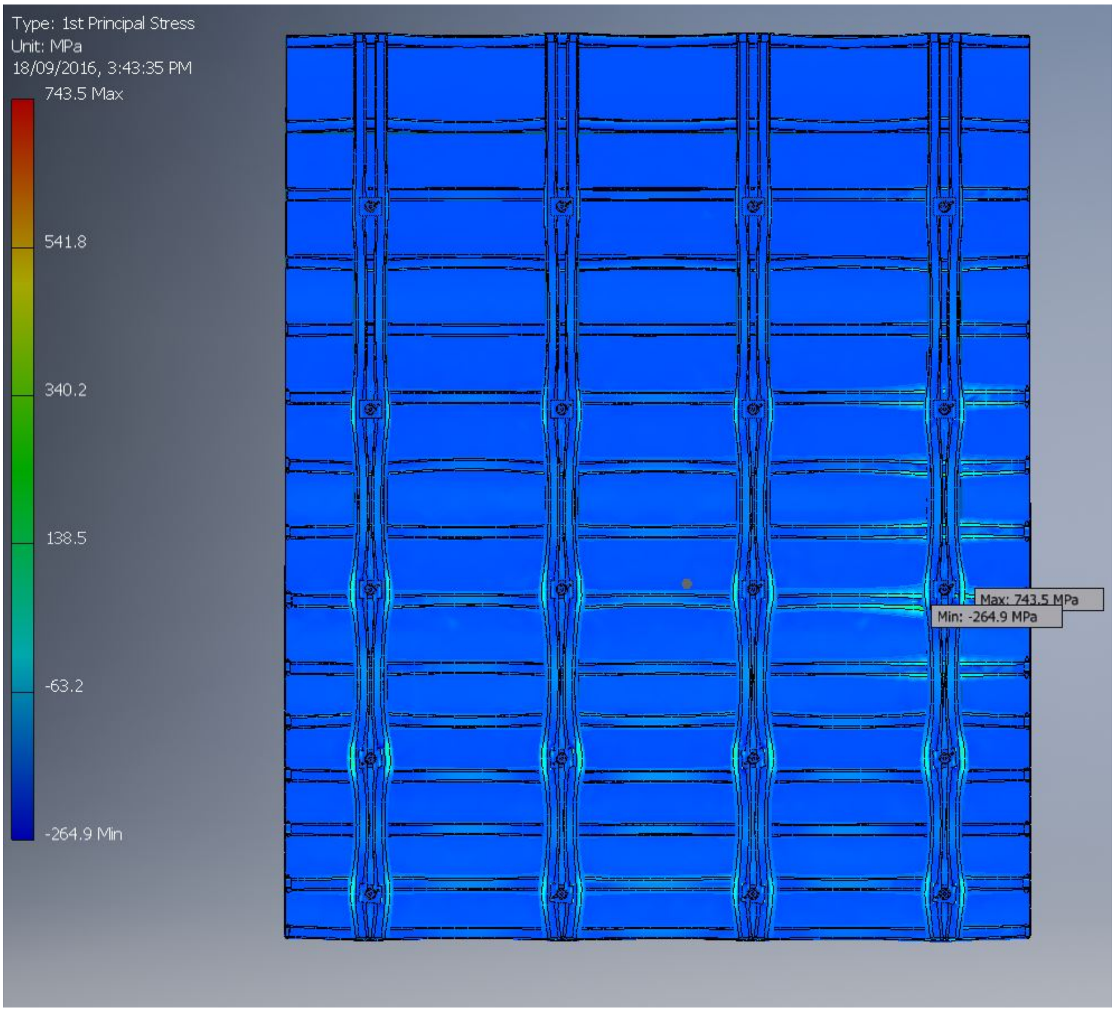

Figure 4-11 RHS Wall Form Principal Stress Contour Rear Elevation

Figure 4-12 indicates the displacement in the RHS wall form assembly as a result of the 280kNm^2 hydrostatic pressure envelope. A maximum displacement of 0.7375mm occurs at the top of the wall form and is indicated in red. The finite element analysis results confirmed the theoretical calculations that the delections caused by a 280kNm^2 hydrostatic pressure envelope would be small enough to maintain a class 1 concrete finish with deflection of the plywood sheathing form face limited to less than span divided by 360.

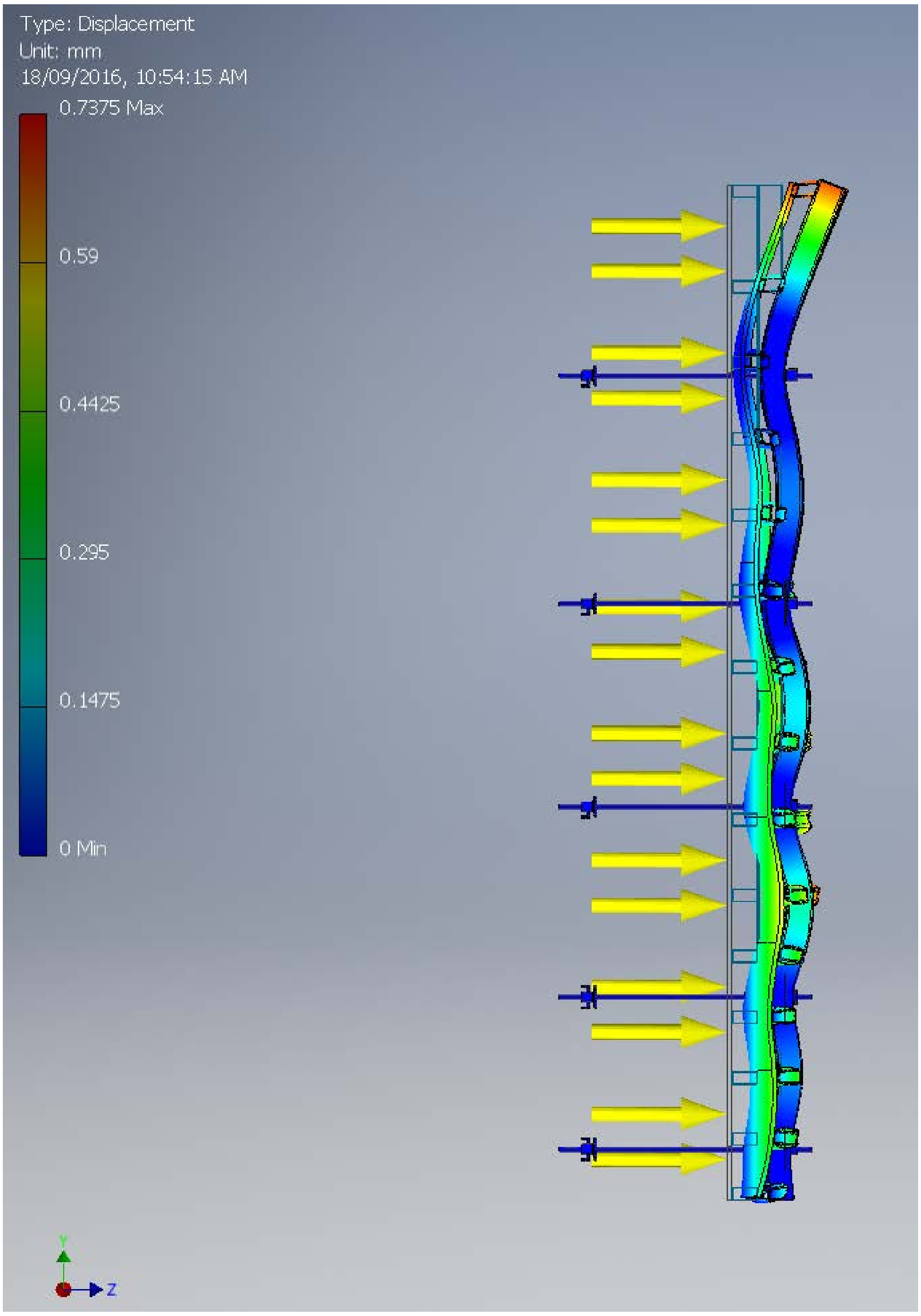

Figure 4-12 RHS Wall Form Displacements Caused by 280kNm Hydrostatic Pressure Envelope

4.5 COMPARATIVE ANALYSIS SUMMARY

The concrete pressure data obtained from the project case study was used to evaluate the adequacy of the 4 formwork varieties identified to be used in the high-rise building industry. As concrete pour heights vary from project to project, concrete pressures within formwork also differ. The maximum permissible concrete pressure for the 3 manufacturer designed formwork systems supplied by Truform, Peri and Ishebeck was sourced from their product design guides. The un-factored theoretical capacity calculated in the limit state analysis for the RHS conventional wall form arrangement was used to assess its suitability. The concrete pressure data from the project case study was then used to assess whether these panels are adequate for use across high-rise construction in Australia.

Table 4-3 Maximum Permissible Concrete Pressure for Wall Formwork Systems

Wall Formwork System	Maximum Permissible Concrete Pressure (kNm^2)
Conventional Steel RHS Wall Forms	280 (un-factored)
Conventional Timber LVL Wall Forms	93.6
Peri Modular Panel Formwork	80
Ischebeck Titan Aluminium Panel Formwork	88

Conventional steel frame Rectangular Hollow Section (RHS) wall forms have become a common building tool in Australian high-rise construction. The frame work of steel RHS conventional wall forms are based on timber design guides with steel RHS members substituted in instead of timber because they are stronger, more durable and have a longer life. As well as adopting the same frame work design and member spacing the steel forms also adopt steel member sizes similar to their timber counterpart, 95mm x 47mm timber LVL's are replaced by 100mm x 50mm steel RHS. At present there is no published literature or design information pertaining to this formwork system as it is an adaptation of another design. The analysis carried out in previous chapters of this research paper deemed the maximum un-factored permissible concrete pressure for this system to be 280 kNm^2. The maximum fresh concrete pressure recorded across the 77 sites of the project case study carried out as part of this research paper found the highest fresh concrete pressure distribution against wall formwork to be 104.4 kNm^2. Therefore, conventional steel RHS wall forms were suitable to be used across all the high-rise construction sites surveyed.

Conventional timber LVL (Laminated Veneer Lumber) wall forms are based on design guides provided by timber manufactures such as Carter Holt Harvey Wood Products Australia. Conventional timber LVL wall forms consists of plywood sheathing, with timber members placed as studs and wales on the back of the formwork connected with bolts and screws to form a frame. Carter Holt Harvey Wood Products Australia specify the use of 95mm x 47mm LVL's in their design guides for their two different vertical wall form assemblies (see Figures 2.9 & 2.10). Carter Holt Harvey Wood Products Australia specify that the maximum permissible concrete pressure for their LVL wall form system to be 93.6 kNm^2. This is well above the mean concrete pressure of 77.77 kNm^2 recorded in the project case study and means that Conventional timber LVL wall forms would have been suitable to resist the bursting pressure of wet concrete in 75 of the 77 sites surveyed in the study.

The modular panel formwork system designed and supplied by Peri are plywood panels set in a steel frame. Specialised patented hardware is a major component of the Peri panel system, it is aimed at simplifying and speeding up erection of the wall formwork (Peri, 2016). Panels can be used and reused as part of a large section and another time as individual units and there is less need for skilled labour since almost all cutting, trimming, and fitting is eliminated. Peri specify that the maximum permissible concrete pressure for their modular panel wall form system to be 80 kNm^2. This is marginally above the mean concrete pressure of 77.77 kNm^2 recorded in the project case study. The Peri modular panel wall form system would have been suitable to resist the bursting pressure of wet concrete in 50 of the 77 sites surveyed in the project case study.

The Ischebeck Titan aluminium wall formwork system is a modular system which is comprised of plywood panels set in a aluminium frame (Ischebeck Titan, 2016). Because these wall forms are aluminium panels they have the advantage of being extremely light making them easier to handle and manoeuvre by both men and machinery. Like other modular manufacturer supplied systems patented components are incorporated so that the forms can be assembled for almost any size or shape. Ischebeck Titan specify that the maximum permissible concrete pressure for their modular panel wall form system to be 88 kNm^2. This is higher than the mean concrete pressure of 77.77 kNm^2 recorded in the project case study. The Ischebeck Titan aluminium panel wall formwork system would have been suitable to resist the bursting pressure of wet concrete in 58 of the 77 sites surveyed in the project case study.

5 Conclusions

The conclusions drawn from the obtained results and discussion, and the extent to which the primary objectives set out at the beginning of this research paper have been achieved are presented in this section.

Primary objective 1 was to research and evaluate the relevant Australian standards and regulations for vertical wall formwork as they apply to the Australian high-rise construction industry. This was achieved by a literature review. Australian standards and regulations were gathered and reviewed as well as other research reports that evaluate current legislation of the formwork industry. From this review it was concluded that although legislative development in formwork practice over the years has been carried out, it can be argued that it has not kept pace with innovation and practice within the industry. Due to the delay in the release of an update of Australian Standard AS3610 Formwork for Concrete (1995) covering formwork design and the issues stopping the release of the proposed Formwork Designers Handbook there is currently a gap in appropriate literature for formwork designers in the Australian formwork industry.

Primary objective 2 was to evaluate the wall formwork currently being used in the Australian multistorey construction, and was achieved over several stages. The first stage was to identify and quantify the types of wall formwork currently being used by carrying out a case study on 77 Australian high-rise construction sites. There were 4 different wall formwork systems identified, used by the 9 different formwork contractors to form the lift cores of the buildings in the study. The case study was also used in identifying the number of uses wall formwork was subjected to at each site, as well as the loads on wall formwork during the construction cycle. The second stage in achieving primary objective 2 was to develop a greater understanding of the lateral concrete pressures that occur against wall formwork and then use this to evaluate the structural capacity of the different types of wall formwork used in high-rise construction.

Conventional steel RHS wall forms were found to be the most popular wall formwork system in Australia multistorey construction as they were being used on 81% of the sites surveyed. At present there is no published literature or design information pertaining to this formwork system as it is an adaptation of another design, developed out of necessity due to the amount of re-uses the forms are subjected to on a high-rise building site. Because this style of formwork system has become a common building tool a thorough structural analysis was carried out as part of this research. From this analysis, a theoretical maximum concrete pressure capacity was attributed to the steel RHS conventional wall form system which will serve as a guide for formwork designers wishing to use this system in the future.

A key finding from this research was the lateral concrete pressure data obtained from the project case study. The concrete pressure data collected in this study will be useful in the design of future wall formwork systems to ensure that the design is suitable for the range of pressures the form will be subjected to when re-used across different projects in the multistorey formwork industry. The mean maximum concrete pressure across the 77 construction sites was 77.77 kNm^2, however this average pressure was increased significantly by the high concrete pressures that occur on office building projects because of their higher pour heights. Perhaps a better indicator for this data set is the median concrete pressure which was calculated as 73.20 kNm^2. The mode or most occurring concrete pressure across the sites surveyed was 69.60 kNm^2.

The concrete pressure data collected highlighted the vast range of pressures that wall formwork is subjected to in multi-storey formwork construction. The maximum hydrostatic pressure was found to be 104.40 kNm^2 and the minimum was 67.20 kNm^2 giving a wide range of 37.20 kNm^2. The concrete pressure data was used to evaluate the adequacy of the 4 wall formwork varieties that the project case study found formwork contractors are currently using. The research found not all wall formwork systems are suitable for blanket use with 3 out of the 4 varieties not suitable to be used on all 77 sites included in the study.

Whilst wall form systems require engineer design certification, this certification can be done once and used as evidence of design compliance. The design certification can be provided as part of the brochure prepared by the manufacturer of the system (Workplace Health and Safety Queensland, 2016), thus when formwork is re-used on future projects there is a danger that formwork will be inadequate for the concrete pressures encountered and failure may occur.

5.1 SCOPE FOR FURTHER STUDY

This research paper can be viewed as a preliminary study, aimed towards understanding and quantifying wall formwork use and its governing regulations within the Australian multi-storey construction industry. This study was limited by the fact that there was limited published literature or past research within this field or industry.

The following recommendations for further research are proposed based on the conclusions and limitations of this study:

- Validation of the project case study research by including a wider sample of building sites will increase the accuracy of the data collected.

- Australian standard AS3610 Formwork for Concrete (1995) and this research study rely on theoretical calculations to estimate design loads on wall formwork. An accurate estimation of the lateral concrete pressures wall formwork is subjected to during construction would be very useful to the industry. This could be done by measuring the actual loads on the formwork while it is being used onsite. This research could be presented to the Standards Development Committee for Formwork to be considered in future amendments of AS3610 Formwork for Concrete.

- Theoretical calculations were used to assess the structural capacities of wall formwork structures in this study. Real world physical testing of formwork components could be performed using specimens removed from formwork assemblies to attain more accurate capacities for the different formwork systems.

- The deterioration of wall formwork capacity through use & reuse could also be studied to assess the useful life cycle of the different formwork systems.

Reference List

ACI, 2005. *The Contractor's Guide to Qaulity Concrete Construction.* Michigan: American Concrete Institute.

Autodesk Inc, 2016. *Finite Element Analysis.* [Online]
Available at: http://www.autodesk.com/solutions/finite-element-analysis

Barnes, M. J. & Johnstone, D. W., 2004. *Fresh Concrete Lateral Pressure On Formwork,* s.l.: ASCE.

Boughton, G. N. & Crews, K. I., 2013. *TIMBER DESIGN HANDBOOK.* Sydney: Standards Australia.

Carter Holt Harvey Wood Products Australia, 2012. *Formwork Solutions Guide,* s.l.: Carter Holt Harvey Wood Products Australia.

Civil Engineering, 2016. *Temporary Structures Formwork.* [Online]
Available at: http://www.learncivilengineering.com/wp-content/themes/thesis/images/construction-engineering/Formwork.pdf

Civil Resources, 2010. *Formwork.* [Online]
Available at: http://civil-resources.blogspot.com.au/2010/06/formwork.html

Clear, C. A. & Harrison, T. A., 1985. *Concrete pressure on formwork,* London: Construction Industry Research and Information Association.

Concrete Institute of Australia, 2016. *Formwork Design Handbook.* [Online]
Available at: https://www.concreteinstitute.com.au/Technical-Groups/Formwork-Design-Handbook

Das, A., 2014. *Risk and Reliability Associated with Use and Reuse of Vertical Formwork,* Oregon : Oregon State University.

Gorenko, B. E., Tinyou, R. & Syam, A. A., 2012. *Steel Designers Handbook.* Sydney: UNSW Press.

Hallowell, M. & Gambatese, J., 2009. Activity based safety risk quantification for concrete formwork construction. *Journal of Construction Engineering Managment,* pp. 990-998.

Hibbeler, R. C., 2012. *Structural Analysis.* Singapore: Prentice Hall.

Hurd, M., 2005. *Formwork for Concrete, Seventh Edition.* Michigan: American Concrete Institute.

Ischebeck Titan, 2016. *NOEtop Panel System.* [Online]
Available at: http://www.ischebeck-titan.co.uk/fwbrochures/NOEtop%20Panels.pdf

Ling, Y. Y. & Leo, K., 2000. Reusing timber formwork: importance of workmens efficiency. *Building and Environment Vol 35,* pp. 135-143.

McAdam, P., 1991. *Plywood in Concrete Formwork,* s.l.: Plywood Association of Australia.

Nemati, K. M., 2007. *Introduction to Concrete Formwork,* Washington: University of Washington.

One Steel Australia Tube Mills PTY LTD, 2010. *Design Capacity Tables for Structural Steel Hollow Section,* Sunnybank QLD: One Steel Australia Tube Mills PTY LTD.

Peri, 2016. *PERI Wall Formwork.* [Online]
Available at: http://www.periaus.com.au/products/formwork/wall-formwork.html

Peurifoy, R. L. & Oberlender, G. D., 2011. *Formwork for Concrete Structures.* USA: McGraw Hill.

Rodin, S., 1952. *Pressures of concrete on formwork,* s.l.: Institute of Civil Engineers.

Safe Work Australia, 2014. *Guide to Formwork.* Canberra: Safe Work Australia.

SRIA, 2016. *EXPERTISE - High Rise construction.* [Online]
Available at: http://www.sria.com.au/highrise.html

Standards Australia, 1995. *AS3610 Formwork for concrete.* Sydney: Standards Australia.

Standards Australia, 1998. *AS4100 Steel structures.* Sydney: Standards Australia.

Standards Australia, 2002. *AS 1170.0 Structural design actions General principles.* Sydney: Standards Australia.

Standards Australia, 2009. *AS3600 Concrete Structures.* Sydney: Standards Australia.

Standards Australia, 2011. *AS1170.2 Structural design actions Part 2 Wind actions.* Sydney: Standards Australia.

Standards Australia, n.d. *AS1720.1 Timber Structures.* Sydney: Standards Australia.

Structx, 2016. *Structural Engineering Resources.* [Online]
Available at: http://www.structx.com/Beam_Formulas_036.html

Whyte, A. & Brandis, P., 2010. *Concrete Formwork Safety and Local Practice,* Perth: Curtin University.

Workplace Health and Safety Queensland, 2016. *Formwork Code of Practice.* Brisbane: Queensland Government.

Appendix A

Project Specification

For: Brad Carson

Title: Analysis of Wall Formwork used in the Australian Multi-storey Construction Industry

Major: Civil engineering

Supervisors: Dr Sourish Banerjee

Enrolment: ENG4111 – EXT S1 2016 & ENG4112 – EXT S2 2016

Project Aim: Conduct a comparative analysis of steel RHS and timber LVL wall formwork commonly used in the Australian Multi-storey Construction industry with the aim of providing suggestions to optimise the design of steel RHS wall formwork.

Programme: Issue A, 16th March 2016

1. Research and investigate types of wall formwork used in Australia and worldwide.
2. Research relevant Australian Standards and regulations for wall formwork.
3. Research and determine the lateral pressure imposed by the fresh concrete against the wall forms as well as other construction loads imposed in service.
4. Compare the properties of timber LVL (Laminated Veneer Lumber) and steel RHS (Rectangular Hollow Section).
5. Conduct a comparative structural analysis using steel and timber capacity tables, and theoretical calculations.
6. Model both steel and timber wall forms and conduct Finite Element Analysis (Strand 7, AutoCAD Inventor) in 3D.
7. Conduct a comparative cost analysis including fabrication cost of the different wall forms.
8. Make recommendation on refinement to the steel RHS wall formwork design.

If time and resources permit:

9. Research and Compare the effects weathering has on timber LVL and steel RHS.

Appendix B

Case Study Data

Project	Location	Building Type	Floors	Formwork Contractor	Type of Vertical Formwork	Pour Height	Max Pressure	1.5 Max Pressure
Air on Broadbeach	Broadbeach, Gold Coast	Apartment	37	Heinrich Constructions	Conventional LVL Wall Forms	3.2	76.8	115.2
Brisbane Square	Brisbane CBD	Office	38	Heinrich Constructions	Conventional RHS Wall Forms	3.7	88.8	133.2
Stamford	Brisbane CBD	Hotel	22	Heinrich Constructions	Conventional RHS Wall Forms	3	72	108
Festival Towers	Brisbane CBD	Hotel	41	Heinrich Constructions	Conventional LVL Wall Forms	2.8	67.2	100.8
Artique Tower	Surfers Paradise, Gold Coast	Apartment	30	Pryme PTY LTD	Conventional RHS Wall Forms	2.85	68.4	102.6
Southport Central	Southport, Gold Coast	Apartment	47	Pryme PTY LTD	Conventional RHS Wall Forms	2.95	70.8	106.2
Ultra	Broadbeach, Gold Coast	Apartment	30	Heinrich Constructions	Conventional RHS Wall Forms	2.9	69.6	104.4
Waves	Broadbeach, Gold Coast	Apartment	34	Heinrich Constructions	Conventional RHS Wall Forms	2.97	71.28	106.92

Project	Location	Building Type	Floors	Formwork Contractor	Type of Vertical Formwork	Pour Height	Max Pressure	1.5 Max Pressure
Reflections Tower 2	Coolangatta, Gold Coast	Apartment	20	Bosform PTY LTD	Conventional LVL Wall Forms	2.85	68.4	102.6
Mantra Sierra Grand	Broadbeach, Gold Coast	Hotel	31	Pryme PTY LTD	Conventional RHS Wall Forms	3	72	108
Evolution	Brisbane CBD	Hotel	36	Heinrich Constructions	Conventional RHS Wall Forms	2.8	67.2	100.8
Meriton Mosaic	Pitt St, Sydney	Hotel	35	Betaform PTY LTD	Conventional RHS Wall Forms	3	72	108
333 Anne St	Brisbane CBD	Office	27	Southgate Formwork	Ishebeck Modular Panel Forms	3.85	92.4	138.6
Northbridge	Brisbane CBD	Office	38	Heinrich Constructions	Conventional RHS Wall Forms	3.8	91.2	136.8
275 George St	Brisbane CBD	Office	32	Southgate Formwork	Ishebeck Modular Panel Forms	3.8	91.2	136.8
Grande Pacific	Southport, Gold Coast	Apartment	25	Ashford Formwork	Conventional RHS Wall Forms	3.25	78	117
Central Plaza 3	Brisbane CBD	Office	14	Heinrich Constructions	Conventional RHS Wall Forms	3.55	85.2	127.8

Project	Location	Building Type	Floors	Formwork Contractor	Type of Vertical Formwork	Pour Height	Max Pressure	1.5 Max Pressure
Elysse Residences	Kirra, Gold Coast	Apartment	12	Heinrich Constructions	Conventional RHS Wall Forms	2.85	68.4	102.6
Oceans	Broadbeach, Gold Coast	Apartment	20	Bosform PTY LTD	Conventional RHS Wall Forms	2.9	69.6	104.4
Ambience	Burleigh Heads, Gold Coast	Apartment	15	Pryme PTY LTD	Conventional RHS Wall Forms	2.9	69.6	104.4
Matisse tower	Brisbane CBD	Office	24	Southgate Formwork	Ishebeck Modular Panel Forms	3.5	84	126
Bundall Corporate Center	Bundall, Gold Coast	Office	15	Heinrich Constructions	Conventional RHS Wall Forms	3.55	85.2	127.8
The Rocket	Robina, Gold Coast	Office	15	Heinrich Constructions	Conventional RHS Wall Forms	3.6	86.4	129.6
111 Eagle St	Brisbane CBD	Office	54	Heinrich Constructions	Conventional RHS Wall Forms	3.75	90	135
Hilton East Tower	Surfers Paradise, Gold Coast	Hotel	57	Heinrich Constructions	Conventional RHS Wall Forms	2.95	70.8	106.2
Hilton West Tower	Surfers Paradise, Gold Coast	Hotel	37	Heinrich Constructions	Conventional RHS Wall Forms	2.92	70.08	105.12

Project	Location	Building Type	Floors	Formwork Contractor	Type of Vertical Formwork	Pour Height	Max Pressure	1.5 Max Pressure
40 Eden Ave	Coolangatta, Gold Coast	Apartment	12	Dolcon PTY LTD	Conventional LVL Wall Forms	2.9	69.6	104.4
225 Miller St	North Sydney	Apartment	25	Betaform PTY LTD	Conventional RHS Wall Forms	2.9	69.6	104.4
Victoria Towers	Southport, Gold Coast	Apartment	37	Heinrich Constructions	Conventional RHS Wall Forms	3	72	108
King George Central	Brisbane CBD	Office	27	Bosform PTY LTD	Conventional RHS Wall Forms	3.75	90	135
3 Hasler Rd	Osbourne Park, Perth	Office	15	G & N Constructions	Peri Modular Panel Forms	3.8	91.2	136.8
Byres St	Newstead, Brisbane	Apartment	17	Bosform PTY LTD	Conventional RHS Wall Forms	2.9	69.6	104.4
127 Charlotte St	Brisbane CBD	Apartment	29	Heinrich Constructions	Conventional RHS Wall Forms	2.9	69.6	104.4
Eclipse	Broadbeach, Gold Coast	Apartment	21	Heinrich Constructions	Conventional RHS Wall Forms	3.1	74.4	111.6
Victoria Park Building A	Zetland, Sydney	Apartment	22	Betaform PTY LTD	Conventional RHS Wall Forms	3	72	108

Project	Location	Building Type	Floors	Formwork Contractor	Type of Vertical Formwork	Pour Height	Max Pressure	1.5 Max Pressure
Victoria Park Building C	Zetland, Sydney	Apartment	20	Betaform PTY LTD	Conventional RHS Wall Forms	3	72	108
8 Chifley Square	Sydney CBD	Office	22	Trazmet PTY LTD	Conventional RHS Wall Forms	3.85	92.4	138.6
G40	Southport, Gold Coast	Office	12	Heinrich Constructions	Conventional RHS Wall Forms	4.35	104.4	156.6
7 Railway St	Chatswood, Sydney	Apartment	44	Trazmet PTY LTD	Conventional RHS Wall Forms	3	72	108
825 Ann St	Fortitude Valley, Brisbane	Office	12	Heinrich Constructions	Conventional RHS Wall Forms	3.65	87.6	131.4
Felicity Hotel	Sydney CBD	Hotel	33	Heinrich Constructions	Conventional RHS Wall Forms	3	72	108
Queens Riverside	East Perth	Apartment	25	G & N Constructions	Peri Modular Panel Forms	3.1	74.4	111.6
Mosaic Apartments	Fortitude Valley, Brisbane	Apartment	17	Heinrich Constructions	Conventional RHS Wall Forms	2.9	69.6	104.4
1 Central Park	Sydney	Apartment	34	Trazmet PTY LTD	Conventional RHS Wall Forms	3.15	75.6	113.4

Project	Location	Building Type	Floors	Formwork Contractor	Type of Vertical Formwork	Pour Height	Max Pressure	1.5 Max Pressure
168 Walters Drive	Osbourne Park, Perth	Office	15	G & N Constructions	Peri Modular Panel Forms	3.67	88.08	132.12
100 Skyring Terrace	Newstead, Brisbane	Office	12	Heinrich Constructions	Conventional RHS Wall Forms	3.8	91.2	136.8
Cloisters on Hay	Perth	Office	11	G & N Constructions	Peri Modular Panel Forms	3.8	91.2	136.8
One William St	Brisbane CBD	Office	44	Heinrich Constructions	Conventional RHS Wall Forms	3.85	92.4	138.6
Kings Square 1	Perth	Office	19	G & N Constructions	Peri Modular Panel Forms	3.85	92.4	138.6
111 Mary St	Brisbane CBD	Office	10	Heinrich Constructions	Conventional RHS Wall Forms	3.85	92.4	138.6
Brooklyn on Brookes	Fortitude Valley, Brisbane	Apartment	15	Heinrich Constructions	Conventional RHS Wall Forms	3	72	108
Crown Towers	Perth	Hotel	38	G & N Constructions	Peri Modular Panel Forms	2.9	69.6	104.4
The Milton	Milton, Brisbane	Apartment	30	Heinrich Constructions	Conventional RHS Wall Forms	2.91	69.84	104.76

Project	Location	Building Type	Floors	Formwork Contractor	Type of Vertical Formwork	Pour Height	Max Pressure	1.5 Max Pressure
Remora Rd	Hamilton, Brisbane	Apartment	17	Bosform PTY LTD	Conventional RHS Wall Forms	3.1	74.4	111.6
RNA Stage 1	Fortitude Valley, Brisbane	Apartment	15	Bosform PTY LTD	Conventional RHS Wall Forms	2.9	69.6	104.4
Pinnacle Apartments	Hamilton, Brisbane	Apartment	15	Heinrich Constructions	Conventional RHS Wall Forms	3	72	108
Synergy	Broadbeach, Gold Coast	Apartment	26	Heinrich Constructions	Conventional RHS Wall Forms	2.9	69.6	104.4
Rhapsody	Surfers Paradise, Gold Coast	Apartment	42	Heinrich Constructions	Conventional RHS Wall Forms	2.85	68.4	102.6
RNA K1	Fortitude Valley, Brisbane	Office	10	Bosform PTY LTD	Conventional RHS Wall Forms	3.75	90	135
Westmark Milton	Milton, Brisbane	Apartment	22	Heinrich Constructions	Conventional RHS Wall Forms	3	72	108
Abian Tower	Brisbane	Apartment	41	Heinrich Constructions	Conventional RHS Wall Forms	3.2	76.8	115.2
Newstead Towers	Newstead, Brisbane	Apartment	14	Heinrich Constructions	Conventional RHS Wall Forms	3.05	73.2	109.8

Project	Location	Building Type	Floors	Formwork Contractor	Type of Vertical Formwork	Pour Height	Max Pressure	1.5 Max Pressure
480 Hay St Perth	Perth	Office	22	G & N Constructions	Peri Modular Panel Forms	3.85	92.4	138.6
300 George St Hotel	Brisbane CBD	Hotel	32	Heinrich Constructions	Conventional RHS Wall Forms	3.05	73.2	109.8
300 George St Residential	Brisbane CBD	Apartment	82	Heinrich Constructions	Conventional RHS Wall Forms	3	72	108
300 George St Office	Brisbane CBD	Office	39	Heinrich Constructions	Conventional RHS Wall Forms	3.92	94.08	141.12
The Springs	Perth	Office	15	G & N Constructions	Peri Modular Panel Forms	3.7	88.8	133.2
Art House	Brisbane	Apartment	30	Heinrich Constructions	Conventional RHS Wall Forms	3.05	73.2	109.8
The Yards	Fortitude Valley, Brisbane	Apartment	18	Heinrich Constructions	Conventional RHS Wall Forms	2.9	69.6	104.4
Spire	Brisbane	Apartment	39	Heinrich Constructions	Conventional RHS Wall Forms	2.9	69.6	104.4
Southpoint	Southbank, Brisbane	Apartment	15	Heinrich Constructions	Conventional RHS Wall Forms	3.08	73.92	110.88

Project	Location	Building Type	Floors	Formwork Contractor	Type of Vertical Formwork	Pour Height	Max Pressure	1.5 Max Pressure
Jupiters Suites Hotel	Broadbeach, Gold Coast	Hotel	22	Heinrich Constructions	Conventional RHS Wall Forms	3.5	84	126
Coorparoo Square	Coorparoo Brisbane	Apartment	19	Heinrich Constructions	Conventional RHS Wall Forms	2.9	69.6	104.4
Jewel Tower 1	Surfers Paradise, Gold Coast	Apartment	42	Heinrich Constructions	Conventional RHS Wall Forms	3	72	108
Jewel Tower 2	Surfers Paradise, Gold Coast	Apartment	48	Heinrich Constructions	Conventional RHS Wall Forms	3.4	81.6	122.4
Jewel Tower 3	Surfers Paradise, Gold Coast	Apartment	35	Heinrich Constructions	Conventional RHS Wall Forms	3.4	81.6	122.4
Casino Towers	South Brisbane	Apartment	30	Heinrich Constructions	Conventional RHS Wall Forms	3.05	73.2	109.8