UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

A COMPARATIVE STUDY OF THE EFFICIENCIES OF VERTICAL BRACING PRACTICES

by

Shawn Wayne Valintino Saunders

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Supervisor:

Professor Alex Elvin

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CANDIDATES DECLARATION

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master in Science in Engineering at the University of Witwatersrand, Johannesburg. It has not been submitted before any degree or examination to any other University.

Signature: ……………………………

Date: 31st day of March 2023

ABSTRACT

The efficiencies of cross sections and configurations applied to vertical bracing are investigated by evaluating reference configurations (RCs), composed of cross-braced circular hollow section (CHS) members, against comparative configurations (CCs), consisting of cross-braced Angle members, and single-CHS members. The metrics used to evaluate efficiencies were mass, raw materials costs, and fabrication and erection costs.

CCs were found to be more efficient than RCs for most analysed cases, metric and configuration dependent. The following results were found:

i. Mass metric
   a. Crossed-Angle more efficient in 79% of analysed cases.
   b. Single CHS more efficient in 87% of analysed cases.
ii. Raw materials costs metric
   a. Crossed-Angle more efficient in 92% of analysed cases
   b. Single CHS more efficient in 88% of analysed cases
iii. Fabrication and erection costs metric
   a. Crossed-Angle more efficient in 90.4% of analysed cases
   b. Single CHS more efficient in 88.5% of analysed cases

Inversions of the efficiency parameter findings, with RCs more efficient than CCs, were observed when:

i. RC CHS member slenderness ratios were less than 80-90.
ii. CC design loads were greater than 225 kN, 1200 kN and 1500 kN for mass, raw materials and total cost efficiency metrics, respectively.

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v. The interviewees who granted me their time, experience, and data with which to conduct the analysis.

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LIST OF SYMBOLS

A	area
A_b	bolt cross sectional area
A_g	gross cross-sectional area
A_{ne}	effective net area
A'_{ne}	effective net area accounting for shear lag
C_r	compressive resistance
$C_{r,\ X\text{-}CHS}$	compressive resistance of crossed CHS member
$C_{r,\ S\text{-}CHS}$	compressive resistance of single CHS member
E	modulus of elasticity
F_H	applied lateral horizontal load
f_u	material ultimate tensile strength
f_y	material yield strength
K	effective length factor
L	member length
∟	referring to Angle section
m	meter
mm	millimetre
N_c	compression axial force
N_t	tension axial force
n	exponent applied in flexural buckling resistance calculation
r	radius of gyration
SR	slenderness ratio
$SR_{X\text{-}CHS}$	crossed CHS member slenderness ratio

T_r	tensile resistance
$T_{r,\ X\text{-}L}$	tensile resistance of crossed angle member
X	shorthand to indicate cross, or crossed, configuration
α_c	compressive load share factor
α_t	tensile load share factor
θ_{br}	bracing inclination angle
λ	non-dimensional slenderness ratio
ϕ	resistance factor for structural steel ($\phi = 0.9$)
ϕ_b	resistance factor for bolts

NOMENCLATURE

angle section

hot rolled structural section consisting of two legs perpendicular to each other

bay

describes the distance, or space, between consecutive columns

beam

a horizontal structural member

brace

a diagonally inclined structural member

circular hollow section (CHS)

hot rolled tubular structural member

column

a vertical structural member

compartment

the space encompassed between consecutive beams

comparative configuration

vertical braced arrangement composed either of diagonally crossed angle sections, or single diagonal CHS struts, whose members are sized to support equivalent loading to the reference configuration from which comparative efficiency metrics are calculated costing model (CM I or CM II)

costing model derived from interview with listed fabricators to determine fabrication, erection and total costs

cross (“X- “) braced arrangement

vertical braced assembly with brace members diagonally arranged to cross at their midspans

edge distance

distance between bolt hole centre and edge of plate, or member

effective length

concept used to define the buckling capacity of a member based on its end restraint conditions

end plate

plate welded to the end of a structural member to serve as a fastening point between the frame and member

frame

assembly of flexural and axial members which create rigid structural support

direct stiffness method (DSM)

an automated numerical method used to solve for member forces and displacements in structures

lateral load

horizontal load applied to the side of structure to simulate a destabilising force load share model

an analytical model followed to design diagonally crossed vertical bracing where these members are assumed to share the share the applied lateral loads in some proportion between them

out-of-plane

specifically, out of the plane of, or perpendicular to, a two-dimensional frame arrangement

reference configuration

controlling vertical brace arrangement comprised of diagonally crossed CHS members

slenderness ratio

measure of the aspect ratio of a cross-section and defined as effective length divided by radius of gyration

strut

a diagonal member sized to resist compressive loading

tension only model

an analytical model followed to design diagonally crossed vertical brace members where these members are assumed capable of resisting applied lateral loads in tension and which buckle elastically under compressive load

1. INTRODUCTION

1.1. Background

Structural bracing acts as a means of providing a load path for lateral forces acting on a structure to the foundations, providing stability to the structure. Bracing is practically used to provide lateral support to columns, beams, and to prevent structural sway (Brown, et al., 2001).

Preventing sway counters second-order effects acting on a structure thereby reducing the load that columns and baseplates need to resist. Lateral support governs member slenderness, effective length, and controls the required cross section to resist design loads (Mahachi, 2004).

Figure 1-1 shows three braced frames, or bays, which are used to illustrate the progression of the analysed frame models in this research report. A vertically braced bay with three diagonally cross-braced compartments in the height is shown in Figure 1-1 (a). Figure 1-1 (a) further shows the frame height, frame width and the brace inclination angle (θ_{br}).

Figure 1-1 (b) includes a lateral horizontal load (F_H) applied at the top left corner of the frame. Brace member loading is indicated to exhibit the load path to the ground. Figure 1-1 (c) removes one of the diagonally crossed members and shows the resultant brace member forces and developed load path. Figure 1-1 (d) reverse the applied lateral load from Figure 1-1 (c) as well as the consequent member forces.

Tension (N_T) and compression (N_C) forces developed in the brace members due to the applied lateral load (F_H) are indicated in Figure 1-1 (b) - (d). Arrows pointing away from the nodes where members intersect denote tension and arrows point towards the intersecting nodes denote compression.

Figure 1-1 (b) is referred to as the shared-load model in this text. The shared-load model assumes that the applied lateral load is collectively resisted between all the cross-braced members. Half the brace members resist the applied horizontal load under compression while the other half resist the load in tension. The applied lateral load is then shared in a near equal ratio between compression and tension brace members.

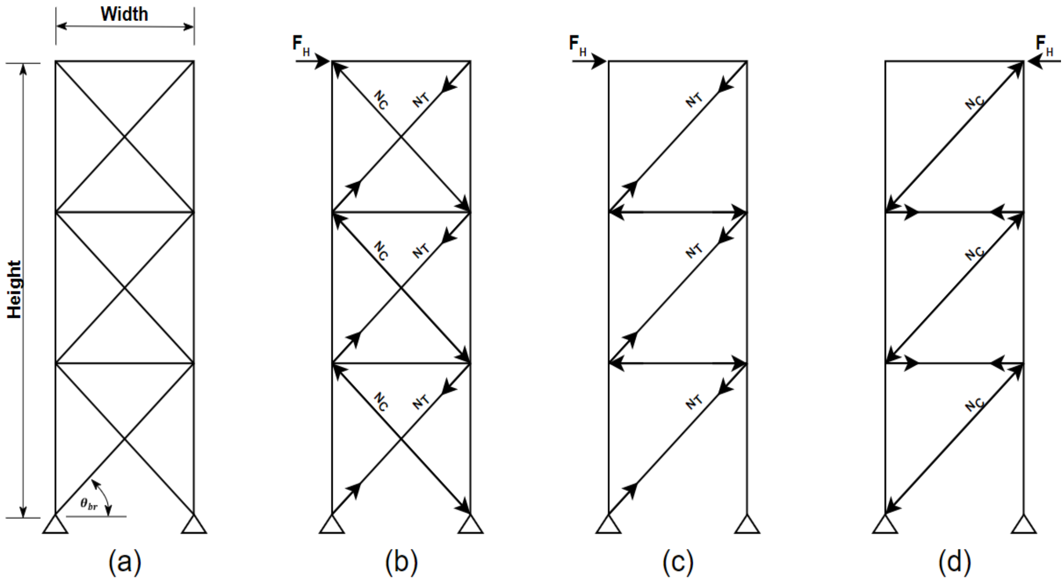


Figure 1-1 Vertical Bracing Arrangement Models

Figure 1-1 (c) removes one of the cross-braced members from Figure 1-1 (b). The applied lateral load F_H from left to right results in tension forces developing in the brace members. Beam members form a pivotal part of the load path in this model, transferring load in axial compression. If the lateral load F_H in Figure 1-1 (c) is reversed to act from right to left as in Figure 1-1 (d) the brace members experience compressive loading and beam members tensile loading.

Vertical cross-braced configurations have traditionally been designed according to the tensile model shown in Figure 1-1 (c) (Mahachi, 2004). Members were assumed to resist the lateral load in tension only. Member design proceeded accordingly. The single member approach simplified analysis prior to the rise advanced computing hardware and structural analysis software (NSC Technical, 2019). Members specified in this approach have traditionally been angle or flat bar sections with very low compressive capacities relative to symmetrical structural members such as hollow, I- or H- sections (Southern African Institute for Steel Construction, 2010).

The shared-load model is a contemporary approach to the design and specification vertical bracing. Both diagonally crossed members are modelled in the analysis as shown in Figure 1-1 (b). Modern computing technology has greatly expedited the analytical task in engineering. A consequence of this approach is that structural members with high compressive capacities, such as CHS members, are required to resist lateral loads in vertical cross-braced arrangements.

The design of traditional tensile members applied to vertical cross-braced arrangements is well documented in normative codes of practice (SABS, 2011). The design of CHS members in vertically cross-braced arrangements is not well researched or outlined in normative references (Kanyilmaz, 2017). CHS members cost more to procure and fabricate than angle members (Labuschagne, 2022).

The present research thus aims to investigate the efficiencies of various cross sections and vertically braced arrangements that result from the different models derived from Figure 1-1.

The various braced arrangement and cross section combinations investigated are referred to as reference and comparative configurations. Reference configurations correlate to the shared-load analysis model shown in Figure 1-1 (b). Comparative configurations correlate to:

i. A tension only analysis model described by Figure 1-1 (c).
ii. A single-member analysis model which considers both compression and tension member loads described conjointly by Figure 1-1 (c) and (d).

A cross-braced CHS arrangement is shown in Figure 1-2. Cross-braced CHS arrangements are referred to as reference configurations through this text. Reference configurations are the primary vertical braced arrangements considered in this study. Reference configurations are the basis from which subsequent comparative configurations are derived.

Figure 1-2 Image of a Typical Reference Configuration showing a Vertical Cross-Braced Arrangement using CHS Members

Reference configurations make use of a single continuous CHS member forming one leg of the cross-braced arrangement. The adjacent leg is formed by two shorter, discontinuous legs adjoining the continuous member through fixing to a welded fin plate.

Comparative configurations were sized to resist the same loading as the reference configuration for each investigated case. Comparative configurations were designed either:

i. As tension only arrangements specified with cross-braced angle sections, or
ii. With single-braced CHS members specified capable of resisting both tensile and compressive loading.

1.2. Scope of Research

Primarily, the present research report aims to evaluate the efficiency of reference vertical cross-braced configurations using CHS members compared to:

i. Vertical cross-braced configurations using Angle members designed as tension only members.
ii. Vertical braced configurations using single CHS members designed to resist both compression and tension loads.

Efficiency metrics were established for:

i. Reference cross-braced CHS configurations
ii. Comparative cross-braced Angle configurations
iii. Comparative single member braced CHS configurations

Metrics evaluated for efficiency comparisons were:

i. Configuration unit mass
ii. Raw materials cost
iii. Fabrication costs
iv. Erection costs.

Additional research objectives identified through the course of this work were:

i. To determine industry motivations for the specification of CHS members in vertical cross-braced arrangements.
ii. To determine the design philosophy behind the use of CHS members in vertical cross-braced arrangements.
iii. To evaluate the proportion of load-sharing between compressive and tensile members in cross-braced arrangements.
iv. To determine valid costing models for the fabrication and erection of vertical bracing against which efficiencies could be relatively compared.

1.3. Limitations

The following limitations were imposed on the study:

i. Configurations
    a. Reference configurations consisted of diagonally cross CHS vertical braced arrangements.
    b. First type comparative configurations consisted of diagonally crossed Angle vertical braced arrangements.
    c. Second type comparative configurations consisted of single CHS diagonal strut member in vertical braced arrangements.

ii. Member Cross Sections
    a. CHS
    b. Angle Sections
    c. Limited to commercially available cross sections.
iii. Efficiency metrics
    a. As described in Section 1.2
iv. Member design
    a. CHS compressive capacity based on out-of-plane flexural buckling resistance as per SANS 10162-2:2011 (SABS, 2011)
    b. Tensile capacity as per the Red Book (Southern African Institute for Steel Construction, 2010) and the Green Book (de Clercq, 2012)
v. CHS member connections
    a. Plates connections generally assumed to be fit for purpose.
    b. Assumed to be controlled by bolt group shear capacity where considered.
    c. Plate and connection capacities not studied in detail.
    d. Characterisation of connection as spring system considered beyond the scope of this study.
vi. Angle member connection capacities specified as per:
    a. The Red Book (Southern African Institute for Steel Construction, 2010), and
    b. The Green Book (de Clercq, 2012).

vii. Total of 52 cases analysed of which:

   a. 32 hypothetical cases were derived from the load share sensitivity analysis, and
   b. 20 cases were based off “Built-site”, or existing, configurations.

1.4. Research Outline

1.4.1. Introduction

An overview of the research outline and hypothesis are provided in this section. A detailed discussion of the research methodology continues in section 3. The research consisted of data collection, load share sensitivity analyses, cross section capacity evaluation for reference and comparative configurations, and numerical modelling to determine and compare efficiency metrics.

The research hypothesis is summarised as follows:

Vertical cross-braced CHS configurations are less economical than traditionally designed comparative arrangements.

1.4.2. Progression of Research

The progression of the research process is divided into five stages for descriptive purposes.

First, a literature survey was conducted. The literature survey sought to determine whether similar research had previously been performed and find background relating to member and component calculations.

Second, interviews were conducted to supplement the literature survey. The interviews sought to:

i. Determine the industry approach to reference configuration design and design philosophy.
ii. Identify appropriate costing models for reference and comparative configurations.
iii. Gather reference configuration built-site data.

Third, structural modelling and analyses were performed to determine the proportion of load-sharing between compressive and tensile members in reference configuration arrangements.

Fourth, reference configuration member capacities were evaluated, and equivalent comparative configuration members sizes were determined. Comparative configuration member sizes were derived from reference configuration member capacity for each case. The load-share factor derived from the sensitivity analysis was applied to determine the comparative configuration design loads from the reference configurations capacities.

Fifth, reference and comparative configuration unit masses, raw materials costs, fabrication and erection costs were determined, and comparisons drawn between efficiency metrics.

1.4.3. Progression of Chapters

The first chapter outlines a brief background on the traditional approach of tensile member design in vertical cross-braced arrangements. The contemporary approach is outlined where configuration cross sections are specified based on shared compressive and tensile load between members. The research scope, limitations, and overview are then discussed.

Chapter 2 elaborates on the research background in greater detail. Findings of from other research pertinent to this research report are further outlined and discussed.

Chapter 3 presents a detailed discussion of the research methodology outlining:

i. Interview methodology and sources
ii. Load share sensitivity analysis
iii. Braced frame analysis to specify and size members in reference and comparative configurations

Chapter 4 presents and discusses the results of:

i. Findings from interviews with engineers
ii. Load share factor sensitivity analysis
iii. Gathered site data
iv. Steel fabricator costing models
v. Specified members and masses for reference and comparative configurations
vi. Cost modelling analysis and evaluation of efficiency metrics

Chapter 5 summarises the findings and conclusions of this research paper and makes recommendations for future research.

References, bibliography, and a series of appendices providing supplementary information and analyses follow Chapter 5.

2. LITERATURE SURVEY

2.1. Introduction

Figure 2-1 shows the analysis model progression presented in this study. The shared-load approach is shown in Figure 2-1 (a). Figure 2-1 (b) describes the tensile model approach. Figure 2-1 (c) underscores the single member approach.

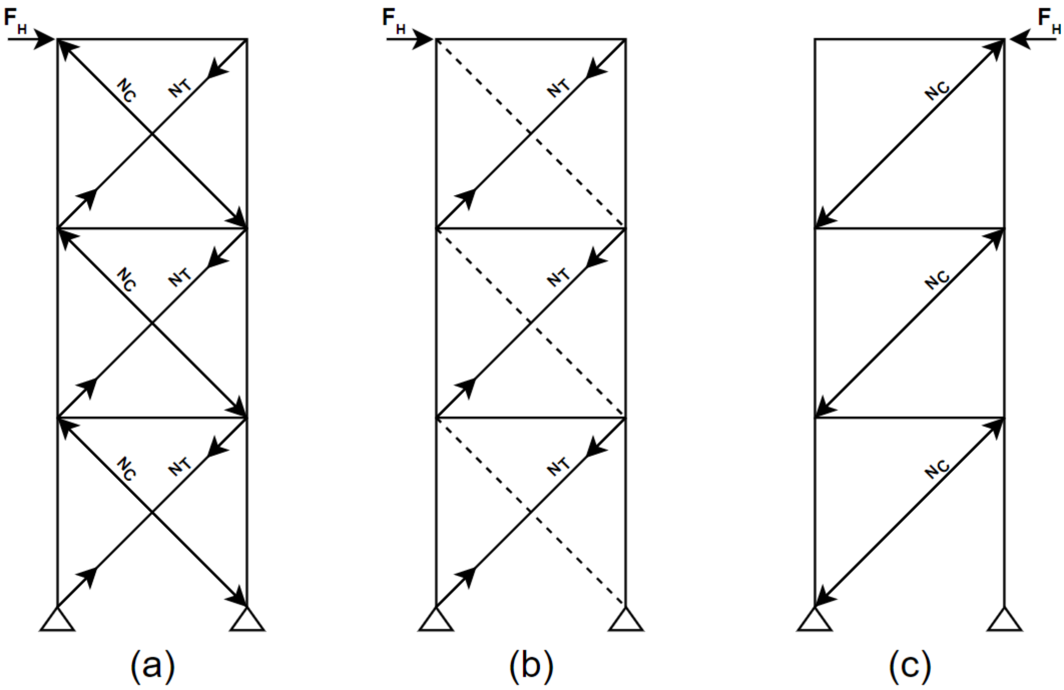


Figure 2-1 Cross- and Single- Member Vertical Brace Arrangements

A structure with cross-braced compartments, as in Figure 2-1 (a), is statically indeterminate. Solutions to statically indeterminate structures are not readily found from the equations of static equilibrium. More intricate approaches, such as the principle of virtual work, are needed to arrive at a solution (NSC Technical, 2019).

Removing one of the diagonally crossed members, as shown in the Figure 2-1 (c), results in a structure which is statically determinate. A statically determinate structure can be simply solved from the principles of static equilibrium (Mahachi, 2004).

Figure 2-1 (b) indicates the tension member analysis approach. The arrangement is analysed as if only a single member were present, as shown in Figure 2-1 (c). The compression member, displayed as the dashed line in Figure 2-1 (b), is assumed to have zero compressive resistance and typically removed from in the analysis model. The structure is built with both brace members as in Figure 2-1 (a).

Vertical cross-bracing is a common form of structural bracing (Brown, et al., 2001). Members in cross-braced arrangements have historically been designed as tension only members (Mahachi, 2004) applying the structural model from Figure 2-1 (b). Tensile members are assumed to have no compressive resistance and to buckle elastically under compressive loading (NSC Technical, 2019).

Tensile members are sized under the assumption that the solid line member in Figure 2-1 (b) acts alone to resist the full lateral load. The dashed line compressive member in the figure is assumed to buckle elastically (Mahachi, 2004). The member loads reverse when the applied lateral load reverses as shown in Figure 2-1 (c).

The tensile member approach was formulated and developed prior to contemporary computer hardware and structural analysis software. The approach provides a straightforward and conservative method to determine member forces in a vertical cross-braced arrangement (NSC Technical, 2019).

Angle, composite angle, and flat bar sections have traditionally been used as tensile members in vertical cross-braced arrangements as these typically have low compressive resistances compared to CHS or other symmetric or doubly symmetric structural members (Brown, et al., 2001).

The tensile resistances of Angle sections and their connections are well formulated and documented in extensively referenced resources in the South African construction industry such as:

i. The Green Book (de Clercq, 2012)
ii. The Red Book (Southern African Institute for Steel Construction, 2010)
iii. The South African Hot-Rolled steel design standard SANS10162-1 (SABS, 2011)

A single-member arrangement is an alternative form of vertical bracing to a cross-braced arrangement (Brown, et al., 2001). A single-member arrangement is configured as in Figure 2-1 (c). The member illustrated in the figure is the only member in the arrangement. Brace elements in single-member arrangements are designed to resist both tensile and compressive loading due to lateral load reversal. Single CHS members are well suited to resisting compression loads (Brown, et al., 2001).

Figure 2-1 (a) defines the shared-load model where the applied lateral loads are collectively resisted by both brace members. The lateral load is resisted proportionally in compression and tension between the two brace members in each compartment. Structural analysis modelling software will output a shared-load result between tensile and compressive members of a vertically cross-braced structure if provision is not made to allow for the elastic buckling of the compressive members in the arrangement (NSC Technical, 2019).

A consequence of the shared-load model is that compressive members need to be specified and sized in what have traditionally been tensile member cross-braced arrangements (NSC Technical, 2019). CHS members are commonly specified as these have good weight to slenderness ratio properties and high axial compressive capacities per unit weight (Southern African Institute for Steel Construction, 2010).

Design and characterisation methodologies of cross-braced CHS connections are not well formulated and codified within South African, or most other (Kanyilmaz, 2017), normative references. Materials and fabrication costs are also higher for CHS members compared to traditional cross sections applied in vertical cross-braced arrangements (Pereira, 2022) (Labuschagne, 2022).

2.2. Efficiencies of Brace Member and Configuration Types

Limited literature could be found directly discussing the comparative efficiencies of cross section type implemented in vertical cross-braced arrangements as observed in Figure 1-2 reference configurations. Literature relating to efficiencies of different vertical brace configuration arrangements was more readily available (Brown, et al., 2001) (Abbassi, 2009) (Razak, et al., 2018).

Relative resistance factors of 2.4 and 4.0 to in-plane shear are quoted when comparing single-member braced (as in Figure 2-1 (b)) and cross-braced (as in Figure 2-1 (a)) frames to unbraced frames (as in Figure 2-1 (a)) (Razak, et al., 2018). The authors further state that, as per the European seismic code, the compression diagonal in vertical cross-braced arrangements is not considered. Reportedly these assumptions are a result of optimising structural performance under high seismic loading but may lead to poor economy in low seismic conditions.

Another source (Abbassi, 2009) found, when using mass as the primary metric for efficiency, rectangular hollow sections used as bracing members produced the lightest braced steel frame structures for 5-20 story buildings. Abbassi (2009) further went on to recommend angles sections not be used for structures greater than 5 stories due to “a lack of capacity and stress”. The methodology used to arrive at the conclusion regarding angle members were not clear at the time of reading.

An experimental study into the performance of compression diagonals under moderate seismic conditions was conducted by Kanyilmaz (2017). Equal leg angle members were used in the study. Kanyilmaz (2017) references Gélinas, et al. (2012) who investigated the impact of hollow section midspan connections on global structural response. Buckling shapes of vertical cross braced arrangements as report by Gélinas, et al. (2012) are shown in Figure 2-2. Member effective length factor recommendations for in-plane and out-of-plane buckling as per Gélinas, et al. (2012) are subsequently reported.

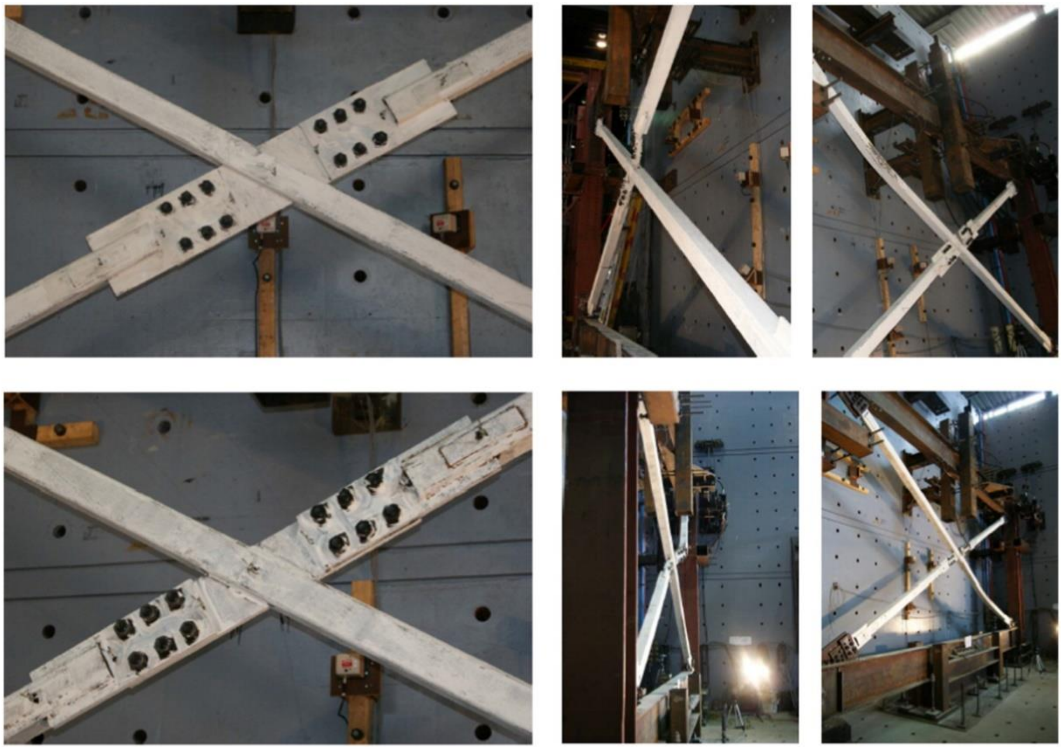


Figure 2-2 Buckled Shapes of Vertical Cross-Braced Arrangements (Gélinas, et al., 2012)

Findings and conclusions drawn from Kanyilmaz (2017) and considered pertinent to this research are:

i. While the tension only assumption in vertical crossed bracing is rational for high seismicity this leads to poor economy under low seismic conditions.

ii. The resistance of frames with and without compression members differ significantly.

iii. Compression braces have a significant influence on global seismic performance.

iv. Member end connection boundary conditions significantly impact buckling shape and effective length.

    a. End connection boundary conditions are functions of end plate detail and member cross section.

b. Gélinas, et al. (2012) quote effective length factors of K = 0.6 for cross brace buckling in plane of fame, and K = 0.7 for buckling out of plane of frame.

c. Figure 2-2 shows out-of-plane buckled shapes found for vertical cross-braced arrangements using rectangular hollow sections as reported by Gélinas, et al. (2012).

v. Brace slenderness ratio is the primary variable in determining structural energy dissipation (Ballio, et al., 1998).

vi. Little experimental research is available to quantify braced frame resistances, stiffness, and ductility under moderate seismic loading.

2.3. Brace Member Compressive Resistance (C_r)

Figure 2-3 shows typical in-plane and out-of-plane buckling shapes for CHS members with welded end plate connections. From the figure, in-plane and out-of-plane directions are controlled by the CHS end plate orientation. Member effective length for out-of-plane buckling is greater than for in-plane buckling as shown in and corroborated by Figure 2-2 (Gélinas, et al., 2012). Effective length is inversely proportional to member buckling resistance (Mahachi, 2004) thus out-of-plane buckling capacity controls the sizing of CHS members in the presented research.

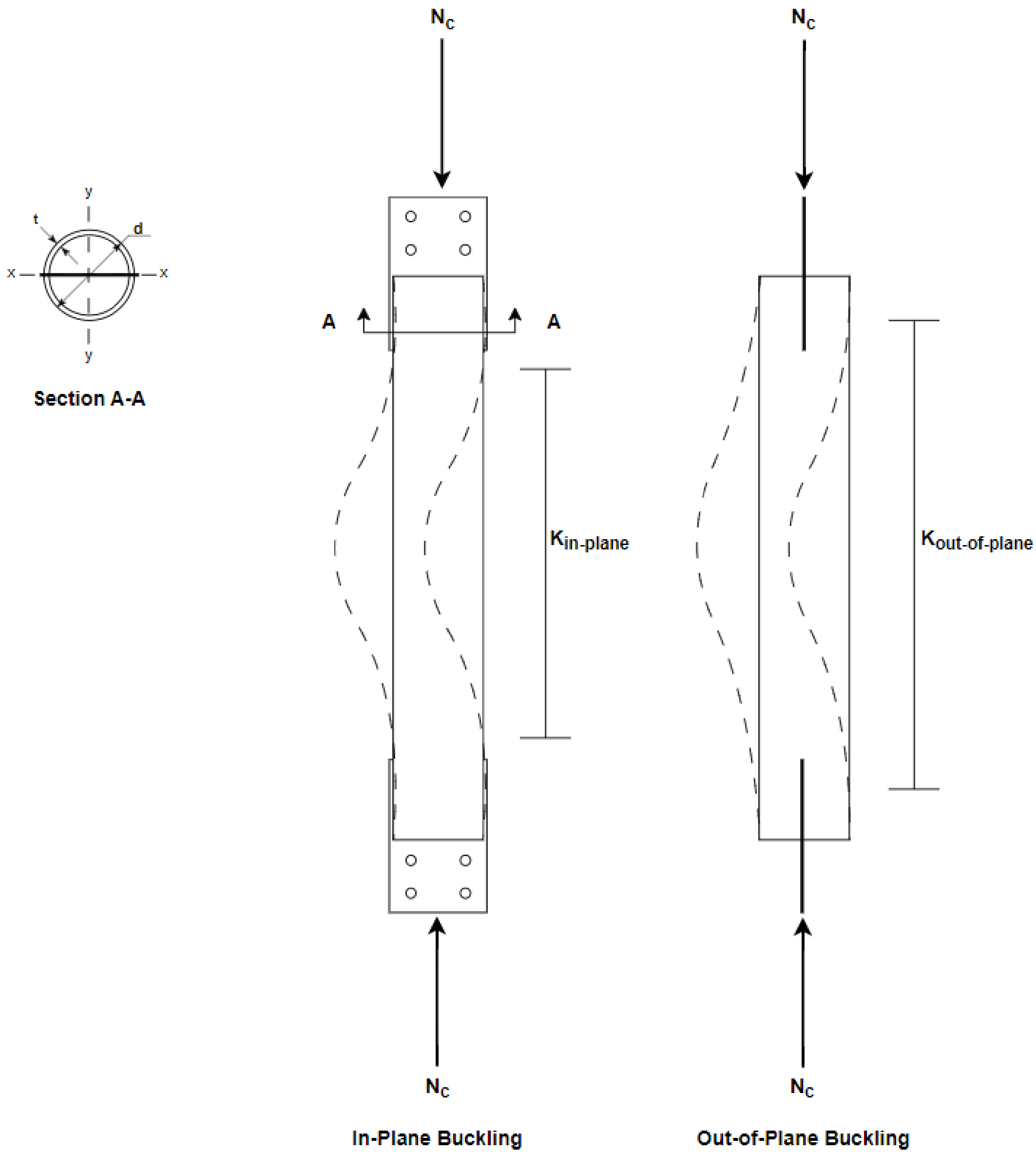


Figure 2-3 Typical CHS Member In the Plane of Frame and Out of the Plane of Frame Buckling Shapes

The out-of-plane compressive capacity for CHS members were calculated as described in clause 13.3.1 of SANS10162-1:2011 (SABS, 2011). CHS compressive resistances were calculated from (SABS, 2011):

$$C_{r,X-CHS} = \phi \cdot A \cdot f_y \cdot (1 + \lambda^{2n})^{-1/n}$$

where

$n = 1.34$

$\phi = 0.90$

$\lambda = K \cdot L / r \cdot \sqrt{(f_y / \pi^2 \cdot E)}$

$K = 0.85$ or $K = 1$

$f_y = 355\ MPa$

$E = 200\ 000\ MPa$

Clause 13.3.1 required member class be checked as outlined in clause 11 of the SANS10162-1:2011 (SABS, 2011). CHS class classification criteria are outlined in Table 2.1. The symbols d and t describe the cross-section diameter and thickness and are further enumerated in.

Table 2.1 CHS Class Classification Criteria

Description	Class 1	Class 2	Class 3
CHS	$d / t \leq 13000 / f_y$	$d / t \leq 18000 / f_y$	$d / t \leq 66000 / f_y$

2.4. Brace Member Tensile Resistance (T_r)

Figure 2-4 shows side, top and front views of an angle section loaded under tension. Tensile member resistance is controlled by the minimum capacity calculated from (SABS, 2011):

i. Gross cross-sectional area in tension, shown by the profile cross section side view in Figure 2-4.

ii. Net area in tension, subtracting the bolt hole perforations from the gross cross-sectional area.

iii. Shear block failure, denoted by tearing along the hatched areas in Figure 2-4 (Southern African Institute for Steel Construction, 2010).

iv. Effective net area reduced for shear lag in instances where load is not transmitted through all elements of a cross section at the connections.

a. For example, when bolting through a single leg in an Angle Section.

Tension members are typically designed so that the resistance of the member-connection arrangement is controlled by the connections (de Clercq, 2012).

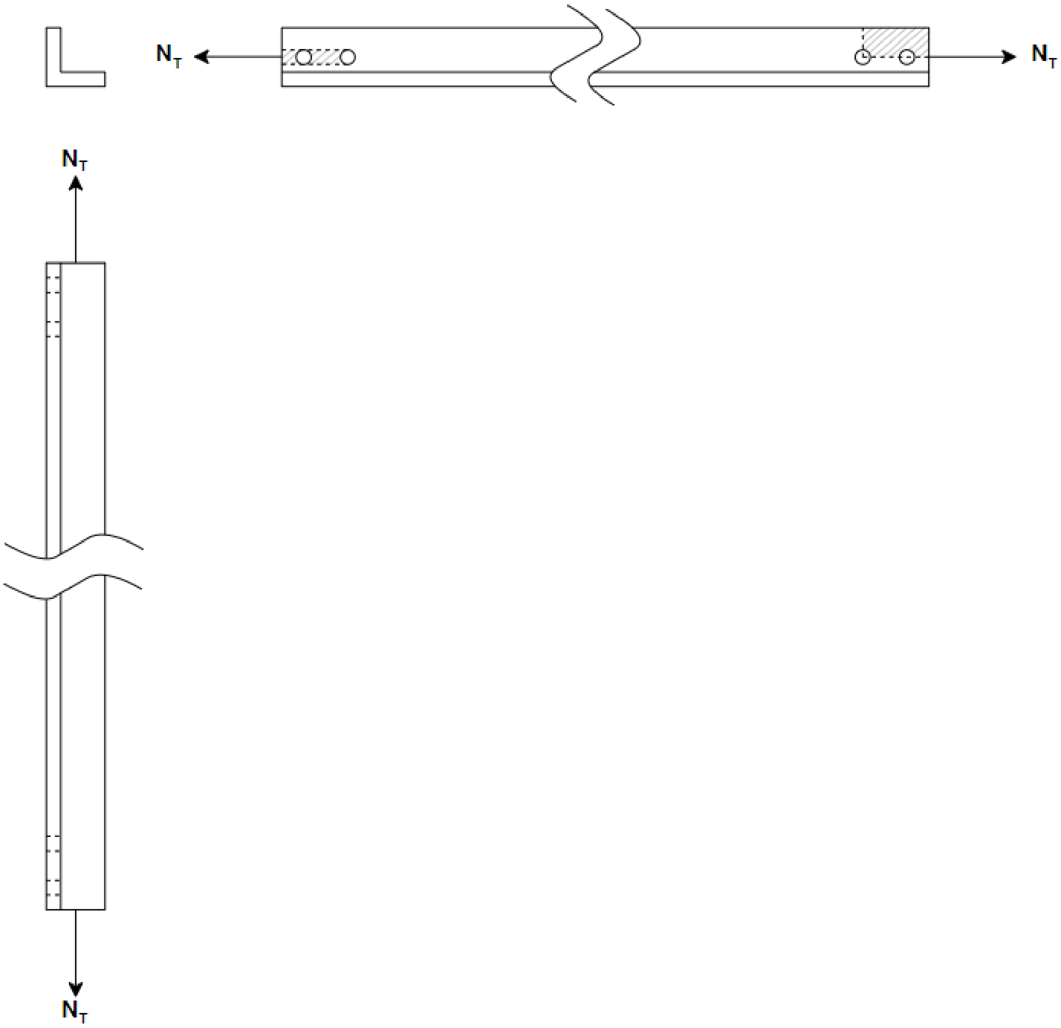


Figure 2-4 Angle Section under Tensile Loading

Member and connection tensile capacity for Angle Section members were derived from Table 12.1 of the Green Book for structural connections (de Clercq, 2012), and Table 3.2 of the Red Book (Southern African Institute for Steel Construction, 2010). Both sources provided standardised member and connection detail and tensile resistances for equal leg angles connected by one leg.

Angle sections are considered standard tensile members. The asymmetry of the cross section results in low axial compressive capacities when compared to symmetric sections (Mahachi, 2004). Referring to both The Red Book (Southern African Institute for Steel Construction, 2010) and The Green Book (de Clercq, 2012) published by SAISC, extensive tables of standard member and connection tensile resistances are provided for angle sections.

Evaluation of the connection tensile capacities, as per SANS10162-1:2011 (SABS, 2011), requires the calculation of the member and connection tensile resistances. The minimum of these values then controls. Tensile resistance of non-pin connected members, as per Clause 13.2 of SANS10162-1:2011 (SABS, 2011) is defined as being the least of:

$$T_{r,1} = \phi \cdot A_g \cdot f_y$$

$$T_{r,2} = 0.85 \cdot \phi \cdot A_{ne} \cdot f_u$$

$$T_{r,3} = 0.85 \cdot \phi \cdot A'_{ne} \cdot f_u.$$

Clause 12.3 of SANS10162-1:2011 (SABS, 2011) stipulated the methodology for calculation of the net (A_{ne}) and effective net (A'_{ne}) areas for connections of members in tension. The net and effective net areas involved separate calculations for bolted and welded connections. Connections applied to CHS members involve both welded and bolted elements.

Clause 13.12 of SANS10162-1:2011 (SABS, 2011) provides the methodology for calculation of bolt capacities in shear and bearing. Table 7.2 in the Red Book (Southern African Institute for Steel Construction, 2010), and Table 3.7 in the Green Book (de Clercq, 2012), provide summaries of bolt capacities by grade and per mm of plate thickness in line with SANS10162-1:2011 Clause 13.12 (SABS, 2011).

Generally, bolt capacities reported in Table 3.7of the Green Book were used for the analysis. Bolt sizes whose capacities were note tabulated were calculated according to SANS code. The equation to determine bolt shear capacity, where the bolt threads are in the shear plane, is given by:

$$V_r = 0.7 \cdot 0.6 \cdot \phi_b \cdot A_b \cdot f_u$$

2.5. Slenderness Ratio (SR)

Figure 2-5 shows a stub column on the left of the diagram and a slender column on the right. A stub column is a short column with low slenderness ratio that is subject to fail by local buckling under axial compressive load (Mohanraj, et al., 2011). A slender column has a high slenderness and is subject to fail by global buckling under axial compressive load (Mahachi, 2004). Slenderness ratio is a measure of the member aspect ratio about each primary axis. Slenderness ratio is defined as member effective length divided by radius of gyration, expressed as (Mahachi, 2004):

$$SR = KL/r$$

Radius of gyration is found by (Mahachi, 2004):

$$r = \sqrt{I/A}$$

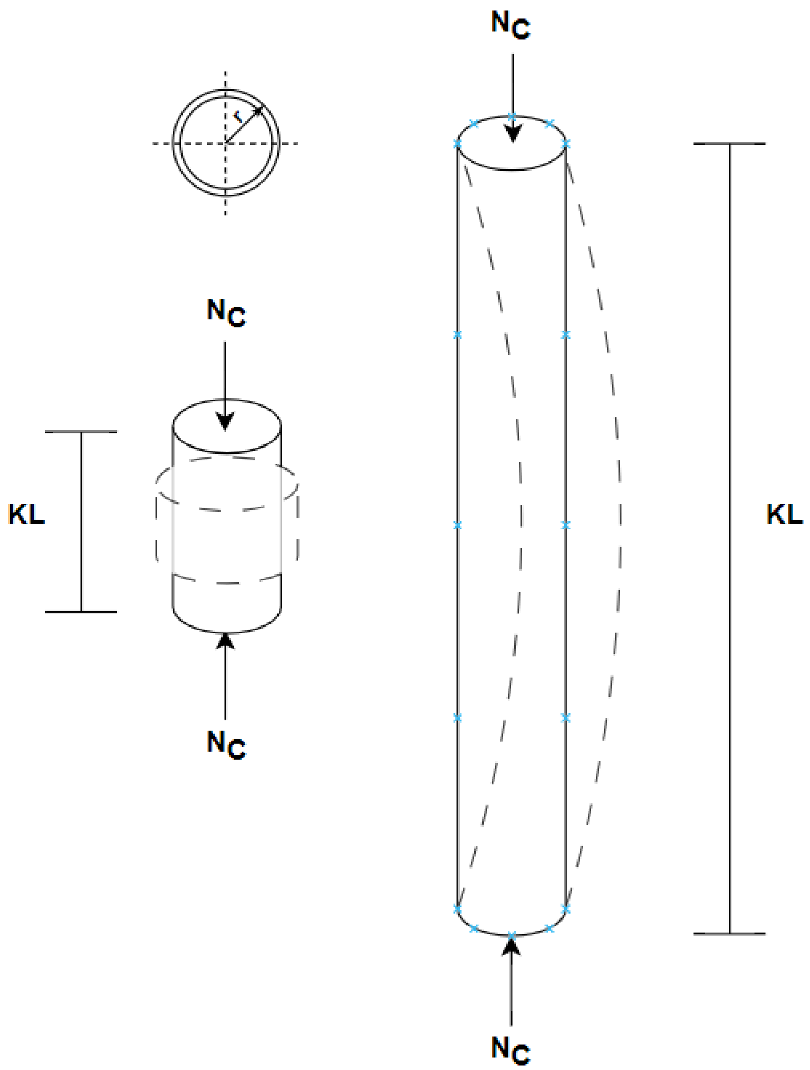


Figure 2-5 Stub (left) and Slender (right) Columns

Slenderness ratio limits are (SABS, 2011):

i. Compressive members: SR $\leq$ 200

ii. Tensile members: SR $\leq$ 300

3. RESEARCH METHODOLOGY

3.1. Introduction

The following chapter expands on the research methods discussed in section 1.1. First, an overview of the data collection methodology is given followed by detail summarising individuals interviewed and gathered data.

Second, the general approach to the load share sensitivity analysis is summarised in the overview. Further detail is then provided relating to:

i. The generic approach to the load-share analysis.
ii. Characteristic cases for the analysis.
iii. Variables applied to derive case permutations.
iv. Characterisation of the applied load-share factors.

Third, member design outlines the approach followed to size brace members in reference and comparative configurations. The member design section provides:

i. An overview of the member design approach.
ii. Detail pertaining to characteristic hypothetical cases and how member sizes were chosen for these.
iii. Notes and limitations relating to the built-site configuration data.
iv. Discussion concerning to how the load-share factor was applied.
v. Elaboration on member compressive and tensile resistance capacity calculations.

The chapter then concludes with a discussion of the characterisation of efficiency metrics and how these were calculated.

3.2. Data Collection

3.2.1. Overview

Figure 3-1 shows an overview of the data collection process flow. Interview processes were conducted with engineers and steel fabricators and site visits were conducted to gather the required data. Engineers provided data on reference configuration design philosophy and built sites. Steel fabricators provided data on costing models and built sites. Site visits were undertaken to gather additional built site data. Findings from the design philosophy data and literature survey determined the structural analysis and member design process. Site data were used to determine comparative configurations from the member design process. Results from the member design process provided mass efficiency metrics and inputs for the costing model process. The costing model process allowed for the determination of the cost efficiency metrics.

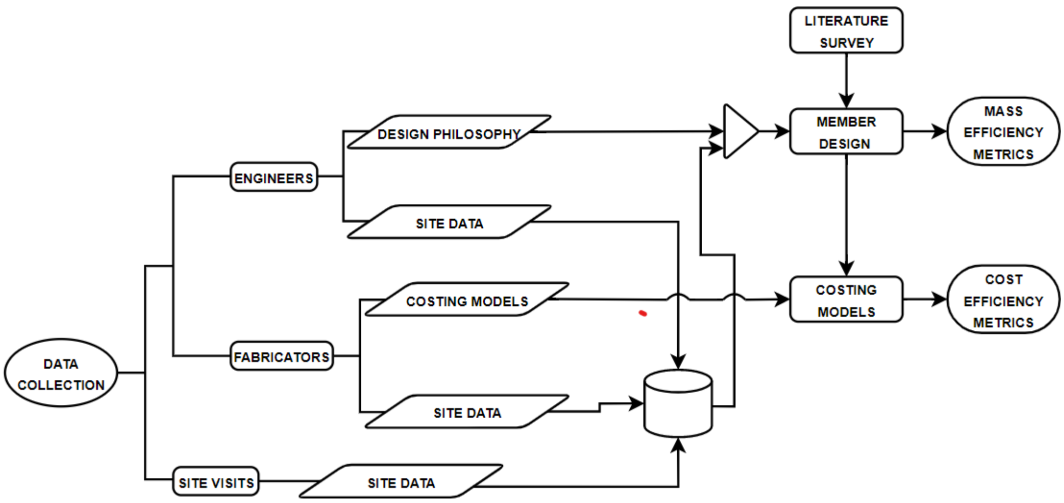


Figure 3-1 Data Collection Process Flow

Interviews were conducted with several Practicing and Professional Engineers to determine motivations and rationale for the use of CHS members in cross-braced configurations, and to request site detail and design information relating to designed and built projects where these configurations had been implemented.

Some Engineers were willing to provide interviews and no site information, whereas others provided site information but no interviews due to time constraints and professional obligations. None of the Engineers interviewed were willing to provide design detail.

Interviews were further conducted with several Steel Fabricators. Data relating to the costing of configuration fabrication and erections, and sites where CHS members had been used in vertical cross-braced arrangements, were gathered.

Several site surveys were conducted, supplemental to interviews, to gather additional site data where CHS members had been used in vertical cross configurations. Site measurements were taken, and assumptions made regarding member wall thicknesses where this could not be measured.

3.2.2. Interview Detail

Interviews were conducted with the Practicing Engineers listed in Table 3.1to understand motivations for the use of CHS members for structural bracing. Interviews were conducted informally taking the format of a discussion around the subject matter.

Table 3.1 List of Interviewed Engineers

Interviewee	Affiliated Consulting Firm *
M Manthe	Greene Group
M Midgley	RMCE
C Waite	RMCE
M Mostert	SMEC

Interviewee	Affiliated Consulting Firm *
D Surat	RMCE
G McRae-Samuel	Lateral Engineering

* Affiliated consultancy time of interview

Further interviews were conducted with the steel fabricators listed in Table 3.2 to ascertain pricing models for various structural members. Interviews were conducted informally and took the format of a discussion around the subject matter. Costing model results are discussed under section 4.2.

Table 3.2 List of Interviewed Steel Fabricators

Interviewee	Affiliated Fabrication Firm *
M Pereira	Mecra Products
M Labuschagne	Bhubezi Projects

Reviewed built-site installations are listed by configuration number, source, and location, where applicable, in Table 3.3. Site numbers denote the various structures from which data were gathered. The gathered built-site data was used to perform efficiency comparisons for different cross sections and bracing configurations.

Limited detail is supplied pertaining to the sites listed in Table 3.3 to protect the privacy of sources and sensitivity of the information gathered concerning built-sites. Site drawings obtained from sources are given from APPENDIX A – SITE C DRAWINGS to APPENDIX E – SITE I DRAWINGS. Individual analysed reference configuration cases, and associated layout data, are discussed in section 4.2.

Table 3.3 List of Investigated Site Locations and Sources

Site No.	Location	Source
Site A	Coega SEZ, Eastern Cape	Site Visit
Site B	Coega SEZ, Eastern Cape	Site Visit
Site C	Tenke Fungurume, DRC	Fabricator
Site D	Not Indicated	Fabricator
Site E	Not Indicated	Engineer
Site F	Moma Mozambique	Engineer
Site G	Illovo, Sandton	Site Visit
Site H	Kalumbila, Zambia	Site Visit
Site I	Hammarsdale, Kwa-Zulu Natal	Fabricator

3.3. Load Share Sensitivity Analysis

3.3.1. Overview

Load-sharing between tensile and compressive members had to be accounted for, this being cited (Midgley, 2022) (Waite, 2022) (Manthe, 2022) as a motivation for the use of CHS members in cross-braced arrangements.

The applied lateral loads are assumed to be shared between both members of the crossed arrangement instead of assuming that only a single member of the configuration works alone in tension.

The load share factor is derived as some factor of compressive to tensile member load which is dependent on brace inclination angle, bracing arrangement, and position of applied horizontal load.

Seven characteristic frame configurations were evaluated, see Table 3.4. The following variables were modified to determine the sensitivity of load-sharing between the tensile and compressive members:

i. Frame height or width as a function brace inclination angle.
ii. Application position of horizontal point load.
iii. Member effective length and resultant cross-section.

Prokon (2022), a widely used South African commercial structural analysis software package, was used to apply nominal lateral loads to 2- dimensional (2D) frame models to determine the resultant member forces developed in the vertically cross-braced frame models.

The average relative load-sharing proportions between tensile (T) and compressive (C) members derived from the sensitivity were 47.3% (T) to 52.7% (C). The stated values are averaged for all analysed brace inclination angles and configurations.

3.3.2. Analysis Detail

A chief motivation cited by interviewed Professional Engineers was that horizontal loads applied to frames with cross-braced CHS members are shared in some proportion between the compressive and tensile members.

Structural models were built in Prokon and used to investigate the degree of load-sharing between brace members. Figure 3-2 provides a visualisation of a typical vertically braced arrangement. The figure shows three braced compartments in the height with a point load applied from left to right at each beam level.

The “Frame” module offered by Prokon (2022) was used to perform the analysis. All members were modelled as pin ended. Nominal horizontal loads equalling 10 kN each were applied at compartment levels to derive bracing member axial forces. The axial forces were then used to determine the load-sharing percentage between tensile and compressive members.

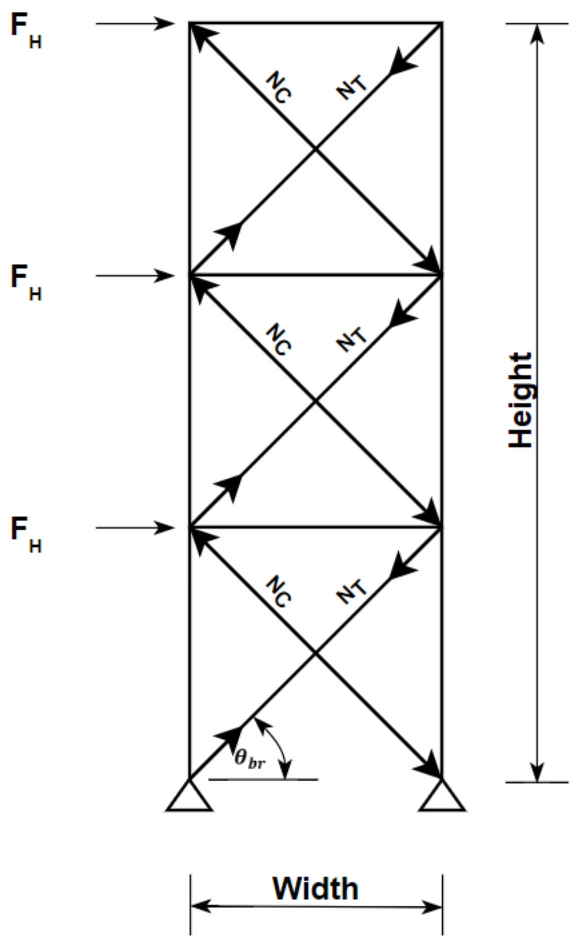


Figure 3-2 Diagram of Typical 2-D Structural Model with Vertical Cross-Bracing

Seven characteristic configurations consisting of single bay, vertically braced frames, as in Figure 3-2, were used to determine load-sharing sensitivity. The characteristic configurations are described in Table 3.4. The controlling variables differentiating the characteristic configurations are:

i. Frame height.

ii. Frame width.

iii. Number of compartments in the frame height.

iv. Brace member effective length (K).

Table 3.4 Description of Load-sharing Sensitivity Analysis Characteristic Configurations

Characteristic Configuration No.	Fixed Height / Width	Value of Fixed Dimension	Compartments in Frame Height	Effective Length Factor
SA C1	Fixed Width	5 m	2	K = 0.85
SA C2	Fixed Width	5 m	1	K = 0.85
SA C3	Fixed Height	8 m	1	K = 1
SA C4	Fixed Height	16 m	2	K = 1
SA C5	Fixed Width	5 m	3	K = 0.85
SA C6	Fixed Height	9 m	2	K = 0.85
SA C7	Fixed Height	9 m	3	K = 0.85

A total of 96 two dimensional (2D) models were derived from the seven characteristic configurations for analysis. The following variables were adjusted to arrive at the 96 case permutations:

i. Brace inclination angle (θ_{br}).
ii. Application position of the lateral horizontal load (F_H).

For each model built either of the dependent variables of frame height or frame width were adjusted to fit the brace inclination angle. Brace inclination angles were evaluated from 30˚ to 65˚, measured from the horizontal, in 5˚ increments.

Figure 3-3 demonstrates the impact of varying brace inclination angle on:

i. Frame dimensions.
ii. Brace member forces (N_C and N_T).
iii. Derived load-share factors (α_C and α_T).

Described in Figure 3-3, load-share factors derived from the sensitivity analysis indicated a greater disparity between compressive and tensile member loads for lower brace inclination angles. Load-share factors tended towards equitable shared load with increasing brace inclination angle.

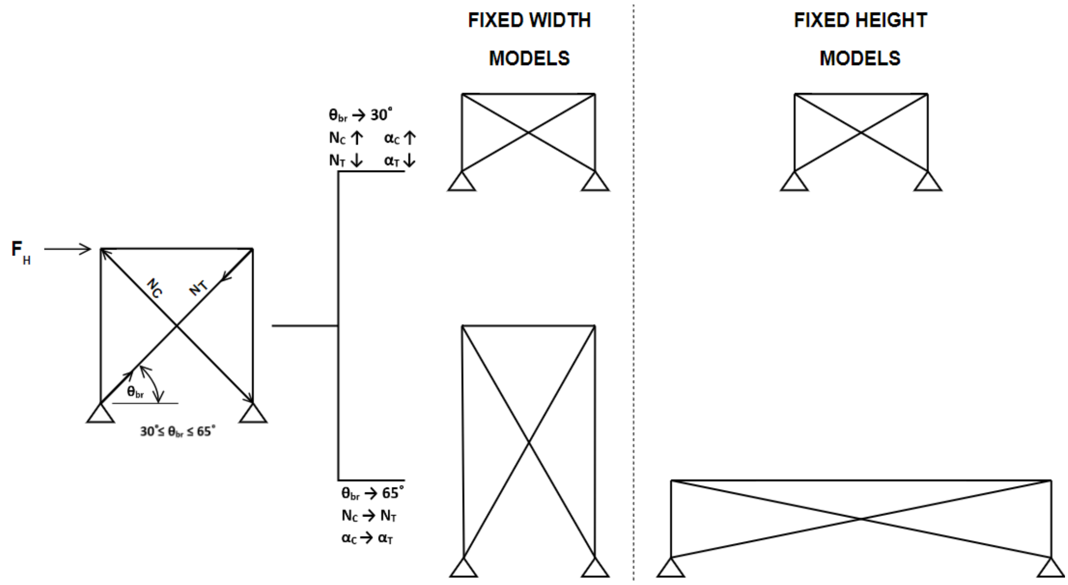


Figure 3-3 Influence of on Brace Inclination Angle (θ_{br}) on Vertical Cross Braced Arrangement

The application positions of the lateral horizontal loads for multi-compartment bays were either situated at each level as in Figure 3-2, or at the top level as in Figure 3-2. Single compartment bays had load application positions situated at the top left corner of the frame model as in Figure 3-3.

Member effective length factors of K=0.85 and K=1 were applied across different characteristic configurations as outlined in Table 3.4 and motivated in section 2.3. The effective length factors impacted the calculated member slenderness ratios and specified members.

The column, beam and brace member slenderness ratios were taken as the controlling design criteria for each case of the sensitivity analysis. The slenderness ratio limit for each member determined the cross section used in the each model. Member strength was not a critical variable in any of the analysed cases as only nominal lateral loads had been applied in the load-share analysis.

The vertical brace member tensile (N_t) and compressive (N_c) loads could then be determined from the structural analysis. The relationships between brace inclination angle, developed member loads and load-share factor are outlined in Figure 3-3.The corresponding tensile (α_t) and compressive (α_c) load-sharing factors for each configuration were calculated from:

$$\alpha_c(\theta_{br}) = N_c(\theta_{br}) \,/\, (N_t(\theta_{br}) + N_c(\theta_{br}))$$

$$\alpha_t(\theta_{br}) = N_t(\theta_{br}) \,/\, (N_t(\theta_{br}) + N_c(\theta_{br}))$$

A statistical analysis was performed on the load-share results to determine the distribution of compressive and tensile load share factors by brace inclination angle. The results of the sensitivity and statistical analysis are listed in section 1.1.

APPENDIX F – SENSITIVITY ANALYSIS DATA provides a summary of the configuration description, load application points, vertical brace member compressive and tensile load results, and load share proportion per member.

3.4. Member Design

3.4.1. Overview

Figure 3-4 outlines the process flow followed to design members. Data were gathered from interviews and site visits. Key data inputs for member design were:

i. Reference configuration cross-sections.
ii. Reference configuration braced bay dimensions.
iii. Design philosophy.

Comparative configuration vertical bracing could be determined from reference configuration data. Equivalent comparative cross-sections were specified by calculating reference cross-section buckling resistances and applying the relevant compressive load-share factor. Comparative configurations consisted of:

i. Tension only crossed-Angle arrangements.
ii. Single CHS arrangements with member size requirements controlled by out-of-plane buckling resistance.

Efficiency metrics could be determined with the reference and comparative arrangements members sizes.

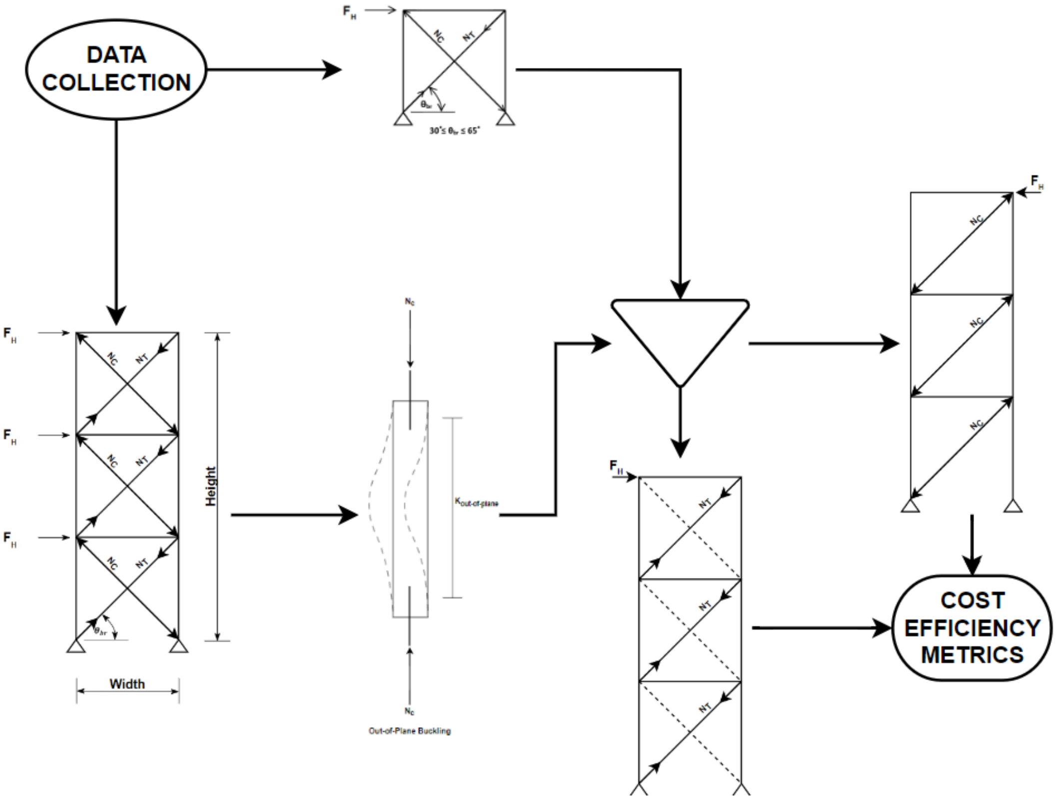


Figure 3-4 Member Design Process Flow

Brace members were assumed to be purely axially loaded members. End restraints were modelled as pinned. Members bending capacities were not evaluated or considered.

Crossed- and single- CHS arrangements had their member sizes based on out-of-plane buckling axial capacity of the continuous member. CHS member out-of-plane buckling capacities were determined as outlined in SANS10162-1 (SABS, 2011) and discussed in section 2.3.

Cross-sections in crossed-Angle arrangements were designed as tension only members. Angles were sized based on their tensile capacity according to SANS10162-1 (SABS, 2011). Member and connection tensile resistances were found referencing The Green Book (Clercq, 2012) and The Red Book (Southern African Institute for Steel Construction, 2010).

A total of 32 hypothetical, and 20 built-site, cases were analysed as:

i. Reference cross-braced CHS arrangements.
ii. Comparative cross-braced Angle arrangements.
iii. Single CHS member arrangements.

The reference configurations were assumed to have some degree of load-sharing in the analysis. The load-share factor was derived from the sensitivity analysis as described in section 3.3.

The reference configuration cross-sections were quantified from the data collection process for built-site members and derived from the load-share sensitivity analysis for hypothetical configurations.

Reference configuration CHS members applied in the 32 hypothetical cases were sized based on the minimum required slenderness ratio for each arrangement.

Specified reference cross-sections for the 20 built-site cases were gathered site data.

The average compressive load share factor for each case was then interpolated from sensitivity analysis data. The load share factor is a function of brace inclination angle which is determined from the configuration dimensions. The design load for each comparative configuration case was then found by dividing the reference configuration compressive capacity by the interpolated compressive load share factor.

Comparative configuration crossed Angle and CHS members were then determined from the calculated design load for each case. The average calculated design load was approximately twice the reference configuration compressive member capacity. The compressive load-factor range derived from the sensitivity analysis is evidence of this.

Vertical cross-braced CHS connection capacities were only tertiarily considered as part of the study, and not for every analysed case. The behaviour and design of midspan connections, as shown in Figure 1-2 and Figure 2-2, are not well characterised or formulated (Kanyilmaz, 2017).

Basic connection calculations for reference configurations were performed. Connection capacities were only considered where high reference configuration member compressive resistances had been calculated and these in turn produced unexpected results in the comparative configuration design.

The connection capacities were evaluated based on bolt group shear capacity. Connection capacity calculations were performed to validate the reference configuration member compressive resistances and to evaluate the impact of comparative configuration design load on efficiency metrics.

3.4.2. Hypothetical Configurations

The results of the sensitivity analysis member specification highlighted a repetition of CHS brace members relating to specific cases. The repetition of CHS members resulted in four characteristic configurations. Characteristic configurations in the braced frame analysis were controlled by the compartment heights, described in Table 3.5. Figure 3-5 should be read in conjunction with Table 3.5. Figure 3-5 describes compartments in the height, compartment height, and frame height and width.

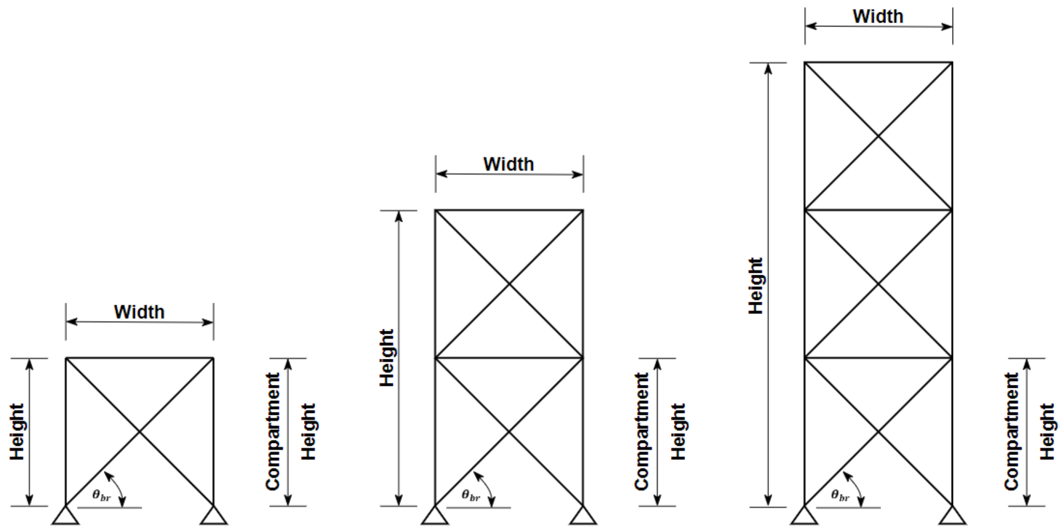


Figure 3-5 Sketch of General Hypothetical Characteristic Configuration Arrangements

Table 3.5 Description of Braced Frame Characteristic Configurations Derived from Sensitivity Analysis

Characteristic Configuration No.	Fixed Variable	Value of Fixed Variable	No. Compartments in Height	Compartment Height
BF C1	Fixed Width	5 m	1, 2, 3	2.89 m
BF C2	Fixed Height	8 m, 16 m	1, 2	4 m
BF C3	Fixed Height	9 m	2	4.5 m
BF C4	Fixed Height	9 m	3	3 m

The bracing inclination angle range applied to the characteristic configurations listed in Table 3.5 resulted in a total of 32 hypothetical cases. The reference brace member cross-sections were taken from the sensitivity analysis calculations. The reference cross-sections were specified in the sensitivity analysis based on compressive slenderness ratio. The CHS element compressive capacities were then calculated as outlined in the SANS10162-1:2011 standard for the limit state design of hot-rolled steelwork. The critical capacity of the CHS members were determined from the out-of-plane flexural buckling lengths for each case. Results are provided and summarily discussed under ANNEX H – MEMBER DESIGN.

3.4.3. Built-site Configurations

Data from nine different built-sites was gathered through interviews with various Engineers, Fabricators, as well as several site visits. No structural design calculations or applied loading for these sites were obtained. Site data supplied by Engineers and Fabricators comprised of general arrangement layout drawings, including frame and bay dimensions, and specified cross sections used.

CHS brace members associated with each site were assumed to be designed to only resist axial load. Member axial capacity was then calculated per

SANS10162-1:2011 assuming out-of-plane flexural buckling to be the critical failure mode.

Cross-sectional data from the built-sites were incomplete for several the sites, specifically where site data were collected in the field. In these instances, assumptions were taken regarding wall thickness. On analysis, several of the built-sites produce unexpected results which motivated additional investigation. In total the nine built-site arrangements produced 18 cases that were analysed. Findings and results are detailed and discussed under section 4.3.

3.4.4. Application of Load-Share Factor

The CHS compressive resistance for each of the 52 hypothetical and built cross-braced configurations were divided average compressive load share factor determined from the sensitivity analysis.

The average compressive load share factor $\left(\alpha_{c,avg.}(\theta_{br})\right)$ was used to determine the applied comparative configuration design load (N_d),. The comparative configuration design load was controlled by the CHS member flexural buckling capacity for each configuration and related to the sensitivity analysis compressive load share factor. The relationship can be expressed mathematically as:

$$C_{r,X-CHS} = N_d(\theta_{br}) \cdot \alpha_{c,avg.}(\theta_{br})$$

The design axial loads for the comparative configurations (N_d), were then used to size the required members for the tension only cross- and single- CHS braced arrangements. Rearranging the previous equation, the comparative configuration design axial loads were then determined from:

$N_d(\theta_{br}) = C_{r,X-CHS} \,/\, \alpha_{c,avg.}(\theta_{br})$

The above relationship is evidenced by the results of the required members for the single CHS braced configurations in section 4.5. Single CHS configurations with relatively high design loads, and whose specified cross sections are limited by commercially available members, are found to require the same number and cross section of members as the original reference cross- CHS configurations. The results in sections 4.5 and 4.5.3 are highlighted where the minimum values of the Total Cost Ratio comparing crossed and single CHS configurations equal 100%, or 1:1.

3.4.5. CHS Connection Capacities

Detailed CHS connection capacity calculations were not considered as part of the study. Characterisation of vertical cross-braced connections considered would form the scope of additional research.

The presented research assumed that specified CHS plate connections were adequate for axial load transferral with members being sized based on the out-of-plane buckling capacity of the continuous, or full length, CHS member.

Connection capacities were preliminarily reviewed for several of the built-site configurations. The preliminary calculations served to verify the calculated out-of-plane flexural buckling capacity. This was done where collected site data was incomplete, or where the costing analysis results were unanticipated.

Connection calculations, where performed, were limited to the calculated member capacity being compared to the bolt group shear capacity. Bearing checks performed were never critical. Plate failure was not considered as the connection checks were only meant to justify the member capacity. Calculations are discussed under relevant cases in section 4.2.

3.4.6. Brace Member Compressive Resistance (C_r)

Vertical cross-braced arrangements are subject to load reversal. Members resistances consequently need to be checked for both tension and compression. CHS member tensile capacity was not evaluated in this study. The proposition was that the member would reach the flexural buckling capacity before attaining the tensile resistance. The proposition is supported by member capacities calculations outlined in section 2.3 and section 2.4.

Typical welded multi-bolt end plate connections applied to cross-braced CHS members offer some degree of rotational stiffness to out-of-plane buckling. Out-of-plane effective length factors of K = 1 (Brown, et al., 2001) and K = 0.85 were applied in the analysis. Research published by Gélinas, et al. (2012) suggests lower effective lengths factors could be applied. The listed effective length factors were applied conservatively for the purposes of this study.

Effective length factors applied to the built-site members were dependent on the end fixing conditions; where an end connection was classically pinned (as in section 1.1) K = 1, and where the end connections consisted of welded end plates and multiple bolts K = 0.85.

3.4.7. Brace Member Tensile Resistance (T_r)

Several analysed built-site cases produced cost comparison results that were unexpected under the proposition that comparative configuration members sizes were determined by the out-of-plane flexural buckling capacity of the crossed CHS reference configurations.

Additional analysis was motivated where the initial results were unexpected. The assumption taken in these instances was that the reference crossed CHS configuration capacity was controlled by the connection tensile capacity instead of the out-of-plane member buckling capacity.

Built-site data pertaining to connections was incomplete. Configuration connections were not initially a primary objective of the research investigation. Connection detail was then not necessarily provided at the time of interviews. Connection detail which was included in site data, or which could be reasonably assumed, were bolt size, grade, quantity and end plate thickness. The method outlined in SANS 10162-1:2011 (SABS, 2011) and described in section 2.4 could not be readily applied with available site data.

Weld and plate connections were consequently assumed to have been adequately designed and implemented for purposes of the analysis. The resistances of member-connection arrangements were then evaluated as a function of the bolt group shear capacity. Net and effective area calculations for welded and bolted connections are consequently not discussed in section 2.4.

The bolt group shear capacity then controlled the upper bound limits for the connection resistance. The outlined rudimentary approach to determination of the connection capacity was determined to be sufficient for purpose. Comparative braced arrangement costs could be conservatively determined from the calculated values. That is to say, the calculated upper bound connection resistance would penalise Angle sections and favour CHS members in the costing comparison results.

The design of Angle Sections applied as tension only members proceeded by referencing member and connection resistances published in The Red Book (2010) and The Greed Book (2012) as discussed in section 2.4.

The Red Book (2010) and The Green Book (2012) are standard, widely used and trusted resources in the South African steel industry. A typical approach followed by commercially practicing Structural Engineers in South Africa would be to size members based on published resistances.

The resistances of tensile member-connection arrangements were controlled by the connection capacities for analysed configurations presented in this report. APPENDIX G – CONFIGURATION ANALYSIS AND MEMBER SPECIFICATION SUPPLEMENTARY DATA provides members and connection configuration requirements specified based on design load and resistances published in the referenced resources.

3.5. Efficiency Metrics

3.5.1. Introduction

The efficiency metrics specified were mass, raw materials cost, and fabrication and erection costs. Data relating to efficiency metrics could be tabulated once the required cross sections for the reference and configurations had been specified.

Member and configuration masses were determined for each analysed case based on the configuration cross section requirements. The configuration unit masses were taken from the member mass per unit length. Thus, a cross-braced configuration would have a unit mass twice that of the specified member mass per unit length, and single-braced configuration would have a unit mass equal to the member mass per unit length. The configuration unit masses were expressed as tons to facilitate the calculation of costing metrics. Member length was an unimportant variable as this was constant across reference and comparative configurations.

Raw materials costs were obtained from MacSteel (MacSteel, 2022). Fabrication and erection costs were gathered from interviews with Steel Fabricators (Labuschagne, 2022) (Pereira, 2022). Raw materials, fabrication and erection costs are expressed in Rand per Ton (ZAR/ton) by industry convention. Cost metrics were then calculated according to the various costing models once the configuration masses had been defined.

3.5.2. Efficiency Metrics

The study objective was to compare reference cross-braced CHS arrangements to comparative crossed Angle section, and single CHS, braced arrangements.

The crossed Angle elements were sized based on member and connection tensile resistance. The single CHS braced elements were sized based on the member out-of-plane flexural buckling capacity.

The design loads, calculated as described in section 3.4.4, were applied to each corresponding comparative crossed Angle and single CHS configuration to determine the required size cross section for each arrangement.

Once the required cross sections for each arrangement had been defined the efficiency metrics could be determined. Efficiency metrics were defined as mass, raw materials cost, fabrication cost, and erection cost.

Member masses were used to determine the associated raw materials, fabrication and erection costs from the costing models. Costing models were expressed as price per unit mass in ZAR per ton for each member type. Configuration unit masses were then determined by taking member mass for each configuration, expressed in kilogram per meter, and multiplying by 1000 to arrive at a unit tonnage.

Raw materials costs were determined from a price list supplied by Macsteel Trading circa January 2022 as per section 1.1. Applied costing models for fabrication and erection are given in section 4.4.2.

4. RESULTS

4.1. Design Philosophy

Table 4.1 summarises the motivations cited by interviewed Engineers for the use of CHS generally and specifically in cross-braced arrangements from the Literature Survey.

Table 4.1 Cited Motivations for Preference of CHS Members

Description	Reasoning
Client Requirement	Aesthetic preference
	Structural specifications client determined (heavy industry)
	Client specified cross section dependent minimum thickness influencing materials costs (i.e., CHS min. thickness < Angle Section min. thickness)
	Prohibition of back-to-back Angle Section or channel configurations
	Additional redundancy in high corrosive, high risk, or high impact environments (heavy industry)
Commercial	Materials availability in market
Erection	Easier to erect due to lower mass
Geometric	CHS symmetry compared to Angle Section
	CHS slenderness ratios generally more favourable than Angle Section for equivalent member capacities
	Improved vibrational response of CHS compared to Angle Section
Housekeeping	Accumulation of corrosive fine particulates on Angle Section flat surfaces accelerating member corrosion
Load-sharing	Angle members in crossed arrangements designed as tension only whereas CHS members designed to share compressive and tensile loads
Retrofitting	Easier to retrofit larger sections if loading requirement changes
Seismic	Code requirement for cross arranged members to meet robustness or redundancy criteria where a single member would suffice

Description	Reasoning
Strength	More favourable buckling resistances compared to Angle Section on per unit mass basis
Subjective bias	Preference for CHS members based off failure of Angle Section (or other) member on a previous project
Transport	Cheaper to transport due to lower mass

4.2. Load-Share Sensitivity Analysis

The results of the statistical analysis performed to determine the compressive load share factor derived from the sensitivity analysis are described in Table 4.2 and Table 4.3. The mean values shown in Figure 4-1 were used to determine the compressive load share factor. The compressive load share factor was interpolated for brace inclination angles within the range of the sensitivity analysis. The upper and lower bound compressive load share factor values were taken for brace inclination angles which fell outside the range of the sensitivity analysis.

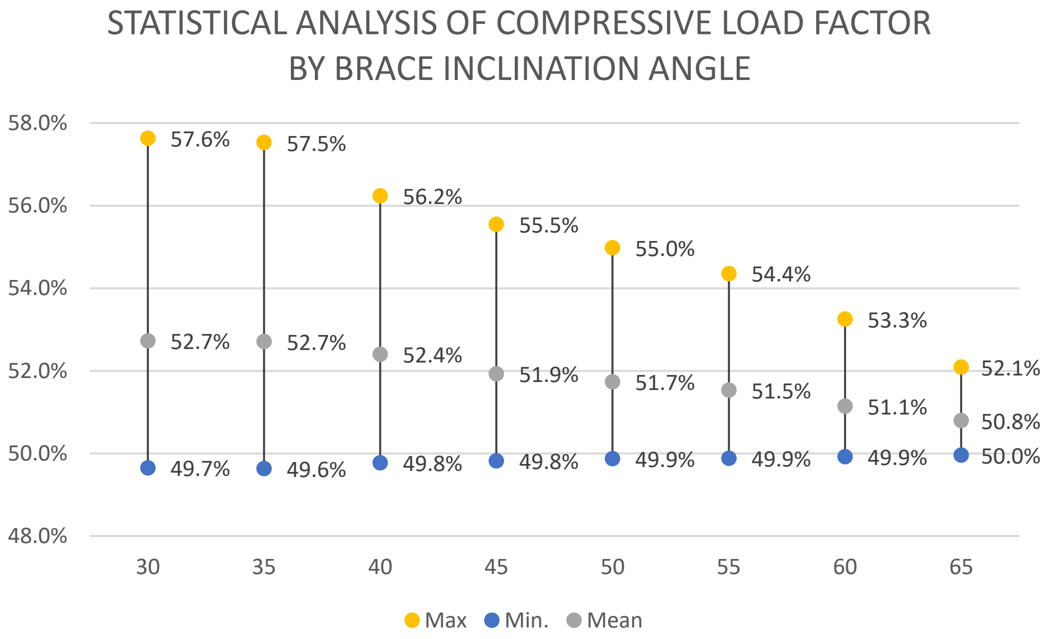


Figure 4-1 Compressive Load Share Factor Min., Mean, and Max Values from Sensitivity Analysis

Table 4.2 and Table 4.3 are to be read together and form supplemental information to the statistical analysis. The compressive load share factor spread is noted to reduce with increasing brace inclination angle. Close agreement is noted between mean and median values. Taking the mean value to determine the comparative configuration design loads was considered the most reasonable approach to estimate the comparative configuration member requirements. The intention was to prevent skewing of the data towards the extreme values.

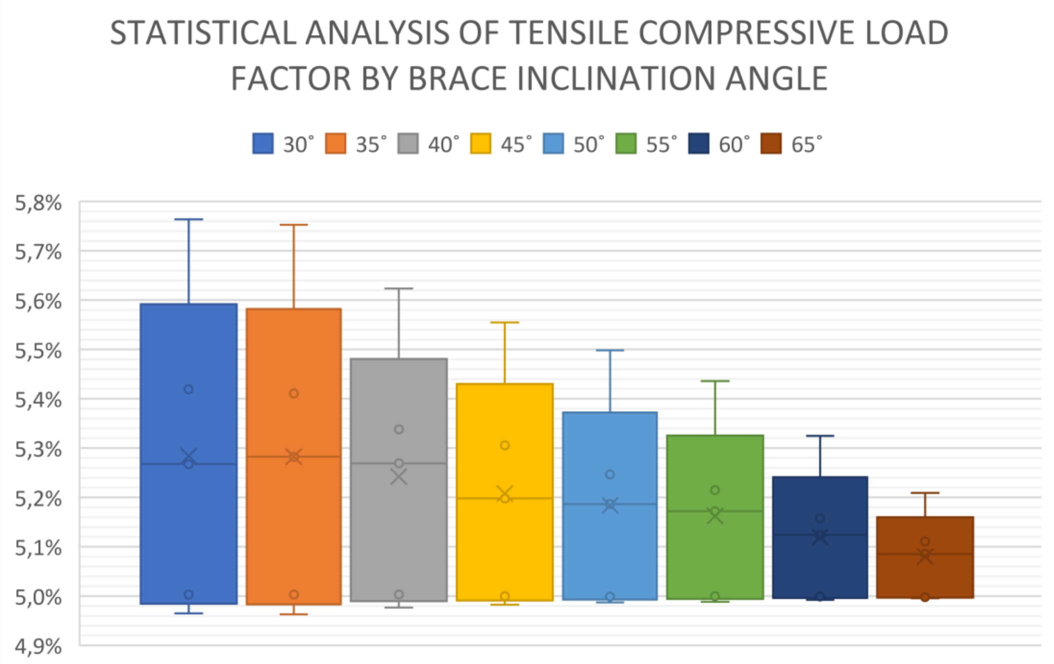


Figure 4-2 Box and Whisker Diagram for Compressive Load Share Factor Statistical Analysis

Table 4.2 Box and Whisker Diagram Tabulated Values for Compressive Load Share Factor

COMPRESSIVE LOAD STATISTICAL ANALYSIS SUMMARY								
Description	**30˚**	**35˚**	**40˚**	**45˚**	**50˚**	**55˚**	**60˚**	**65˚**
Min.	49,7%	49,6%	49,8%	49,8%	49,9%	49,9%	49,9%	50,0%
Q1	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%
Median	52,7%	52,8%	52,7%	52,0%	51,9%	51,7%	51,2%	50,9%
Q3	54,2%	54,1%	53,4%	53,1%	52,5%	52,1%	51,6%	51,1%

COMPRESSIVE LOAD STATISTICAL ANALYSIS SUMMARY								
Description	**30˚**	**35˚**	**40˚**	**45˚**	**50˚**	**55˚**	**60˚**	**65˚**
Max.	57,6%	57,5%	56,2%	55,5%	55,0%	54,4%	53,3%	52,1%

Table 4.2 and Table 4.3 outline the tensile load factor statistical analysis results derived from the sensitivity analysis. The tensile load factor results were note used for the purposes of the analysis but do serve to corroborate the compressive load share factor derivations. A near equal split is noted for the derived mean values of the tensile and compressive statistical analysis, as expects. The values approach a 50:50 split as the brace inclination tends towards 90˚.

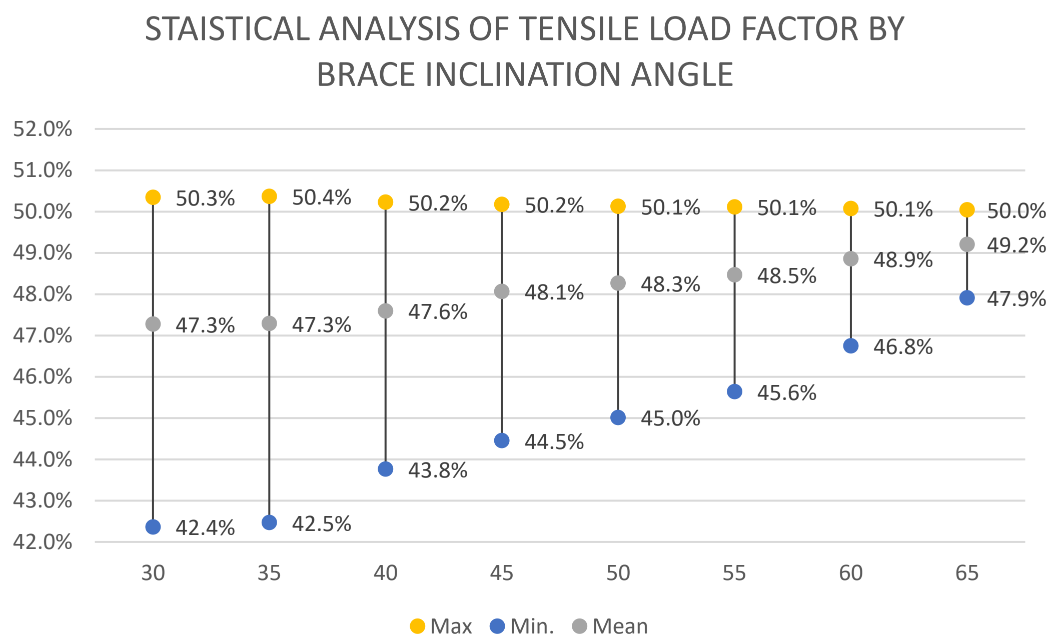


Figure 4-3 Tensile Load Share Factor Min., Mean, and Max Values from Sensitivity Analysis

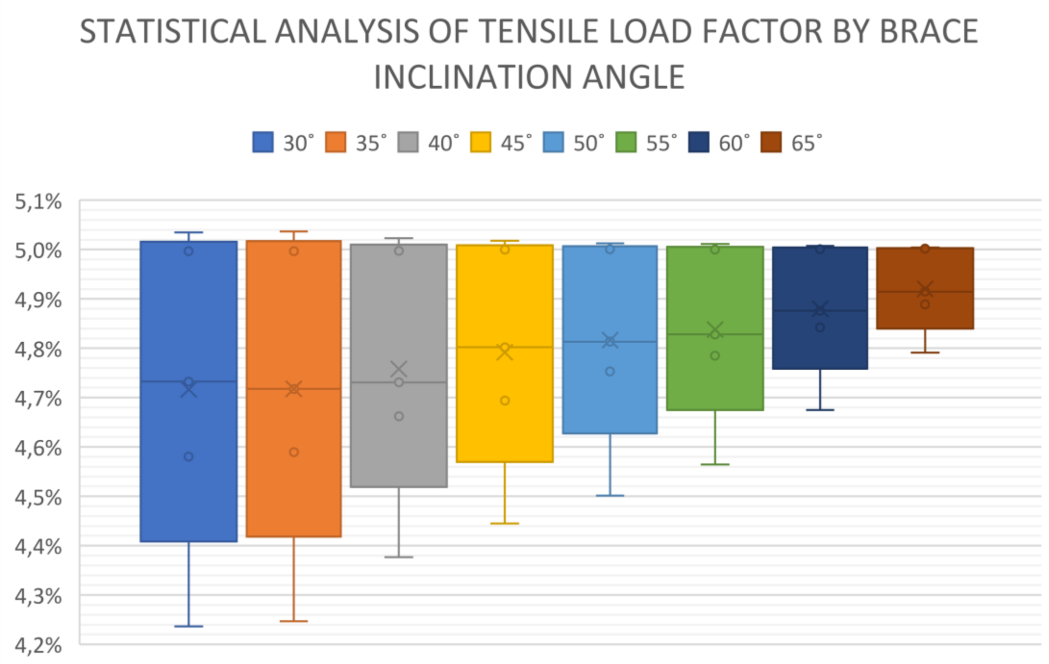


Figure 4-4 Box and Whisker Diagram for Tensile Load Factor Statistical Analysis

Table 4.3 Box and Whisker Diagram Tabulated Values for Tensile Load Factor

TENSILE LOAD STATISTICAL ANALYSIS SUMMARY								
Description	**30 ˚**	**35˚**	**40˚**	**45˚**	**50˚**	**55˚**	**60˚**	**65˚**
Min.	42,4%	42,5%	43,8%	44,5%	45,0%	45,6%	46,8%	47,9%
Q1	45,8%	45,9%	46,6%	46,9%	47,5%	47,9%	48,4%	48,9%
Median	47,3%	47,2%	47,3%	48,0%	48,1%	48,3%	48,8%	49,1%
Q3	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%
Max	50,3%	50,4%	50,2%	50,2%	50,1%	50,1%	50,1%	50,0%

4.3. Site Data

Site data are presented in no order of consequence. Details and assumptions relating to specific sites are listed and discussed. Sites are arbitrarily named from

Site A to Site G. Pertinent details and analysis results relating to sites of interest are listed and discussed under site case numbers.

Sites numbered “Site A – Case 1” or “Site A – Case 2” denote different configurations associated with the same site or project. The site numbering convention “Site A – Case 1-1” or “Site A – Case 1-2” imply the same configuration but differing assumptions relating to the configuration capacity determination, for instance based on either member capacity or bolt group shear capacity.

Site sub-cases were investigated in greater detail where initial costing analysis results yielded unexpected results. Initial analysis assumptions were reviewed and revised for each sub-case investigated as discussed under section 3.4.5.

4.3.1. Site A

Two different configurations were noted at Site A classified as configuration numbers Site A – Case 1 (Site A-C1) and Site A – Case 2 (Site A-C2). Figure 4-5 and Figure 4-6 respectively show Site A-C1 and Site A-C2.

Table 4.4 provides the measured system geometry, bracing inclination angle, brace member cross section and capacity, basic connection detail and bolt shear capacity. The case count number introduced in acts as a convenient way to track and express efficiency metric results in sections 4.5.1, 4.5, and 4.5.3.

Figure 4-5 Site A Case 1 Cross-braced CHS Configuration (Site A-C1)

Configuration Site A-C2 could not be safely reached to take measurements due to its height above the ground. From other collected site data, it was noted that cross sections and end plate connections are often repeated for similarly dimensioned configurations at any given site. The cross sections and connections for the two configurations appeared similarly sized when observed on site. The properties marked with a “*” under Site A-C2 in are thus assumed values taken to be equivalent to those measured on Site A-C1.

Figure 4-6 Site A Cross-braced CHS Configuration (Site A-C2)

The brace inclination angle was used to determine to compressive load share factor as discussed in section 4.2. The compressive load share factor acted as scaling tool to determine the magnitude of the equivalent load the comparative cross Angle and single CHS braced configuration members would need to resist, as described in section 3.4.4.

The load factor calculated in the sensitivity analysis for brace inclination angles from 30˚ to 65˚. Where site inclination angles given in site data deviated from the sensitivity analysis range if inclination angles, as with Site A-C2, the next closest load factor was applied.

The calculated brace member cross section and bolt group shear capacities are reported in Table 3.1. The member capacity was calculated using an effective length factor of K = 0.85. The bolt capacities were calculated assuming single shear across the bolt threads. The results of the calculations show the connection resistance to be less than that of the member axial capacity.

The configuration capacity used in subsequent analysis for Site A-C1 was taken to be that of the bolt group single shear capacity. The calculated member capacity was taken for case Site A-C2. The rationale for this was to provide a better distribution in the results of the final analysis from which to draw conclusions.

Table 4.4 Analysis Detail of Site A-C1 and Site A-C2 Cross-braced Configurations

Configuration No.	**Site A-C1**	**Site A-C2**
Case Count No.	33	34
Compartment Width	6000 mm	6000 mm
Compartment Height	5500 mm	2500 mm
θ_{br}	42.5°	22.6°
$\alpha_{c,avg.}$	0.522	0.527
Controlling Section	CHS 152.4x3.0	CHS 152.4x3.0*
$C_{r,\ CHS}$	125 kN	180 kN
End Plate	12 mm	12 mm*
Connection Bolts	4x Gr8.8 M12	4x Gr8.8 M12*
$V_{r,\ bolt\ group}$	120 kN	120 kN
Design Load	230 kN	309 kN
Comparative Cross Angle Section	70x70x8	80x80x10
$T_{r,\ X\text{-}L}$	255 kN	350 kN
Comparative Single CHS Section	CHS 193.7x3.5	CHS 193.7x3.5
$C_{r,\ X\text{-}CHS}$	271 kN	360 kN

4.3.2. Site B

The configuration shown in Figure 4-7 was located within a warehouse. Limited space was available from which to photograph the full arrangement. Further, the glare from the window in the background resulted in poor image quality.

The measured system geometry, bracing inclination angle, brace member cross section and capacity, basic connection detail and bolt shear capacity, and comparative member results are given in Table 4.5.

Figure 4-7 Site B Cross-braced CHS Configuration (Site B-C1)

The bolt group shear capacity, assuming single shear, was determined sufficient to support the member loads from cursory calculations. The method described in section 3.4.4 was then used to determine equivalent comparative cross-braced Angle and single- braced CHS configuration member requirements.

Table 4.5 Analysis Detail of Site B-C1 Cross-braced Configuration

Configuration No.	**Site B-C1**
Case Count No.	35
Compartment Width	7550 mm
Compartment Height	5475 mm
θ_{br}	36.0˚
$\alpha_{c,avg.}$	0.526
Controlling Section	CHS 152.4x3.0
$C_{r,\ CHS}$	99 kN
End Plate Thickness	10 mm
Connection Bolts	4x Gr8.8 M16
$V_{r,\ bolt\ group}$	141 kN
Design Load	189 kN
Comparative Cross Angle Section	70x70x6
$T_{r,\ X\text{-}L}$	192 kN
Comparative Single CHS Section	CHS 193.7x3.5
$C_{r,\ X\text{-}CHS}$	222 kN

4.3.3. Site C

Data for Site C were obtained from an assembly drawing of the cross-braced CHS member, shown in Figure 4-8. Connection detail was not supplied for the member.

The data source supplied general arrangement drawings of typically applied connections to CHS members, but not specifically to the members associated with Site C. APPENDIX A – SITE C DRAWINGS outlines all gathered data associated with Site C, including the supplied typical connection configurations.

The configuration shown in Figure 4-8 described in Table 4.6 produced unanticipated results in the costing analysis, noting case count no. 36 results in sections 4.5.1, 4.5, and 4.5.3. The initial results motivated further analysis by two cases for Site C namely, Site C-C1-1 and Site C-C1-2 corresponding to cases 36 and 37 in the abovementioned sections.

The comparative configuration design load calculated for case 36 was controlled by the reference configuration member capacity, with case 37 controlled by the bolt group shear capacity. Various detail and results associated with the respective sites are listed .

An overview of the efficiency metrics indicated that Case 36 required comparative configuration angles approximately 230% heavier and 160-180% more expensive than the reference CHS configuration. Case 37, in comparison to Case 36, required comparative configuration angles approximately 170% heavier and 125-133% more expensive than the reference. provides detail and results pertinent to the investigated cases.

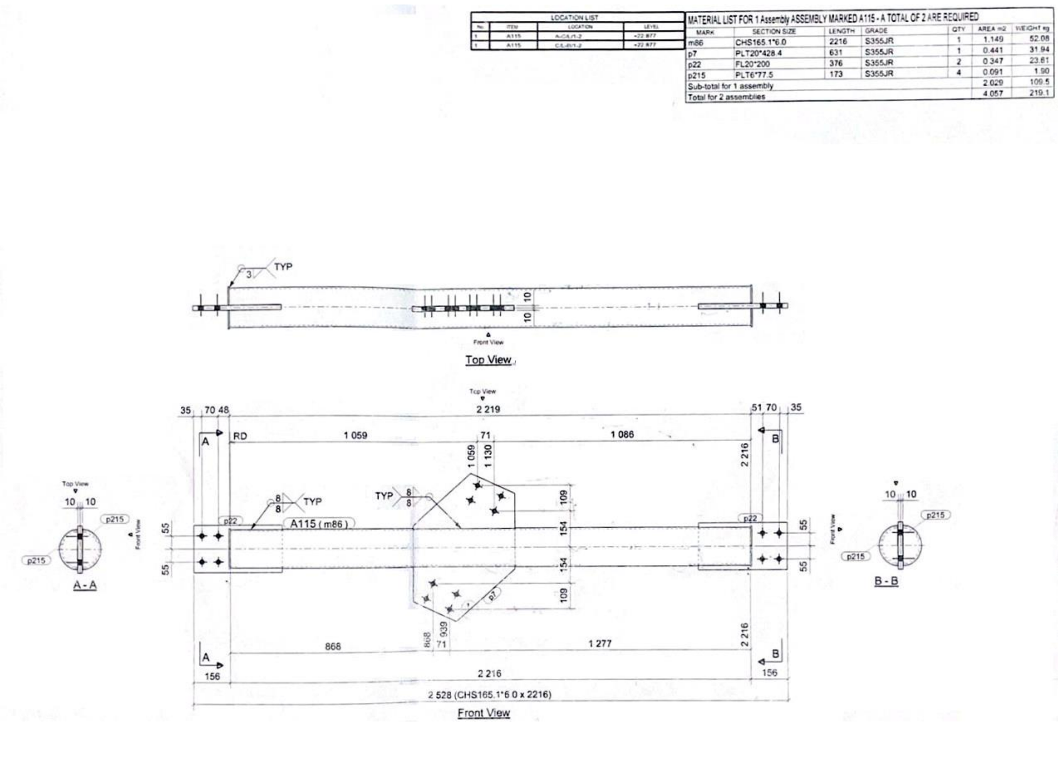


Figure 4-8 Site C Cross-braced CHS Member Assembly Drawing (Site C-C1)

The bolt group capacity was calculated on the assumption of double shear resistance, apparent from the end-plate thickness in conjunction with typical connection data supplied. The connection bolt sizes were not explicitly stated and thus assumed to be M20. The connection bolt size assumption was supported by the edge distances shown in Figure 4-8.

The short member length combined with relatively large cross section in resulted in a high reference configuration load capacity. The result was equivalently large member requirements for the comparative crossed Angle and single CHS configurations.

Commercial availability of CHS members is limited to a maximum size of CHS 219.1x6.0, noted from acquired data (MacSteel, 2022). Thus, for the single- CHS configuration, two smaller cross section single members were specified to meet the design load requirement and determine efficiency parameters.

Table 4.6 Analysis Detail of Site C-C1-1 and Site C-C1-2 Cross-braced Configurations

Configuration No.	**Site C-C1-1**	**Site C-C1-2**
Case Count No.	36	37
θ_{br}	45˚	
$\alpha_{c,avg.}$	0.519	
Controlling Section	CHS 165.1x6.0	CHS 165.1x6.0
$C_{r,\ CHS}$	882 kN	-
End Plate	20 mm	20 mm
Connection Bolts	4x Gr8.8 20*	4x Gr8.8 M20*
$V_{r,\ bolt\ group}$	-	700 kN
Design Load	1700 kN	1349 kN
Comparative Cross Angle Section	200x20x18	150x150x18

Configuration No.	Site C-C1-1	Site C-C1-2
$T_{r, X-L}$	1698 kN	1350 kN
Comparative Single CHS Section	2x CHS 165.1x6.0	2x CHS 139.7x6.0
$C_{r, X-CHS}$	2x 882 kN = 1764 kN	2x 709 kN = 1418 kN

4.3.4. Site D

The Site D configuration, shown in Figure 4-9, is a chevron braced arrangement instead of the vertical cross-braced arrangements that were the focus of this research. Analysis was nonetheless undertaken to evaluate the efficiency parameters of the CHS members against the investigated comparative configurations.

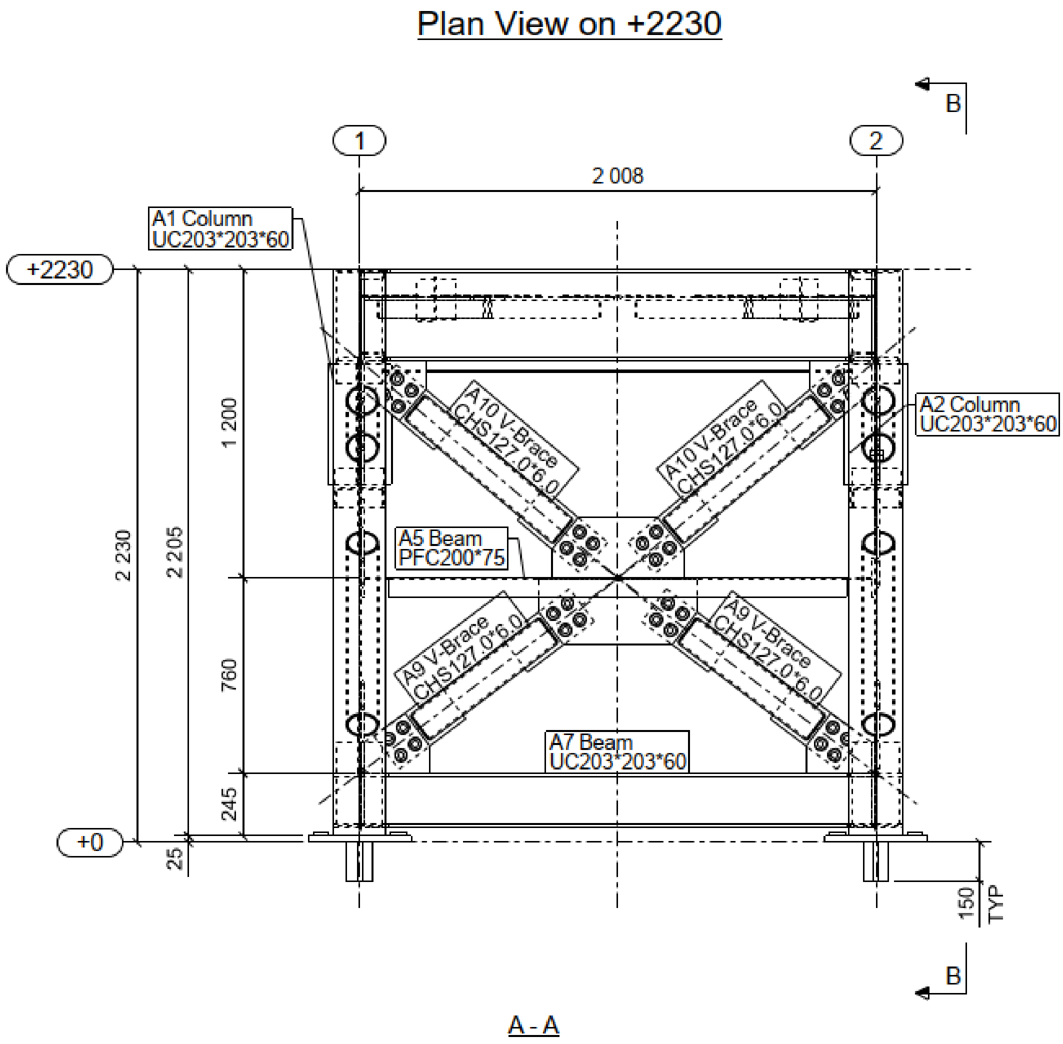


Figure 4-9 Site D Cross-braced CHS Member General Arrangement Elevation (Site D-C1)

The results for Site D efficiency metrics again proved unexpected, noting case count no. 38 results in sections 4.5.1, 4.5, and 4.5.3. Case 38 required comparative configuration angles approximately 230% heavier and 170% more expensive than the reference CHS configuration. Further analysis of the arrangement was thus motivated.

The general arrangement drawing notes specified Gr 8.8 M24 bolts for vertical bracing. The bolt group was determined to be in single shear from the site data. Noting Table 4.7, the bolt group capacity was calculated to be substantially less than the CHS 127x6.0-member compressive resistance. Comparative arrangements were then specified based on both the member compressive, and bolt group shear, capacities.

The costing analyses for Case 38 and Case 39 were then controlled by the member and bolt group shear capacities, respectively. Case 39, in comparison to Case 38, required comparative configuration angles approximately 170% heavier and 130-150% more expensive than the reference CHS configuration. Table 4.7 provides detail and results pertinent to the investigated cases.

Table 4.7 Analysis Detail of Site D-C1-1 and Site D-C1-2 Cross-braced Configurations

Configuration No.	Site D-C1-1	Site D-C1-2
Case Count No.	38	39
Member Width	1004 mm	
Compartment Height	760 mm	
θ_{br}	37.1°	
$\alpha_{c,avg.}$	0.526	
Controlling Section	CHS 127x6.0	CHS 127x6.0
$C_{r,\ CHS}$	627 kN	-
Connection Bolts	4x Gr8.8 M24	4x Gr8.8 M24
$V_{r,\ bolt\ group}$	-	504 kN
Design Load	1184 kN	951 kN
Comparative Cross Angle Section	150x150x18	150x150x15
$T_{r,\ X\text{-}L}$	1190 kN	1030 kN
Comparative Single CHS Section	219.1x6.0	177.8x6.0
$C_{r,\ X\text{-}CHS}$	1238 kN	972 kN

4.3.5. Site E

Figure 4-10 indicates the bracing configuration applied at Site E. The braced bays consisted of single CHS members presumably designed to act in both tension and compression. The analysis for Site D accordingly proceeded on the proposition of first calculating the single-braced configuration member capacity. The calculated capacity was then used to determine the member requirements for equivalent cross- braced CHS and Angle configurations. Table 4.8 outlines pertinent design variables and results for Site E.

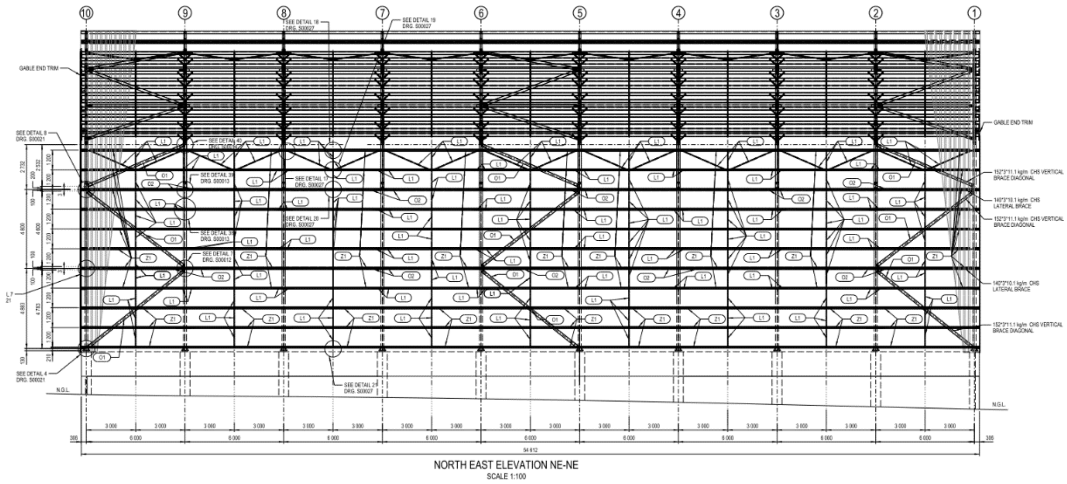


Figure 4-10 Site E CHS Single Brace Member General Arrangement Elevation (Site E-C1)

The two investigated cases were controlled by cross section compressive capacity and bolt group shear capacity, as with Sites C and D. The calculated member capacity was greater than the bolt group shear capacity, noting the values reported in Table 4.8. The bolt group capacity was calculated based on single shear. The bolt group would fail in single shear before the member capacity was achieved. A comparative investigation governed by the member and bolt group resistance listed in Table 4.8 followed.

The angle member specification for site E was controlled by the member slenderness ratio, for both cases, due to large compartment dimensions and low design loads. Two different cross sections were specified for the crossed CHS configurations in the reverse analysis. The aim was to provide the most economically competitive comparison and informative results from which to draw conclusions.

Noting Cases 40 and 41 in sections 4.5.1, 4.5, and 4.5.3 the comparative configuration results produced masses about one third lighter, and at 40-60% of the cost, compared to the reference configuration.

Table 4.8 Analysis Detail of Site E-C1-1 and Site E-C1-2 Cross-braced Configurations

Configuration No.	**Site E-C1-1**	**Site E-C1-2**
Case Count No.	40	41
Compartment Width	6000 mm	
Compartment Height	4883 mm	
θ_{br}	39.1˚	
$\alpha_{c,avg.}$	0.525	
Controlling Section	CHS 152.4x3.0	CHS 152.4x3.0
$C_{r,\text{ Single CHS}}$	136 kN	-
Connection Bolts	2x Gr8.8 M16	2x Gr8.8 M16
$V_{r,\text{ bolt group}}$	-	108 kN
Comparative Cross CHS Section	127x3.0	114.x3.0
$C_{r,\text{ X-CHS}}$	83 kN	61 kN
Comparative Cross- Angle Section	70x70x6	70x70x6
$T_{r,\text{ X-L}}$	144 kN	114 kN

4.3.6. Site F

Five cases were derived from the data received for Site F. Figure 4-11 and Table 4.9 are associated with cases Site F-C1 and Site F-C2. Figure 4-12 and Table 4.10 are associated with case Site F-C3. Figure 4-13 and Table 4.11 are associated with cases Site F-C4 and Site F-C5.

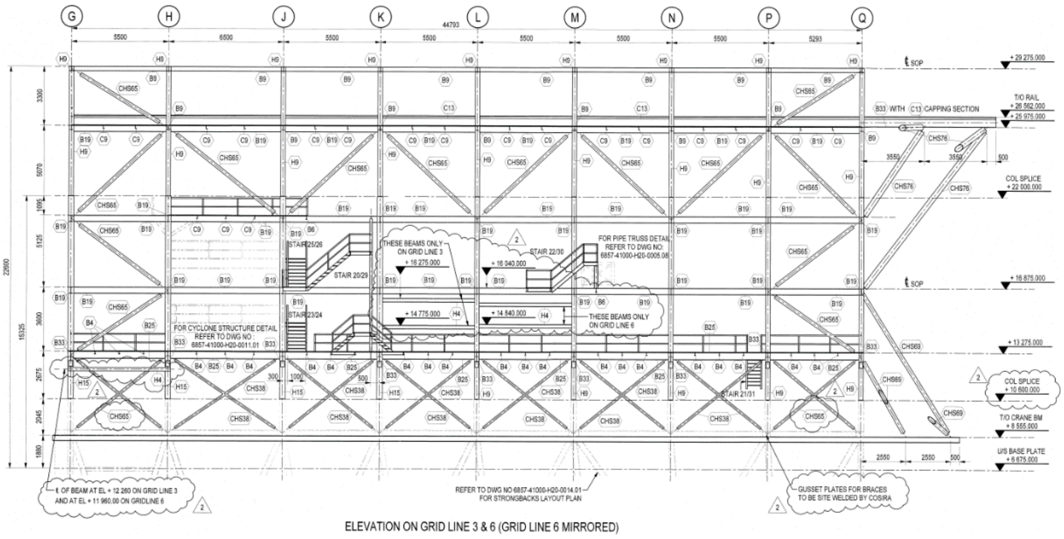


Figure 4-11 Site F Case 1 and Case 2 Cross-braced CHS Configurations (Site F-C1 and Site F-C2)

All cases were controlled by the member cross section capacities, instead of the bolt group shear capacities. Design loads were high for cases Site F-C2 and Site F-C3. Comparative configuration member requirements were equivalently sized. A consequence was that the single-braced configurations required two members to meet load requirements, analogous to Site C-C1.

Table 4.9 Analysis Detail of Site F-C1 and Site F-C2 Cross-braced Configurations

Configuration No.	**Site F-C1**	**Site F-C2**
Case Count No.	42	43
Compartment Width	6000 mm	5500 mm
Compartment Height	4314 mm	4314 mm
θ_{br}	33.6˚	38.1˚
$\alpha_{c,avg.}$	0.527	0.525
Controlling Section	CHS 127x6.0	CHS 193.7x6.0
$C_{r,\text{ CHS}}$	153 kN	550 kN
End Plate	16 mm	20 mm
Connection Bolts	6x Gr8.8 M24	9x Gr8.8 M24
$V_{r,\text{ bolt group}}$	756 kN	1134 kN
Design Load	290 kN	1048 kN
Comparative Cross Angle Section	80x80x8	150x150x15

Configuration No.	Site F-C1	Site F-C2
$T_{r,\ X\text{-}L}$	308 kN	1114 kN
Comparative Single CHS Section	CHS 165.1x6.0	2x CHS 193.7x6.0
$C_{r,\ X\text{-}CHS}$	317 kN	2x 550 kN = 1100 kN

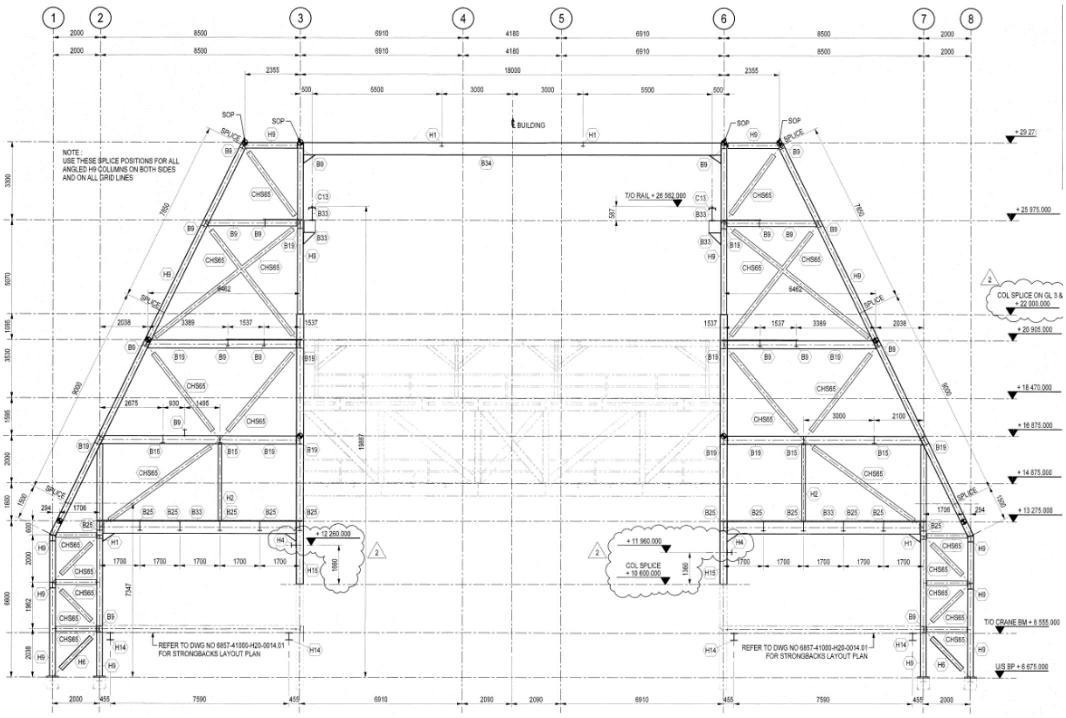


Figure 4-12 Site F Case 3 Cross-braced CHS Configuration (Site F-C3)

Table 4.10 Analysis Detail of Site F-C3 Cross-braced Configuration

Configuration No.	Site F-C3
Case Count No.	44
Compartment Width	6463 mm
Compartment Height	6165 mm
θ_{br}	43.7˚
$\alpha_{c,avg.}$	0.521
Controlling Section	CHS 193.7x6.0
$C_{r,\ CHS}$	392 kN
End Plate Thickness	20 mm
Connection Bolts	9x Gr8.8 M24
$V_{r,\ bolt\ group}$	1134 kN
Design Load	753 kN

Configuration No.	Site F-C3
Comparative Cross Angle Section	150x150x10
$T_{r,\text{ X-L}}$	192 kN
Comparative Single CHS Section	2x CHS 193.7x6.0
$C_{r,\text{ X-CHS}}$	2x 392 kN = 784 kN

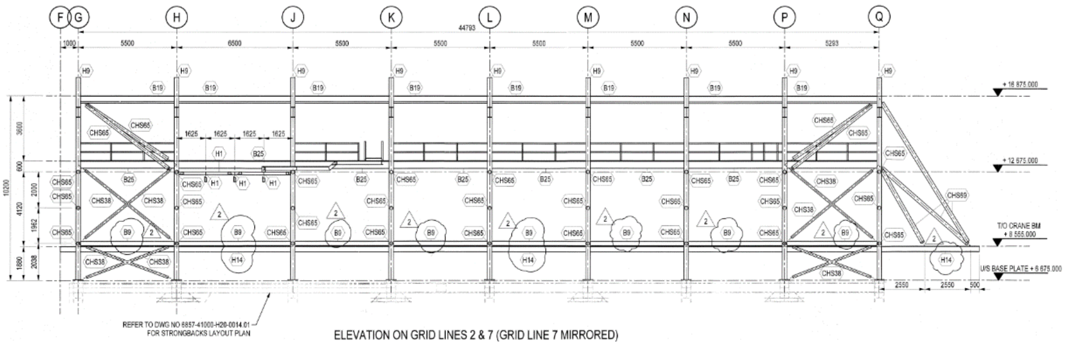


Figure 4-13 Site F Case 4 and Case 5 Cross-braced CHS Configurations (Site F-C4 and Site F-C5)

Table 4.11 Analysis Detail of Site F-C4 and Site F-C5 Cross-braced Configurations

Configuration No.	Site F-C4	Site F-C5
Case Count No.	45	46
Compartment Width	5500 mm	5500 mm
Compartment Height	5500 mm	2038 mm
θ_{br}	37.8˚	20.3˚
$\alpha_{c,avg.}$	0.525	0.527
Controlling Section	CHS 127x6.0	CHS 127x6.0
$C_{r,\text{ CHS}}$	186 kN	245 kN
End Plate	16 mm	16 mm
Connection Bolts	6x Gr8.8 M24	6x Gr8.8 M24
$V_{r,\text{ bolt group}}$	756 kN	756 kN
Design Load	355 kN	465 kN
Comparative Cross Angle Section	80x80x10	100x100x10
$T_{r,\text{ X-L}}$	365 kN	483 kN
Comparative Single CHS Section	CHS 165.1x6.0	CHS 165.1x6.0
$C_{r,\text{ X-CHS}}$	376 kN	472 kN

4.3.7. Site G

Site G is characterised as per Figure 4-14. Connection detail was not gathered for this site. Subsequently, a parametric analysis was conducted investigating the influence of the connector capacity, and consequent control configuration capacity, on the comparative configuration member requirements.

Figure 4-14 Site G Case 1 Cross-braced CHS Configurations (Site G-C1-1 to Site G-C1-4)

The member ends were fixed with a single bolt forming a classic pinned connection. The pin sizes were assumed to be M24, M20, and M16 for Site G-C1-2, Site G-C1-3, and Site G-C1-4, respectively. Analysis of Site G-C1-1 was governed by the member capacity.

Table 4.12 outlines details and results for Site G-C1-1 and Site G-C1-2. Table 4.13 outlines details and results for Site G-C1-3 and Site G-C1-4. A pin sized

M24 would be the most efficient of those studied noting the single-braced CHS results for Site G-C1-2 in Table 4.14.

Table 4.12 Analysis Detail of Site G-C1-1 and Site G-C1-2 Cross-braced Configurations

Configuration No.	**Site G-C1-1**	**Site G-C1-2**
Case Count No.	47	48
Compartment Width	2660 mm	
Compartment Height	1900 mm	
θ_{br}	35.5°	
$\alpha_{c,avg.}$	0.527	
Controlling Section	CHS 101.6x3.0	CHS 101.6x3.0
$C_{r,\ CHS}$	186 kN	-
Connection Bolts	-	1x Gr8.8 M24
$V_{r,\ bolt\ group}$	-	126 kN
Design Load	315 kN	239 kN
Comparative Cross Angle Section	70x70x10	70x70x8
$T_{r,\ X\text{-}L}$	314 kN	250 kN
Comparative Single CHS Section	CHS 152.4x3.0	CHS 139.7x3.0
$C_{r,\ X\text{-}CHS}$	315 kN	269 kN

The specified angle member resistance under Site G-C1-4 in Table 4.13 is approximately 2.5% below the design load which was considered acceptable for the purposes of this study. Interestingly for Site G-C1-4 a M16 pin required a CHS 101.6x3.0 member for the single-braced configuration.

Table 4.13 Analysis Detail of Site G-C1-3 and Site G-C1-4 Cross-braced Configurations

Configuration No.	**Site G-C1-3**	**Site G-C1-4**
Case Count No.	49	50
Compartment Width	2660 mm	
Compartment Height	1900 mm	
θ_{br}	35.5°	
$\alpha_{c,avg.}$	0.527	

Configuration No.	Site G-C1-3	Site G-C1-4
Controlling Section	CHS 101.6x3.0	CHS 101.6x3.0
$C_{r,\ CHS}$	-	-
Connection Bolts	1x Gr8.8 M20	1x Gr8.8 M16
$V_{r,\ bolt\ group}$	88 kN	54 kN
Design Load	166 kN	103 kN
Comparative Cross Angle Section	60x60x8	50x50x6
$T_{r,\ X\text{-}L}$	165 kN	100 kN
Comparative Single CHS Section	CHS 114.3x3.0	CHS 101.6x3.0
$C_{r,\ X\text{-}CHS}$	178 kN	137 kN

4.3.8. Site H

Figure 4-15 and Table 4.14 outline the reference configuration for Site H. The results of the comparative configuration member requirement are further indicated in Table 4.14. The design load was controlled by the configuration member capacity. The connection capacity was evaluated based on the bolt group in single shear.

Figure 4-15 Site H Case 1 Cross-braced CHS Configurations (Site H-C1)

Table 4.14 Analysis Detail of Site H-C1 Cross-braced Configuration

Configuration No.	**Site H-C1**
Case Count No.	51
Compartment Width	6600 mm
Compartment Height	7200 mm
θ_{br}	50.2˚
$\alpha_{c,avg.}$	0.517
Controlling Section	CHS 219.1x6.0
$C_{r,\ CHS}$	498 kN
End Plate Thickness	25 mm
Connection Bolts	6x Gr8.8 M24
$V_{r,\ bolt\ group}$	756 kN
Design Load	964 kN
Comparative Cross Angle Section	150x150x15
$T_{r,\ X\text{-}L}$	1030 kN
Comparative Single CHS Section	2x CHS 219.1x6.0
$C_{r,\ X\text{-}CHS}$	2x 498kN = 996 kN

4.3.9. Site I

Site I is characterised in Figure 4-16 and Table 4.15. No connection detail was obtained for Site I. The comparative configuration analysis is then controlled by the reference configuration member capacity.

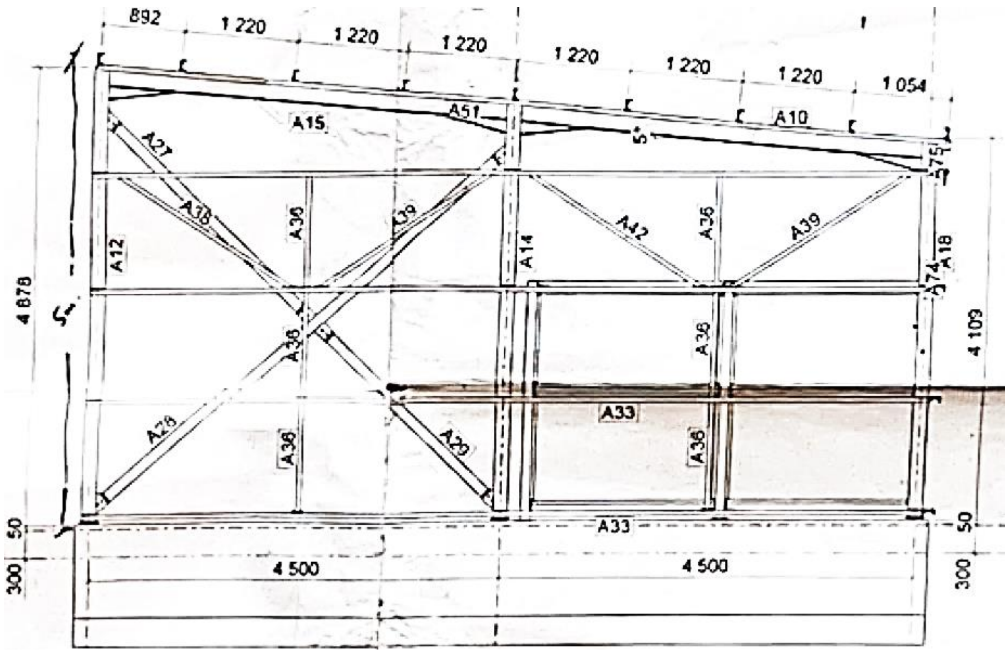


Figure 4-16 Site I Case 1 Cross-braced CHS Configurations (Site I-C1)

Table 4.15 Analysis Detail of Site I-C1 Cross-braced Configuration

Configuration No.	Site I-C1
Case Count No.	52
Compartment Width	4500 mm
Compartment Height	4320 mm
θ_{br}	43.8˚
$\alpha_{c,avg.}$	0.520
Controlling Section	CHS 114.3x3.5
$C_{r,\ CHS}$	103 kN
Design Load	197 kN
Comparative Cross Angle Section	100x100x8
$T_{r,\ X\text{-}L}$	197 kN
Comparative Single CHS Section	CHS 165.1x3.0
$C_{r,\ X\text{-}CHS}$	227 kN

4.4. Costing Models

Applied costing models are presented. Costing data were obtained for raw materials costs and for fabricator associated cost. Costing models derived from the obtained data are described under respective subsections.

4.4.1. Raw Materials

Raw materials costs associated with members specified for each case and respective configuration are presented in Figure 4-17 and Figure 4-18. Figure 4-17 gives raw materials cost per ton for the hypothetical configurations analysed. Figure 4-18 gives raw materials cost per ton for the built-site configurations analysed.

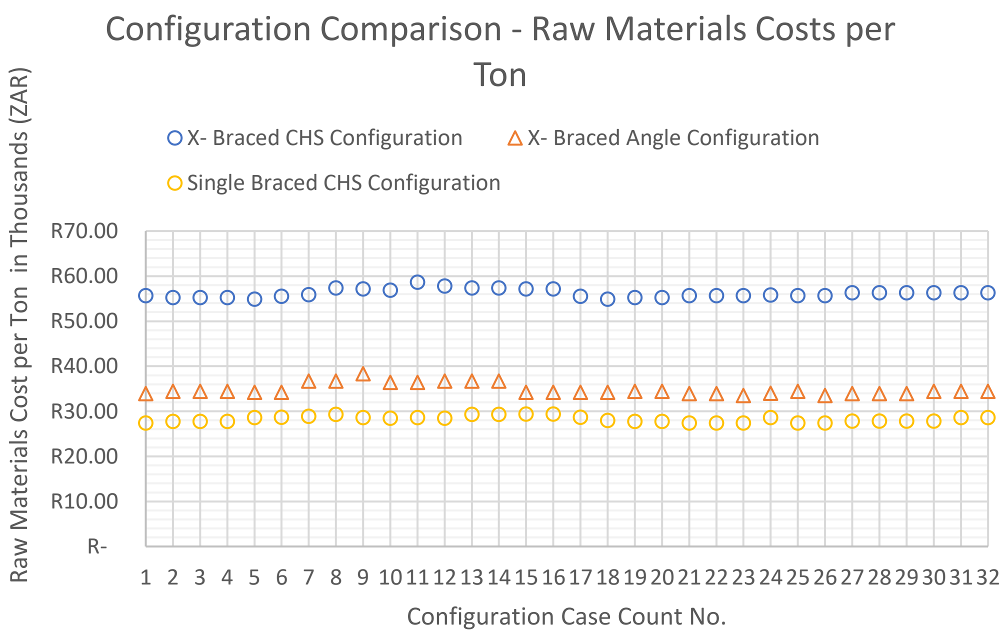


Figure 4-17 Hypothetical Configuration Raw Materials Cost per Ton by Case Count Number

Raw materials costs for reference and comparative configurations are combined in Figure 4-17 and Figure 4-18.The crossed CHS reference configurations are described by blue circles. The crossed Angle comparative configurations are described by orange triangles. The single CHS comparative configurations are described by yellow circles. Comparisons between configuration costs may thus be readily observed.

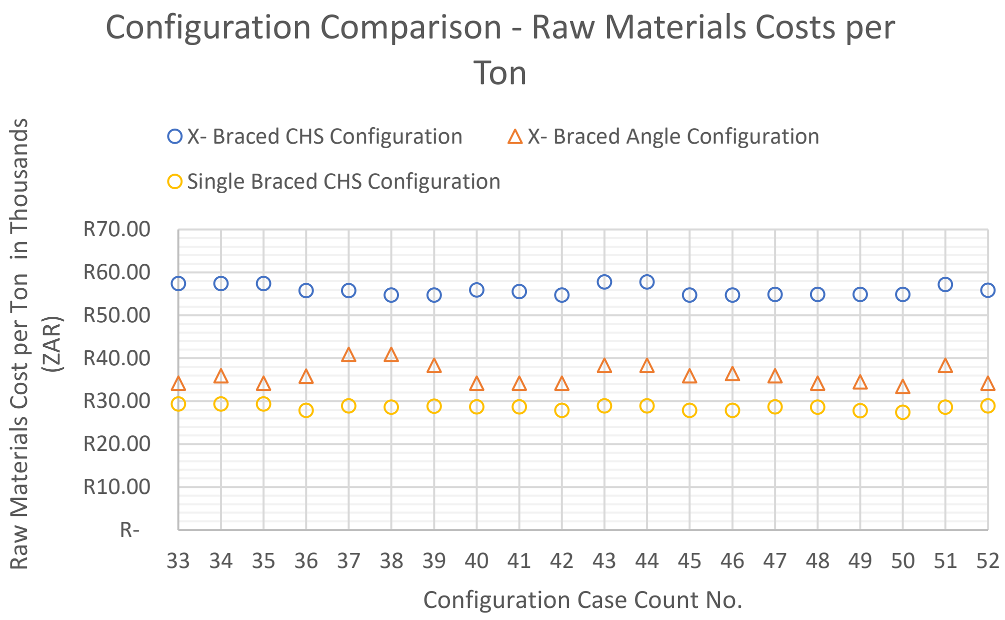


Figure 4-18 Built-site Configuration Raw Materials Cost per Ton by Case Count Number

The reference configuration costs per ton are the greatest for all cases presented in both Figure 4-17 and Figure 4-18 The raw materials cost per ton of the cross-braced Angle comparative configurations are approximately two thirds the cost of reference crossed CHS configurations. The raw materials cost per ton of the single-braced CHS comparative configurations are approximately half the cost of reference crossed CHS configurations.

4.4.2. Fabrication and Erection

Costing models were derived from two separate steel fabricators. The models are arbitrarily referred to as Costing Model I (CM I) and Costing Model II (CM II). The costing models are presented from Figure 4-19 to Figure 4-22

The models comprise of fabrication and erection costs. Fabrication costs encompass labour, wastage, and materials costs. The total costs reported are taken as the sum of fabrication and erection costs. The indicated costs are member dependent with different pricing ascribed to light structural steel (0-25 kg/m), medium structural steel (25-40 kg/m), and CHS members. Colloquial definitions using the terms “CHS”, and “structural steel”, are applied in making costing model member differentiations.

Figure 4-19 illustrates labour and wastage costs. CM II did not make explicit provision for wastage, as with CM I, but the absolute indicated labour costs were higher. Factoring in wastage costs for CM I, labour costs for CHS members are approximately 35% and 23% higher for medium and light steel, respectively. CHS member labour costs are approximately 28% higher than structural steel considering CM II.

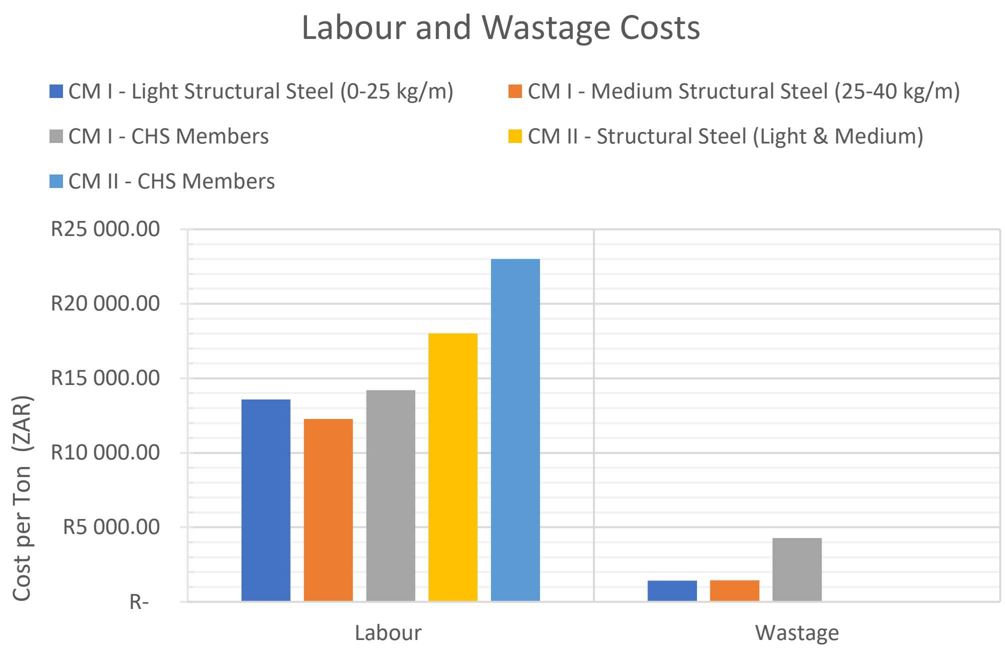


Figure 4-19 Steel Fabricator Costing Models - Labour and Wastage Costs

Figure 4-20 exhibits materials and total fabrication costs, excluding plate needed to fabricate member connections. Total fabrication costs are taken as the sum of labour, wastage and materials costs. CHS materials costs are approximately 61% and 59% higher for CM I light and medium steel, respectively, and 23% higher than structural steel for CM II. Total fabrication costs are approximately 44% and 48% higher for CM I light and medium steel, respectively, and 25% higher than structural steel for CM II.

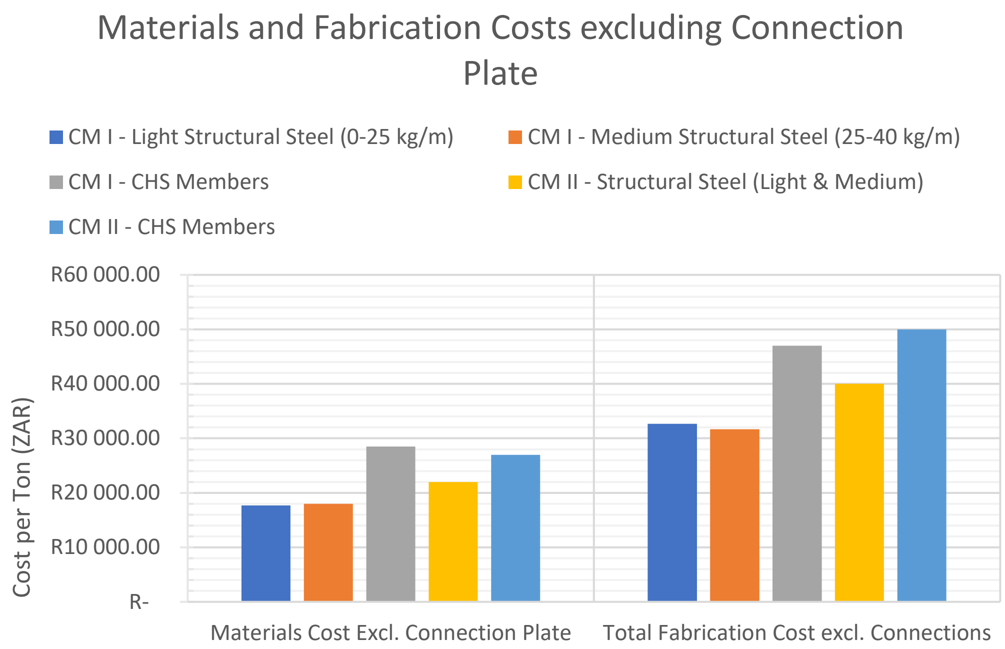


Figure 4-20 Steel Fabricator Costing Models - Materials and Fabrication Costs (excluding Connection Plate)

Figure 4-21 provides materials and total fabrication costs, including plate needed to fabricate member connections. CHS materials costs are both approximately 58% higher for CM I light and medium steel, and 28% higher than structural steel for CM II.

Total fabrication costs are approximately 44% and 49% higher for CM I light and medium steel, respectively, and 28% higher than structural steel for CM II. Connecting plate costs are applied as a percentage of the member costs. The applied percentage varies from 10% to approximately 19% dependent on member and costing model.

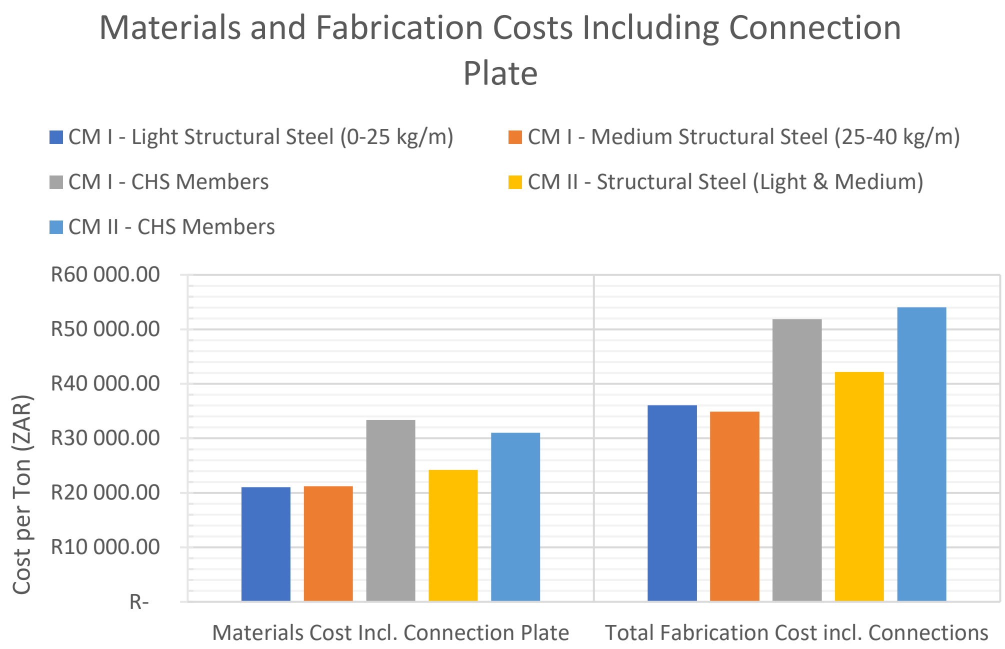


Figure 4-21 Steel Fabricator Costing Models - Materials and Fabrication Costs (including Connection Plate)

Figure 4-22 offers erection and total costs, including plate needed to fabricate member connections. Erection costs are taken as a fixed amount per ton regardless of section type. Comparing CHS to structural steel member costs, total costs are approximately 26% and 29% higher for CM I light and medium steel, respectively, and 23% higher than structural steel for CM II. Total costs in vary by approximately 13% to 18% between CM I and CM II dependent on cross section type.

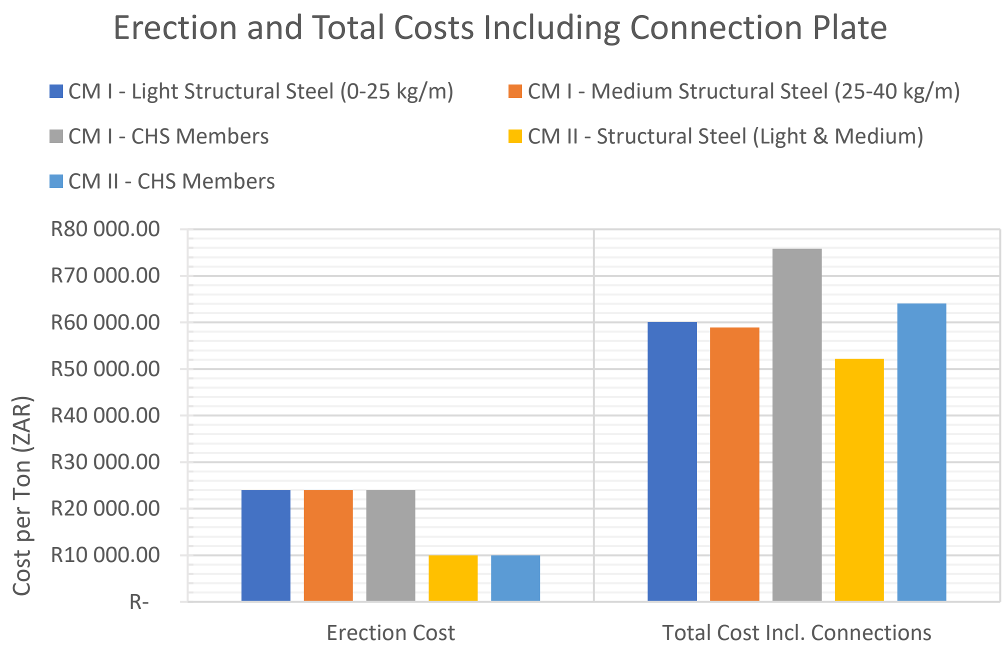


Figure 4-22 Steel Fabricator Costing Models – Erection and Total Costs (including Connection Plate)

4.5. Efficiency Metrics

4.5.1. Unit Masses

Relative configuration unit masses are shown to draw comparisons in Figure 4-23 and Figure 4-24 for the hypothetical and built-site cases, respectively. Figure 4-23 highlights that, for 84% of the analysed hypothetical cases, the comparative cross-braced Angle and single-braced CHS arrangements are, on average, 30% lower by unit mass than the reference cross-braced CHS configurations.

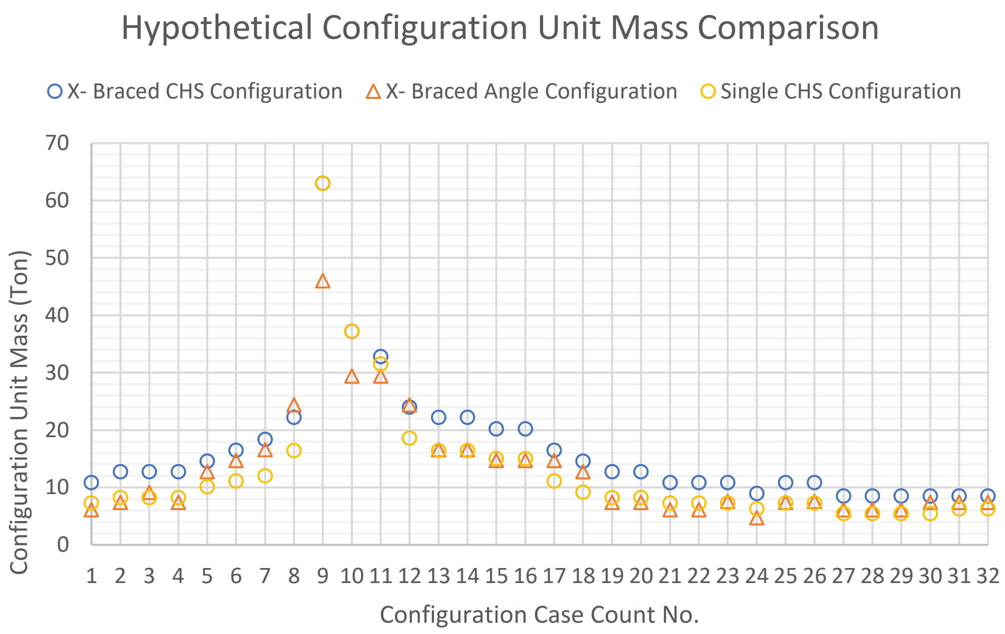


Figure 4-23 Reference and Comparative Hypothetical Configuration Unit Mass Analysis

Outliers are noted from Case 8 to Case 12 where the compartment dimensions were comparatively large, and an effective length factor of K = 1 was applied to the member sizing calculations. The member sizes for the hypothetical case reference configurations were determined by slenderness ratio. The results were comparably heavy CHS members in the reference configurations and high design loads applied to the comparative configuration cases.

Figure 4-24 provides insights into the built-site data. Six instances are noted where the reference configurations are not the heaviest by unit mass. The built-site data are discussed in section 4.2. Cases where the reference configuration unit masses are lighter, or equal to, those of the comparative configurations were associated with either low reference configuration member slenderness ratio, high configuration design load, or both.

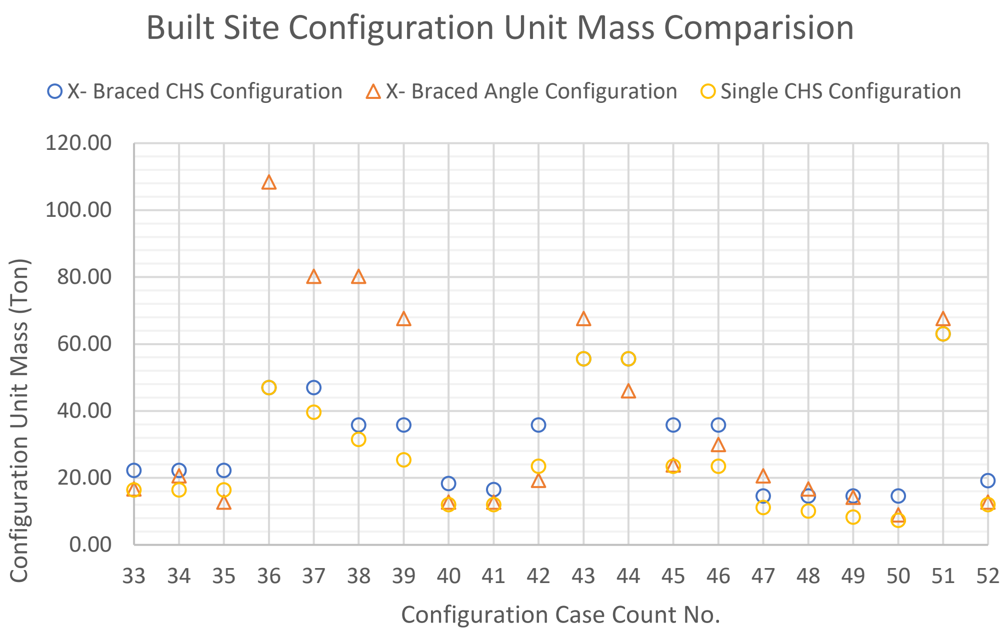


Figure 4-24 Reference and Comparative Built-site Configuration Unit Mass Analysis

Figure 4-25 to Figure 4-30 delve into trends in the relative mass ratios between the reference and comparative configurations. The relative mass ratios in these figures were found by dividing the mass of the reference case by the mass of the comparative case.

Figure 4-25, Figure 4-26, and Figure 4-27 provide a relative unit mass ratio analysis between crossed CHS, and crossed Angle, braced arrangements. Figure 4-28, Figure 4-29, and Figure 4-30 provide a relative unit mass ratio analysis between crossed CHS, and single CHS, braced arrangements.

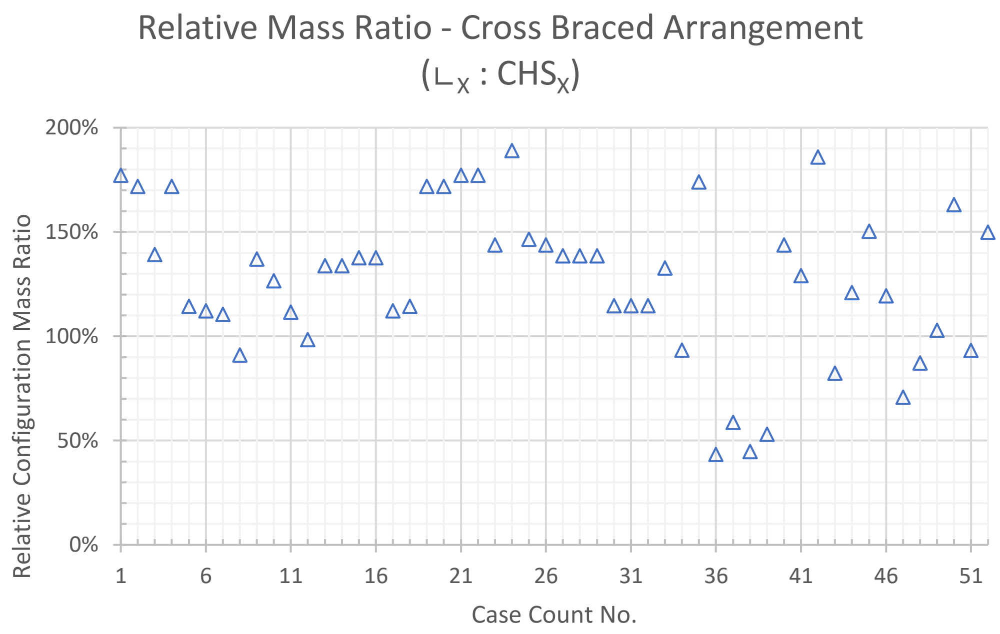


Figure 4-25 Relative Mass Ratio Comparison for Cross-braced CHS and Angle Arrangements by Case Count Number

The relative mass ratio between the reference crossed CHS, and comparative crossed Angle, configurations by case count number are seen in Figure 4-25. Apparent is that, in about 77% of the investigated cases, the mass of the reference configuration is at least 10% greater than the mass of the comparative configuration. Figure 4-26 describes the correlation between reference configuration CHS member slenderness ratio and calculated relative mass ratio. Figure 4-27 describes the correlation between relative mass ratio and comparative configuration design load for each case.

A strong direct correlation is observed in Figure 4-26 between the relative mass and slenderness ratios. An increase in reference configuration slenderness ratio points to an increase in relative mass ratio.

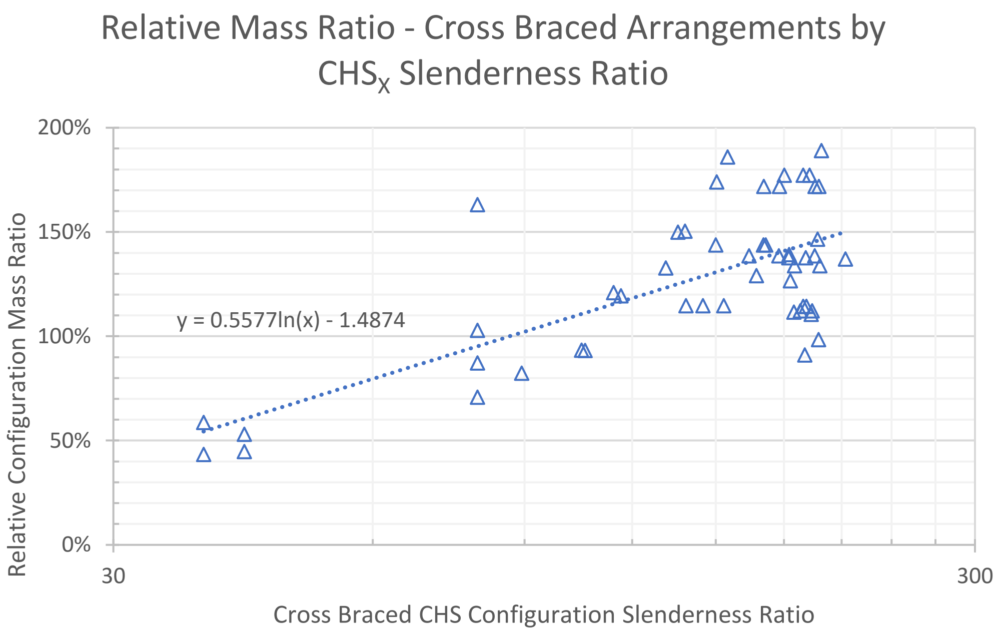


Figure 4-26 Relative Mass Ratio Comparison for Cross-braced CHS and Angle Arrangements by Cross-braced CHS Slenderness Ratio

A distribution of approximately 90% to 190% in the relative mass ratio results is noted in Figure 4-26 for at the upper bound of slenderness ratio range. The distribution points to a correlation with configuration design capacity which is presented in Figure 4-27. From the figure, cases with high comparative configuration design loads tend towards lower relative mass ratios.

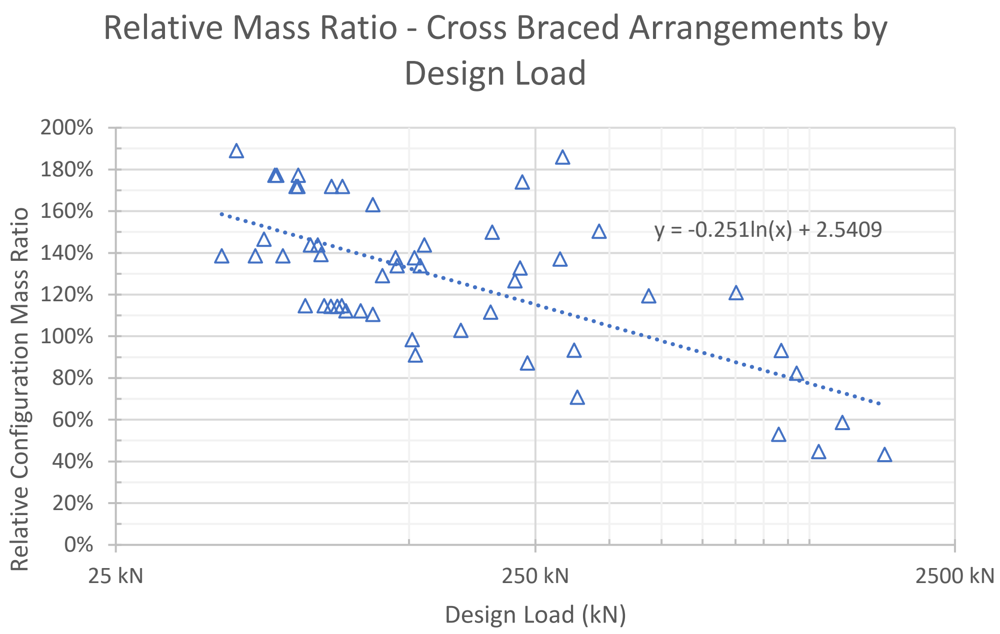


Figure 4-27 Relative Mass Ratio Comparison for Cross-braced CHS and Angle Arrangements by Comparative Configuration Design Load

Figure 4-28 provides the relative mass ratio between the reference crossed CHS, and single-braced CHS, configurations by case count number. The distribution of the results is lower for the crossed-to-single CHS mass comparisons, as expected. Figure 4-28 shows that for approximately 85% of the investigated cases the mass of the reference configuration is at least 10% greater than the mass of the comparative configuration.

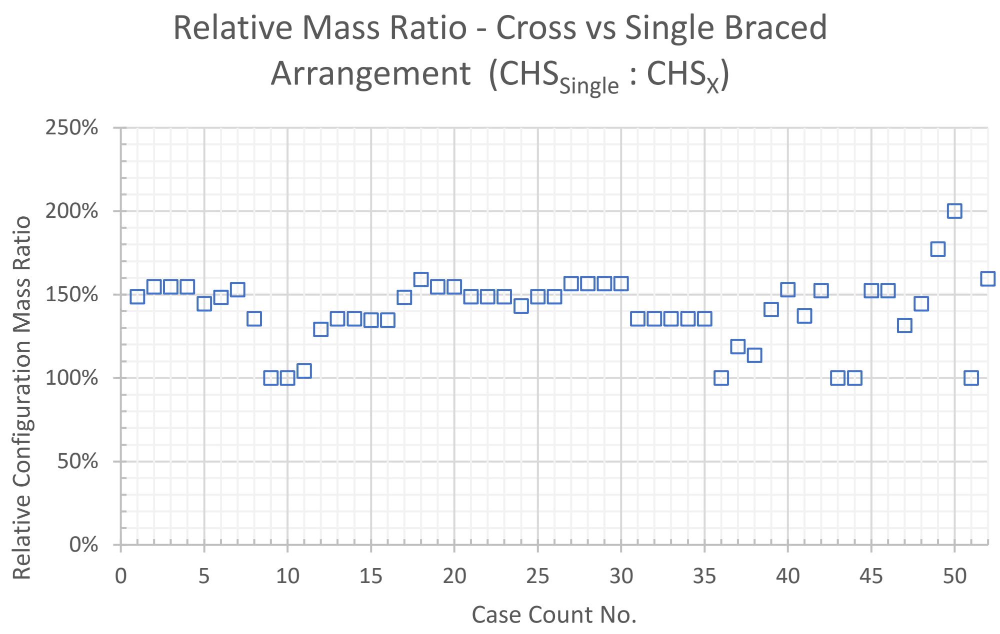


Figure 4-28 Relative Mass Ratio Comparison for Cross- and Single-braced CHS Arrangements

A comparison between Figure 4-29 and Figure 4-30 points to a stronger correlation between relative mass ratio and design load, than between relative mass and slenderness ratios. Figure 23 provides no clear discernible relationship between the relative mass ratio and reference configuration slenderness ratio. The lack of discernible relationship between relative mass ratio and slenderness ratio is expected as the cross sections are the same geometry across the comparison cases.

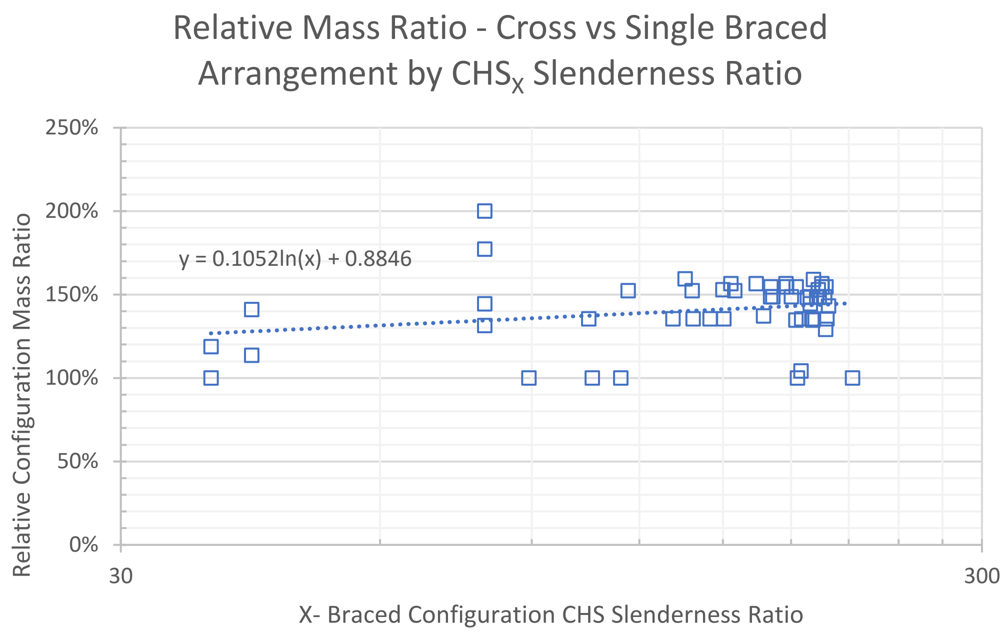


Figure 4-29 Relative Mass Ratio Comparison for Cross and Single-braced CHS Arrangements by Cross-braced CHS Slenderness Ratio

Figure 4-24 shows that the relative mass ratio decreases with increasing design load. The relationship reflects the limit imposed by commercially available CHS members. The largest commercially available CHS members noted were CHS 219x6.0. These sections controlled the upper bound design load applied to the comparative configurations. Consequently, the same size and number of members were required for the upper bound comparative configurations, as for the reference configurations, this is reflected by the relative mass ratios of 100% in Figure 4-29 and Figure 4-30.

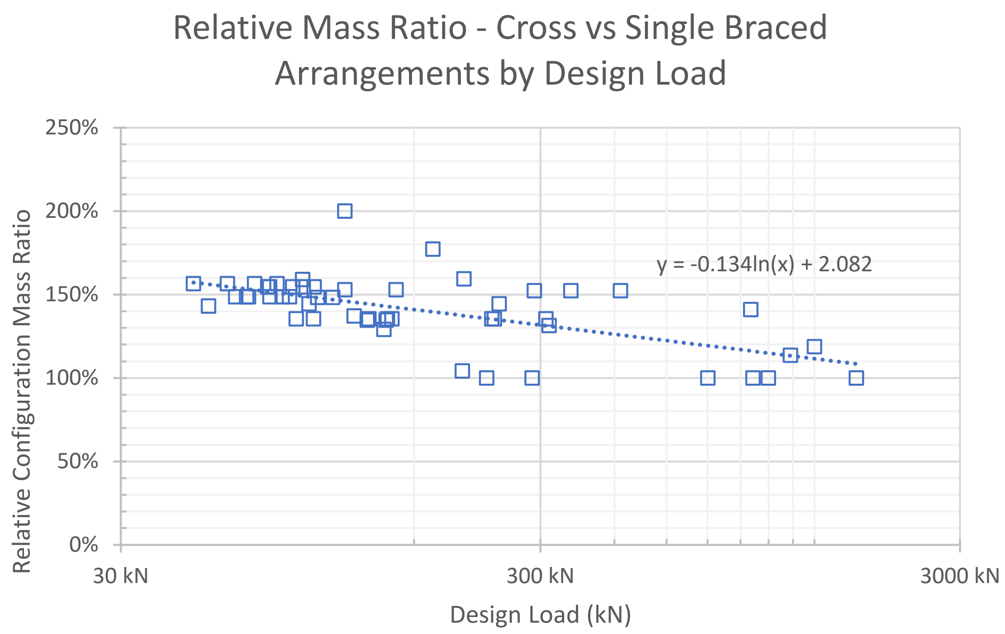


Figure 4-30 Relative Mass Ratio Comparison for Cross and Single-braced CHS Arrangements by Comparative Configuration Design Load

4.5.2. Raw Materials Costs

The hypothetical configuration unit cost comparison can be seen in Figure 4-31. The pattern follows the configuration unit mass comparison as expected. From the analysis roughly 90% of the comparative hypothetical configurations are cheaper per unit mass than the reference configurations. Cross-braced Angle, and single-braced CHS, configuration unit costs are 45% and 30% cheaper, respectively, on average compared to the reference configuration costs.

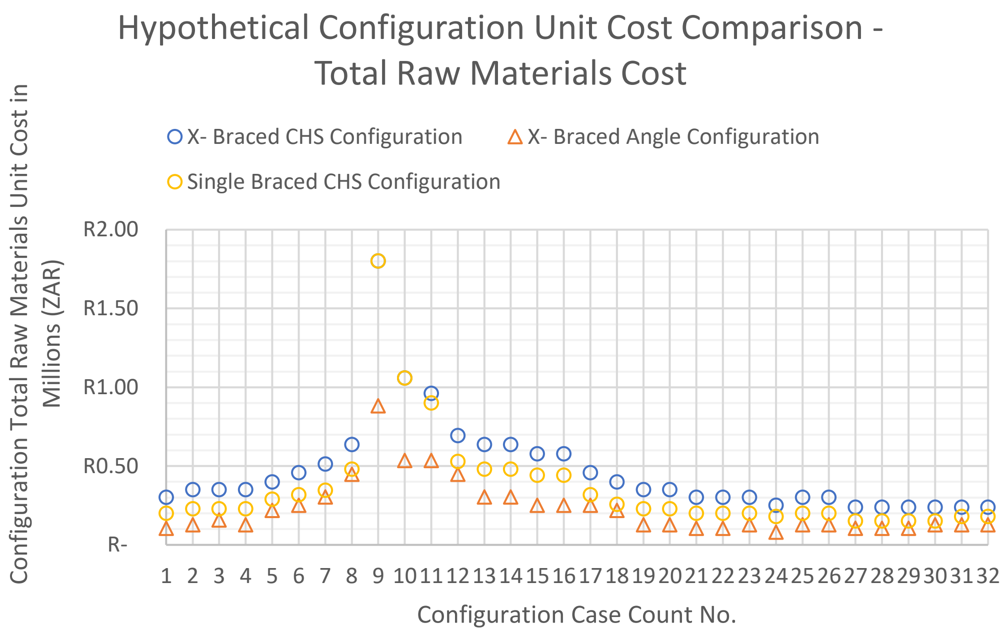


Figure 4-31 Hypothetical Configuration Unit Cost Comparison for Raw Materials Costs

The built-site unit cost comparison in Figure 4-32 shows that 80% of the investigated cases produce more economic results for both the comparative cross-braced Angle and single-braced CHS configurations relative to the reference configurations. Reasons explaining the outliers noted in Figure 4-32 are discussed under section 4.5.1.

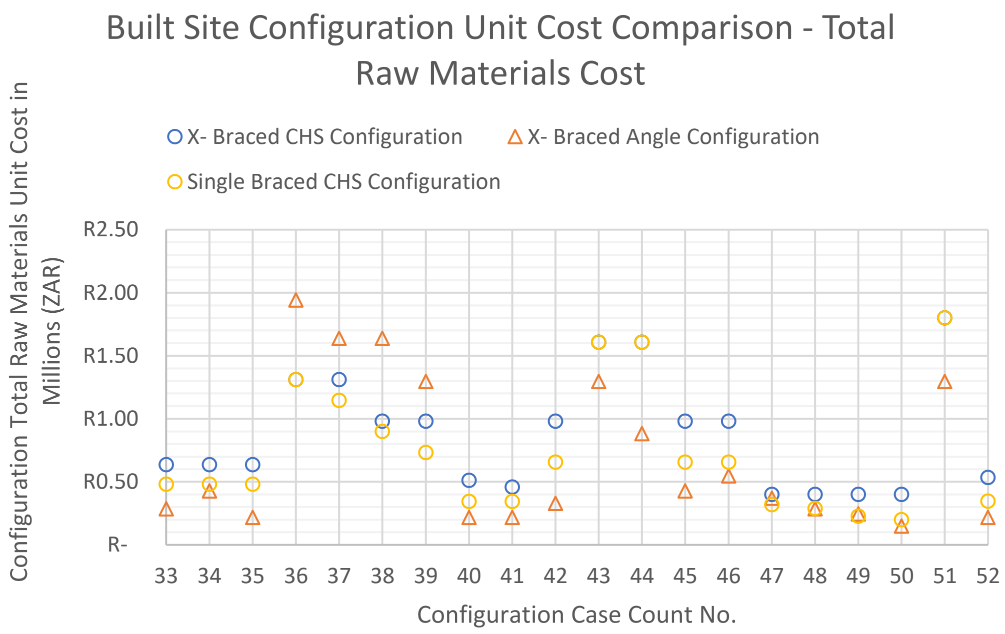


Figure 4-32 Built-site Configuration Unit Cost Comparison for Raw Materials Costs

Citing results reported in Figure 4-33, reference configuration unit costs are at least 110x the comparative configuration costs in roughly 92% of reviewed cases. Figure 4-34 illustrates the raw materials unit cost ratio as a function of crossed CHS slenderness ratio. Figure 4-35 shows cost ratio as a function of design load. Close correlation is observed with the mass results reported in section 4.5.1. Correlation to mass results is expected as costs are reported per ton.

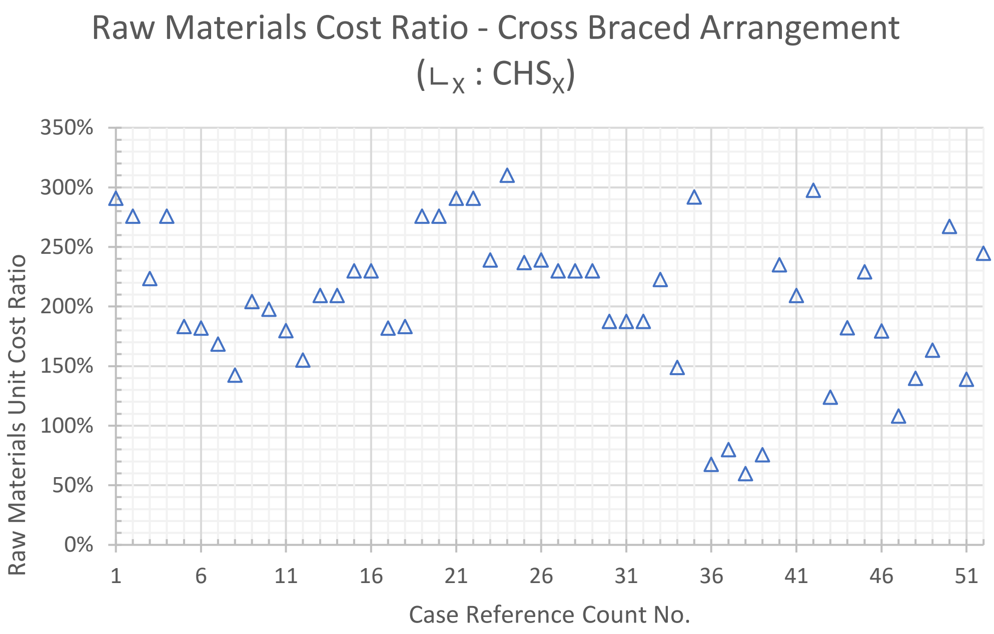


Figure 4-33 Raw Materials Cost Ratio Comparison for Cross-braced CHS and Angle Arrangements by Case Count Number

A reference configuration CHS member slenderness ratio of approximately 80 is observed to be a boundary for raw materials cost ratio, referring to Figure 4-34 Raw Materials Cost Ratio Comparison for Cross-braced CHS and Angle Arrangements by Cross-braced CHS Slenderness Ratio. Slenderness ratios below 80, for the analysed cases, result in raw materials cost ratios below 100%. The implication of a sub 100% cost ratio is that the respective reference configuration is more economical than the comparative configuration.

The four cases below a cost ratio of 100% in Figure 4-33, Figure 4-34 and Figure 4-35 are associated with Site C and Site D in section 4.2. The reference configuration cases for Site C and Site D have low member slenderness, high reference member flexural buckling capacity, and resultant high comparative case design loads.

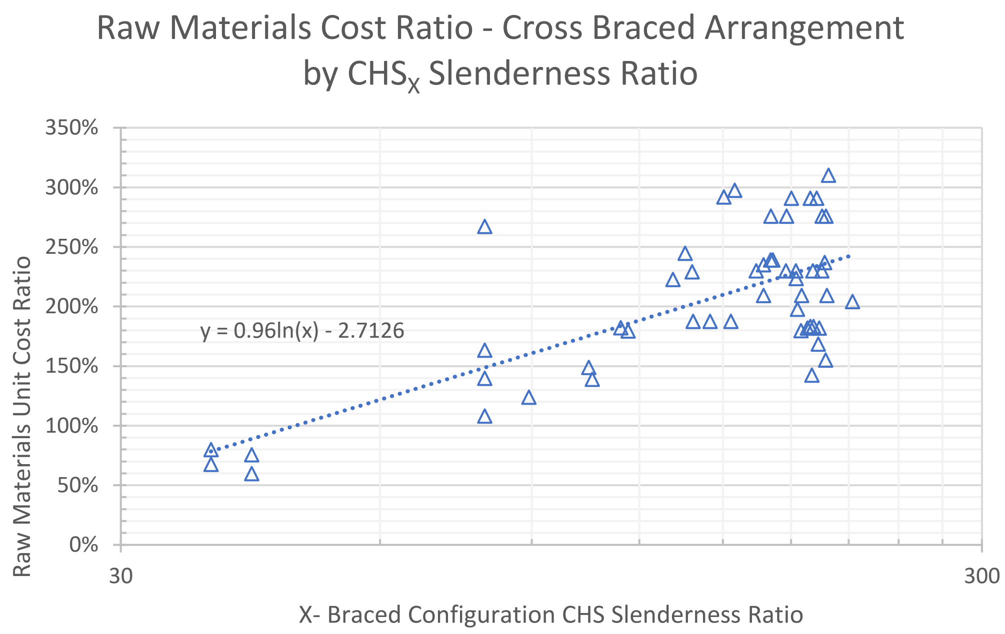


Figure 4-34 Raw Materials Cost Ratio Comparison for Cross-braced CHS and Angle Arrangements by Cross-braced CHS Slenderness Ratio

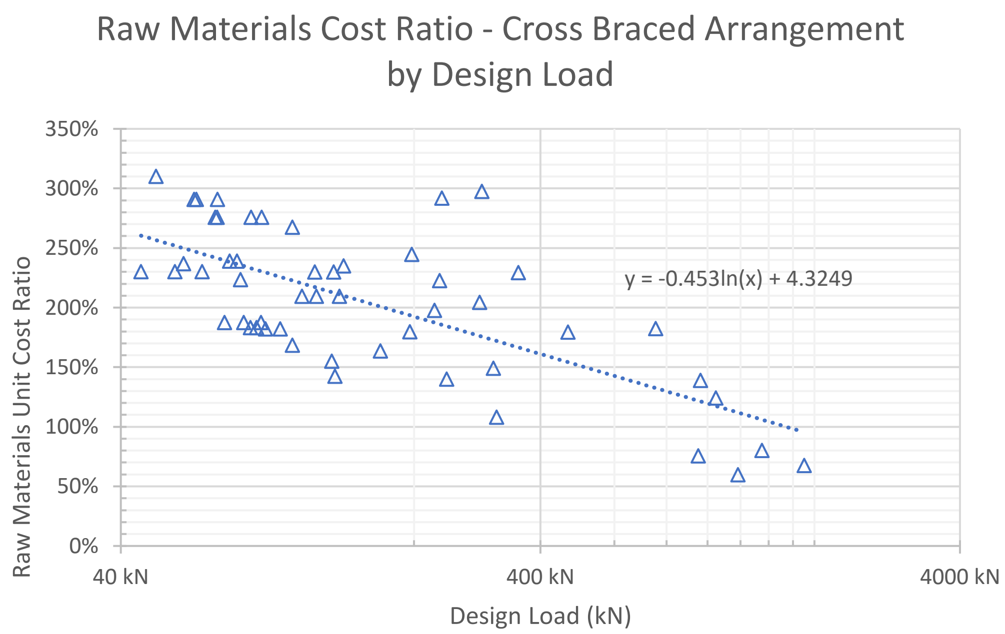


Figure 4-35 Raw Materials Cost Ratio Comparison for Cross-braced CHS and Angle Arrangements by Design Load

Figure 4-36, Figure 4-37, and Figure 4-38 show results for the cross versus single-braced arrangements raw materials cost ratio comparisons. The data shows a lower bound cost ratio of 100%, or 1:1, as expected.

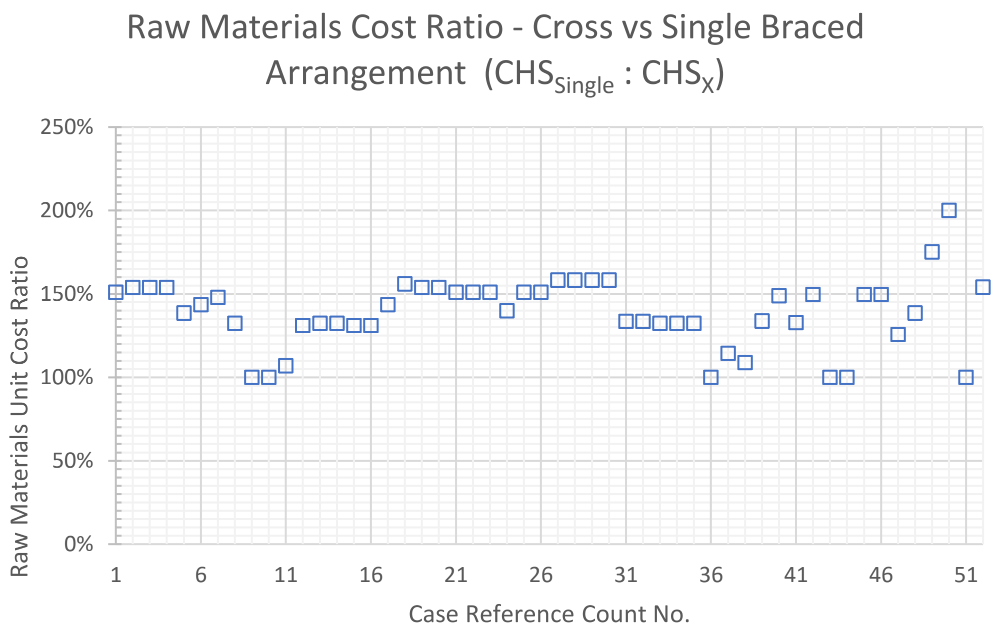


Figure 4-36 Raw Materials Cost Ratio Comparison for Cross and Single-braced CHS Arrangements by Case Count Number

A correlation of high design load and lower bound cost ratio limit is noted from Figure 4-38. CHS members selection was limited by commercially available cross sections. The largest commercially available cross sections are CHS 219x6.0 (MacSteel, 2022). Approximately 85% of analyses cases produced a raw materials cost ratio greater than 110%.

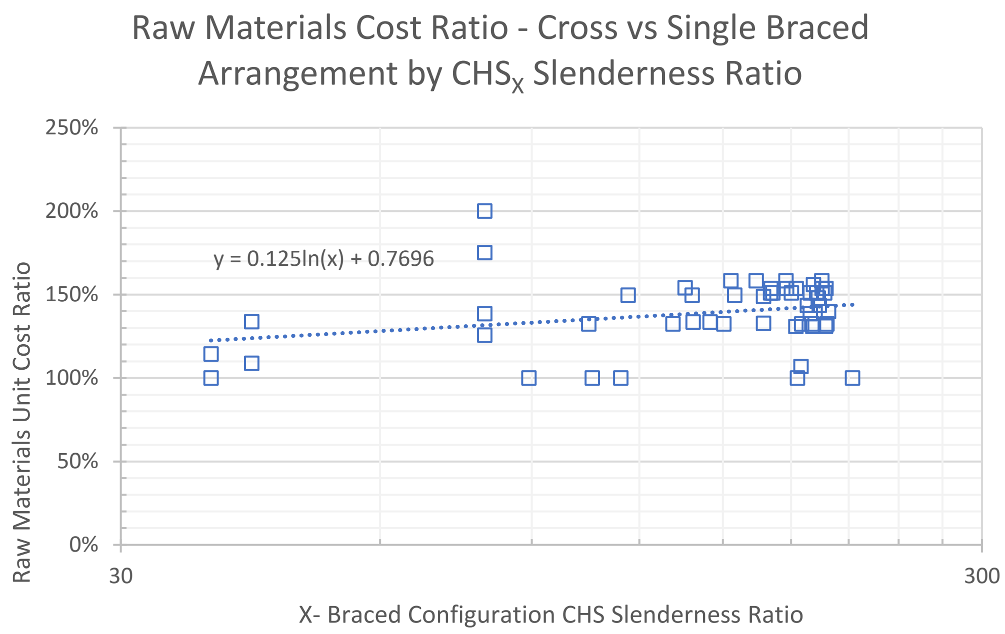


Figure 4-37 Raw Materials Cost Ratio Comparison for Cross and Single-braced CHS Arrangements by Cross-braced CHS Slenderness Ratio

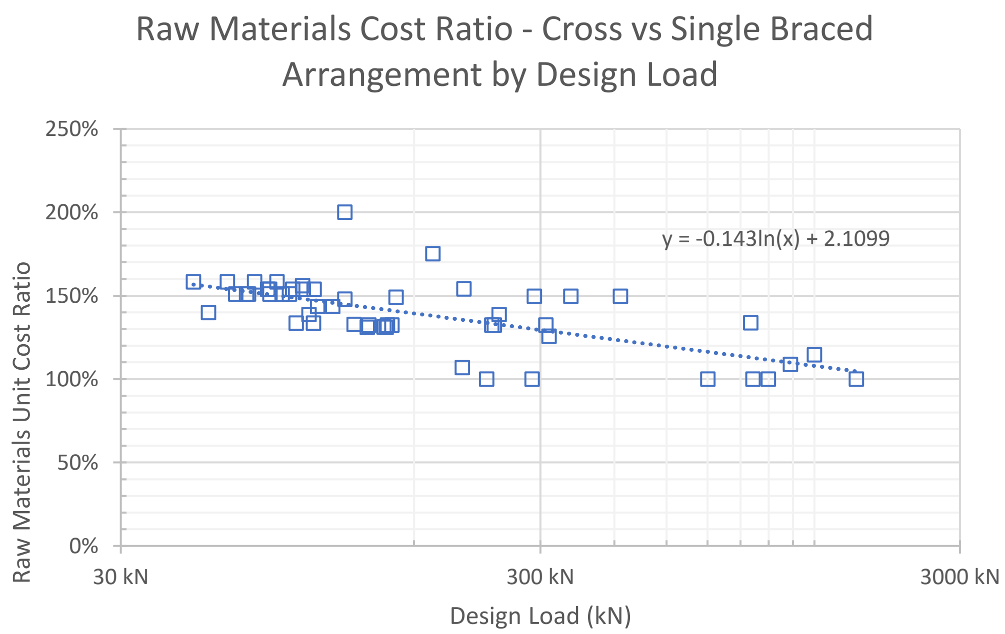


Figure 4-38 Raw Materials Cost Ratio Comparison for Cross and Single-braced CHS Arrangements by Design Load

4.5.3. Fabrication, Erection and Total Costs

Costing models results derived from the interviews that were conducted with two steel fabricators (Pereira, 2022) (Labuschagne, 2022) are discussed in this section.

Fabrication of CHS sections in vertical cross-braced arrangements necessitate cutting, slitting and welding processes (Labuschagne, 2022). These fabrication processes need to be implemented with good precision through the member centre-of-gravity to prevent additional member stresses through misalignment and eccentricities.

Fabrication sections for use in cross-braced arrangements typically necessitate only cutting and punching processes (Pereira, 2022). Consequently, fabrications costs are higher for CHS members compared to traditional cross sections.

CHS members are classed and priced separately from other structural steel members and cost approximately 25% more per unit mass (Labuschagne, 2022) (Pereira, 2022) on average according to steel fabricator costing models which consider materials, fabrication and erection costs.

Fabrication, erection and total costs are subsequently quantified and discussed. Costs were calculated to include connecting plates for members. The objective was to determine realistic unit configuration costs derived from costing model data obtained from local steel fabricators. The reported costs were calculated by multiplying the configuration unit mass by the relevant costing components.

Fabrication costs (including connecting plate) comprise of labour, wastage, and materials components as described in and . Fabrication cost results are presented in section 4.4.2.

Erection costs are calculated as a flat rate per unit mass, regardless of cross section, as shown by . Erection cost results are presented in section 4.4.2. Total cost results reported in section 4.4.2 are determined by the summation of Fabrication and Erection costs.

Fabrication Costs

Fabrication costs derived from CM I and CM II are taken from Figure 4-39 to Figure 4-42. Hypothetical configuration costs are indicated in Figure 4-39 and Figure 4-40. Built-site configuration results are given in Figure 4-41 and Figure 4-42. CM I and CM 2 results are shown respectively in consecutively enumerated figures. Reasons explaining the outliers noted in Figure 4-39 are discussed under section 4.5.1.

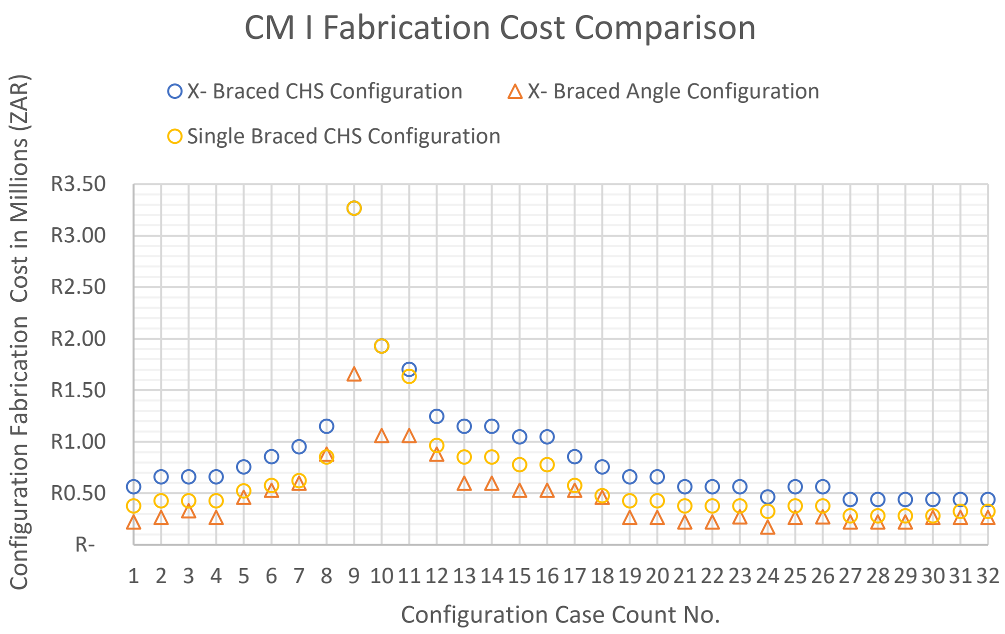


Figure 4-39 Hypothetical Configuration Fabrication Cost Comparison for CM I

Fabrication cost results presented in Figure 4-39 and Figure 4-40 point to the reference configurations being the most expensive in 100% of hypothetical cases. Two cases are noted where the single CHS comparative, and crossed CHS reference, configurations produce equivalent results. The single CHS comparative configurations produce the next highest fabrication costs for approximately 90% of analysed cases for CM I and 72% of cases for CM II. The comparative crossed angle configurations produce the lowest costs in 97% of cases for CM I and 78% of cases for CM II.

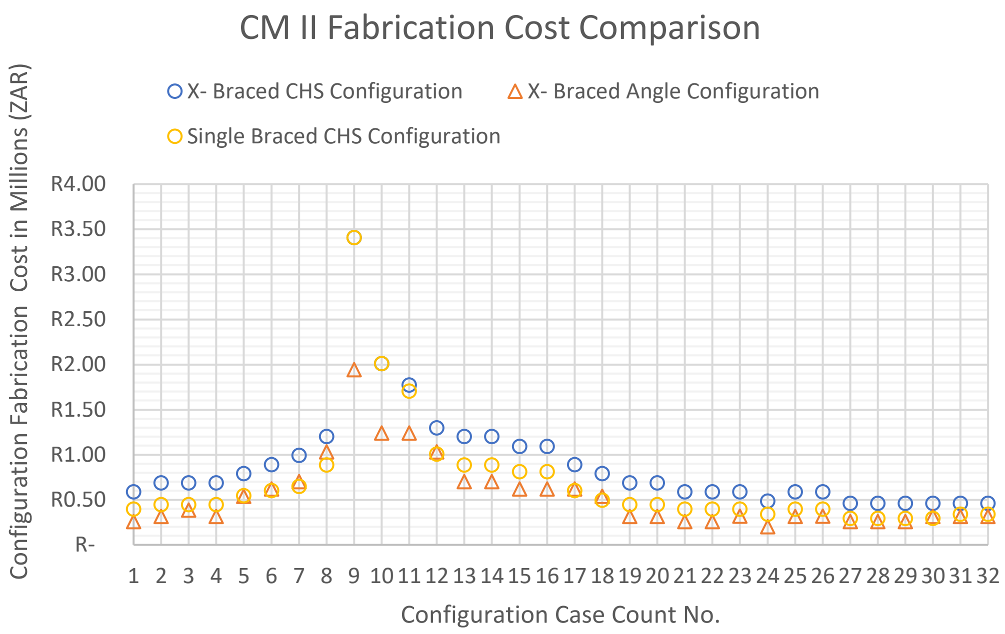


Figure 4-40 Hypothetical Configuration Fabrication Cost Comparison for CM II

Fabrication cost results presented in Figure 4-41 and Figure 4-42 indicate the comparative crossed angle configurations to be the most cost-effective in 60% of the built-site cases analysed. The CHS reference and comparative configurations produce equivalent, and the lowest cost, results in 5% of analysed cases. The comparative CHS configurations produce the most inexpensive results in 35% of cases. Similar trends are noted to the raw materials cost and configuration unit mass analyses.

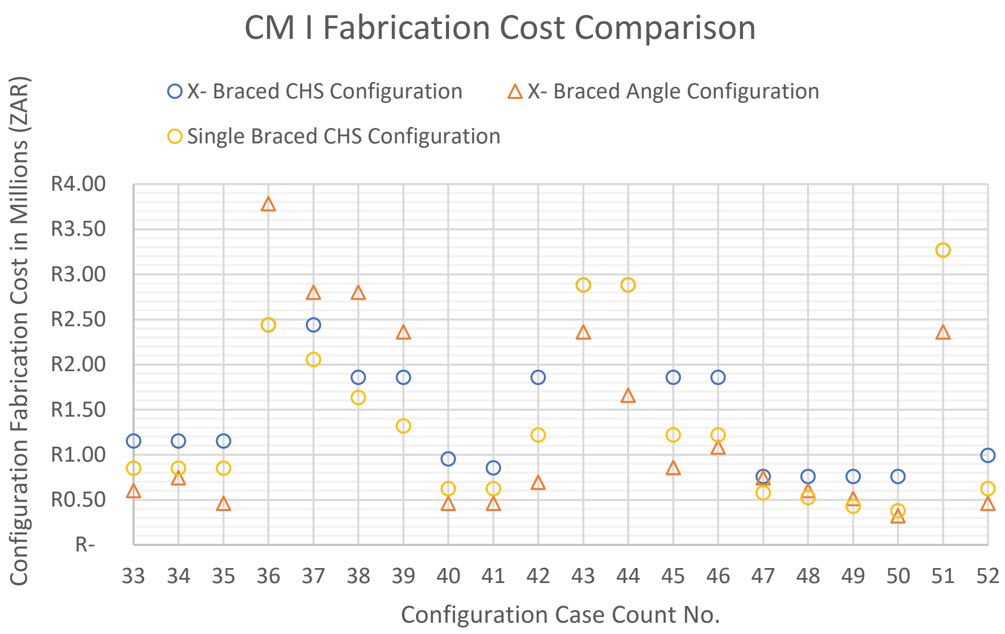


Figure 4-41 Built-site Configuration Fabrication Cost Comparison for CM I

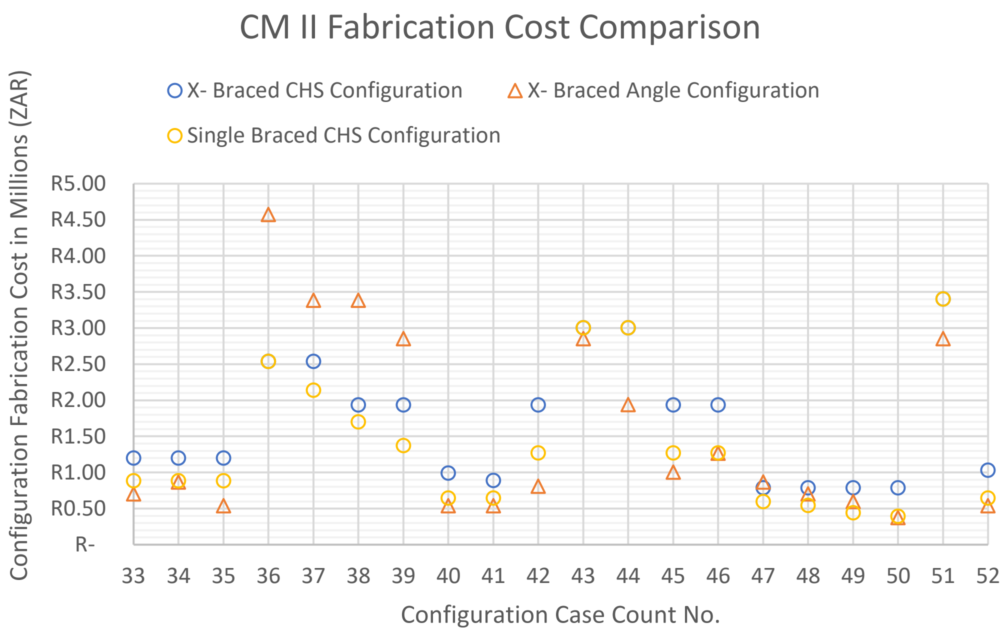


Figure 4-42 Built-site Configuration Fabrication Cost Comparison for CM II

Erection Costs

Erection costs resulting from CM I and CM II are confirmed from Figure 4-43 to Figure 4-46. Hypothetical configuration costs are specified in Figure 4-43 and Figure 4-44. Built-site configuration results are provided in Figure 4-45 and Figure 4-46. CM I and CM 2 results are shown respectively in sequentially numbered figures.

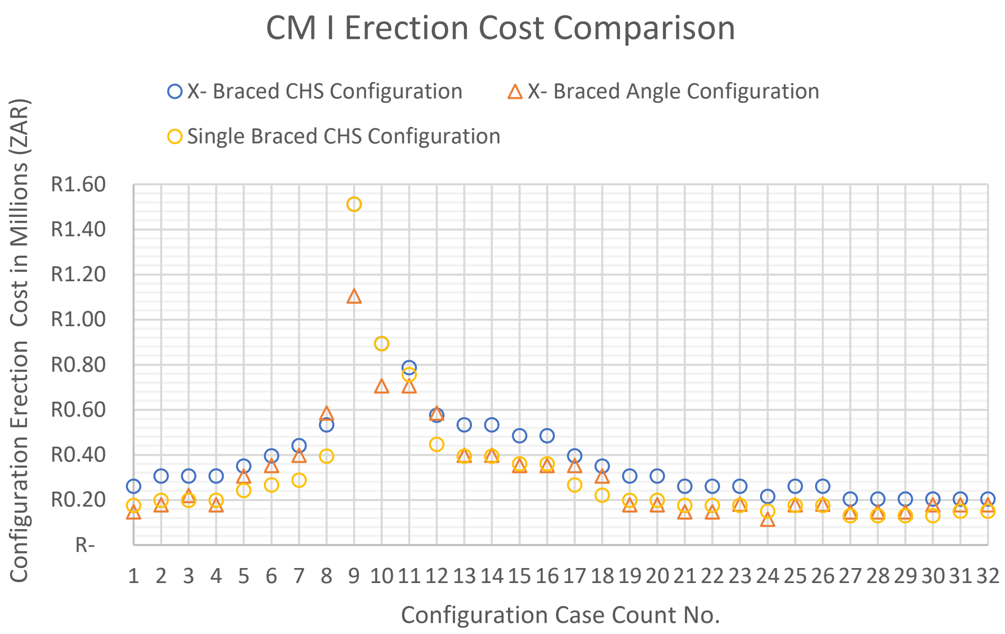


Figure 4-43 Hypothetical Configuration Erection Cost Comparison for CM I

Erection cost results presented in Figure 4-43 and Figure 4-44 show the reference configurations to be the most expensive in 100% of hypothetical cases. The single CHS comparative configurations produce the next highest erection costs for approximately 34% of analysed cases for both CM I and CM II. The comparative crossed angle configurations produce the lowest costs in 41% of cases for both costing models. The single CHS configurations tended to produce the lowest erection costs which is expected.

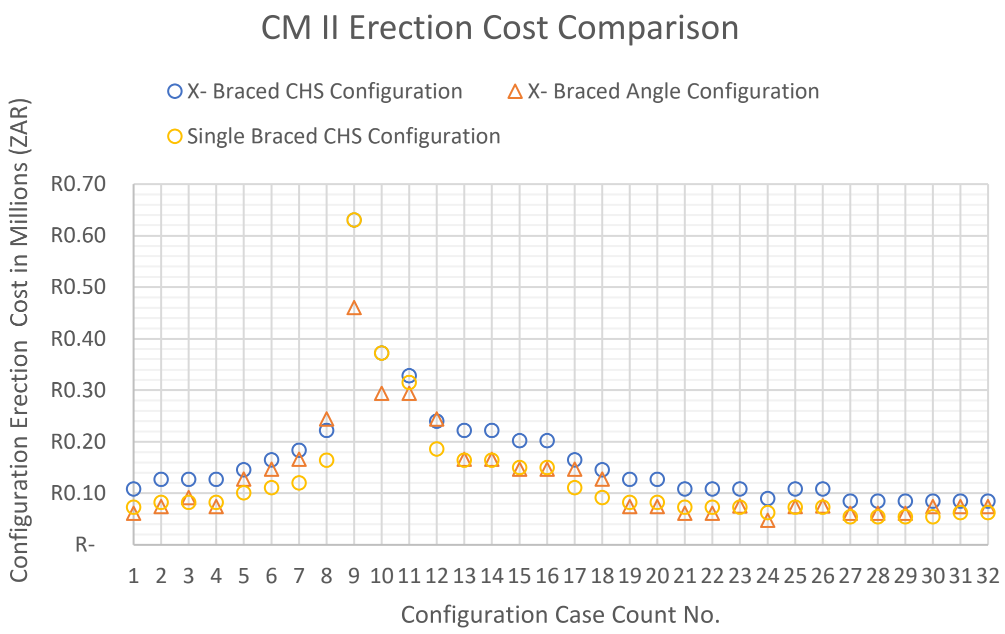


Figure 4-44 Hypothetical Configuration Erection Cost Comparison for CM II

Erection cost results presented in Figure 4-45 and Figure 4-46 suggest the comparative crossed angle configurations to be the most cost-effective in only 15% of the built-site cases analysed. The CHS reference and comparative configurations produce equivalent, and the lowest cost, results in 15% of analysed cases. The comparative single CHS configurations produce the most economical results for 70% of cases. The findings are expected due to the reduced number of sections required in single CHS configurations, the relatively high compressive capacity of CHS members, and the flat erection cost rate applied.

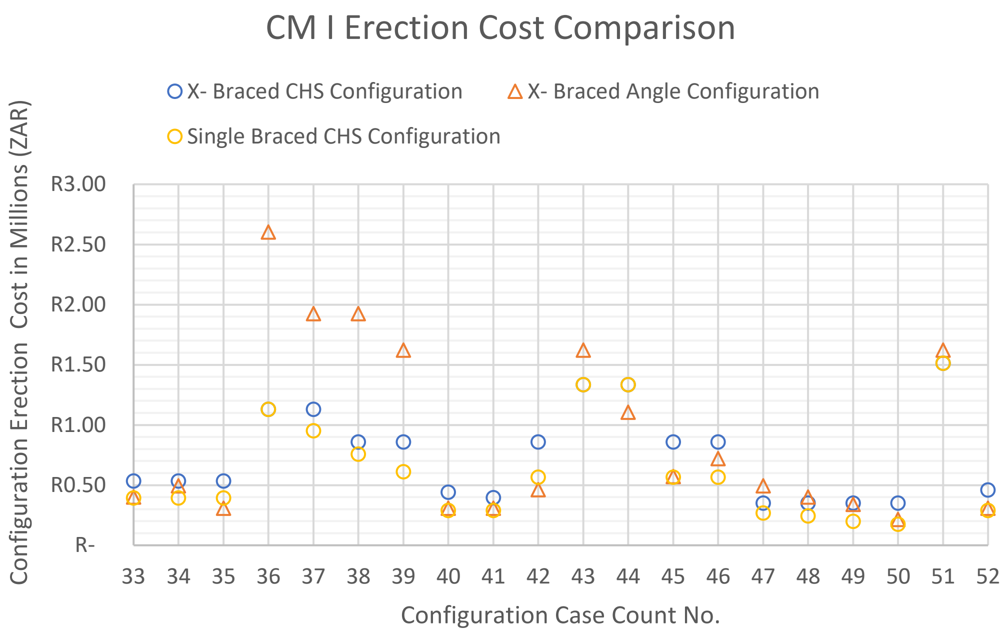


Figure 4-45 Built-site Configuration Erection Cost Comparison for CM I

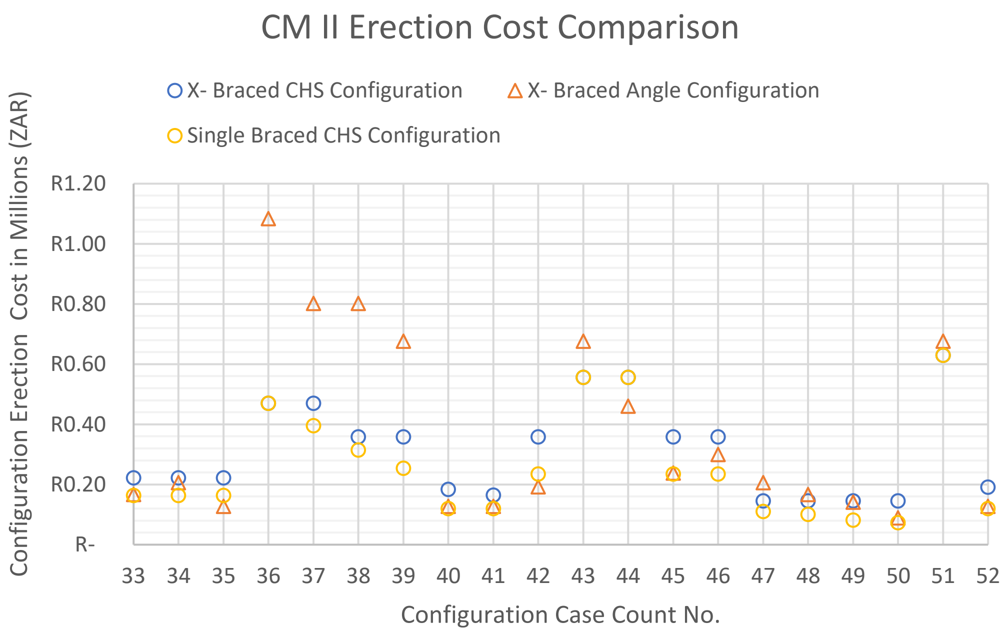


Figure 4-46 Built-site Configuration Erection Cost Comparison for CM II

Total Costs

Combined total fabrication and erection costs resulting from CM I and CM II are established from Figure 4-47 to Figure 4-50. Hypothetical configuration costs are specified in Figure 4-47 and Figure 4-48. Built-site configuration results are provided in Figure 4-49 and Figure 4-50. CM I and CM 2 results are shown respectively in successive figures.

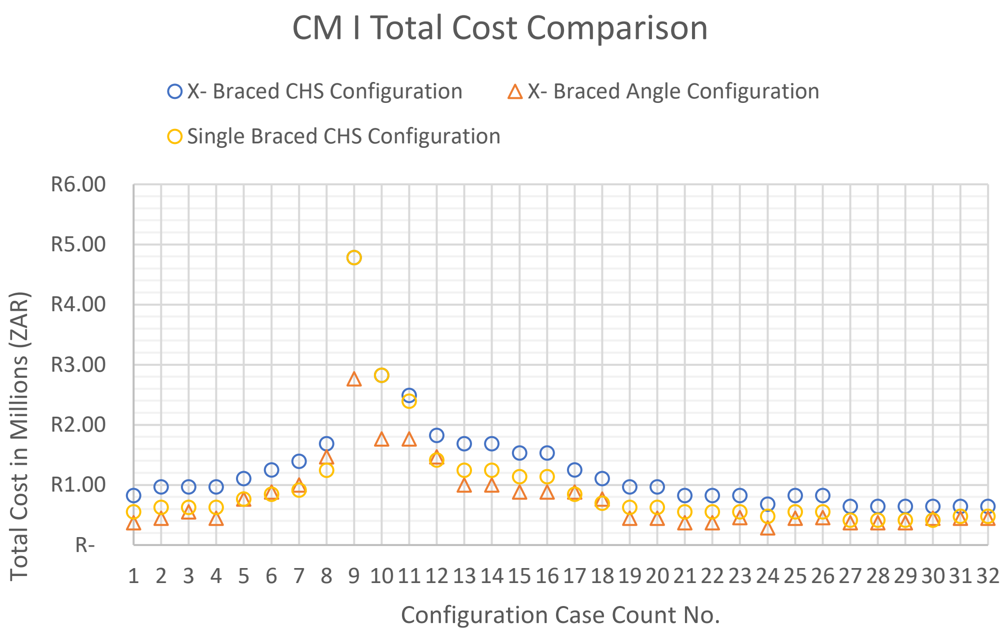


Figure 4-47 Hypothetical Configuration Total Cost Comparison for CM I

Total cost results available in Figure 4-47 and Figure 4-48 show the reference configurations to be the most expensive in 100% of the analysed hypothetical cases. The single CHS comparative configurations produce the next highest total costs for approximately 69% of analysed cases for both CM I and CM II. The comparative crossed angle configurations produce the lowest costs in 75% of cases for both costing models.

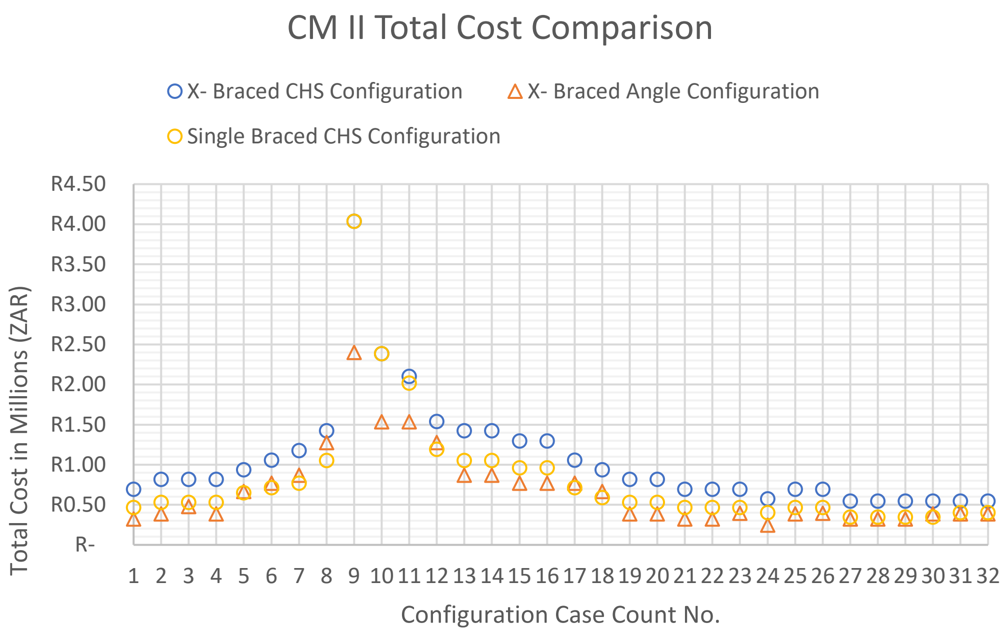


Figure 4-48 Hypothetical Configuration Total Cost Comparison for CM II

Total cost results presented in Figure 4-49 and Figure 4-50 indicate the comparative crossed angle configurations to be the most cost-effective in 55% of the built-site cases analysed. The CHS reference and comparative configurations produce equivalent, and the lowest cost, results in 5% of analysed cases. The comparative single CHS configurations produce the most economical results for 40% of cases.

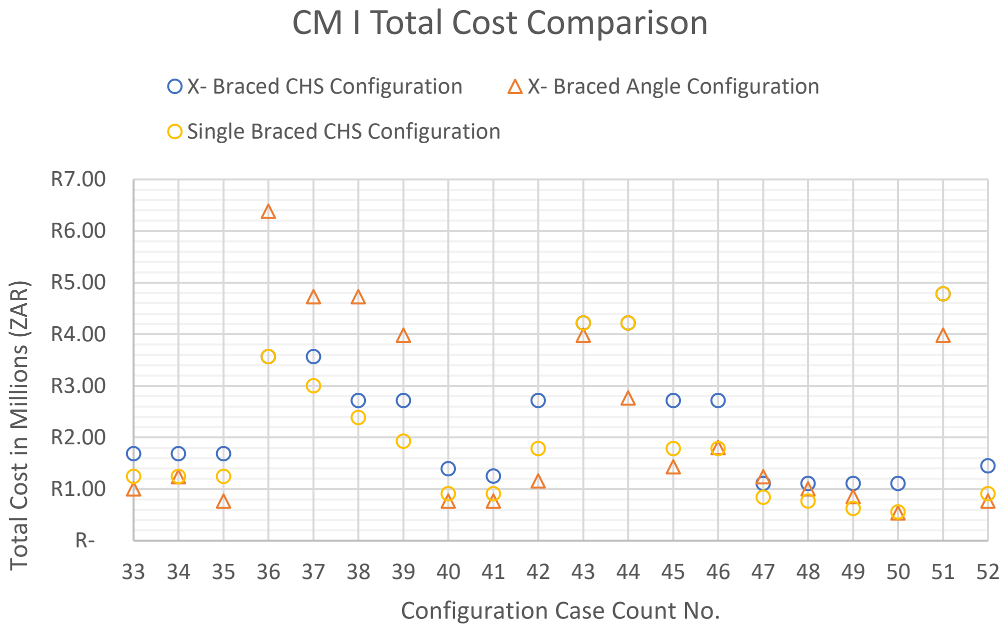


Figure 4-49 Built-site Configuration Total Cost Comparison for CM I

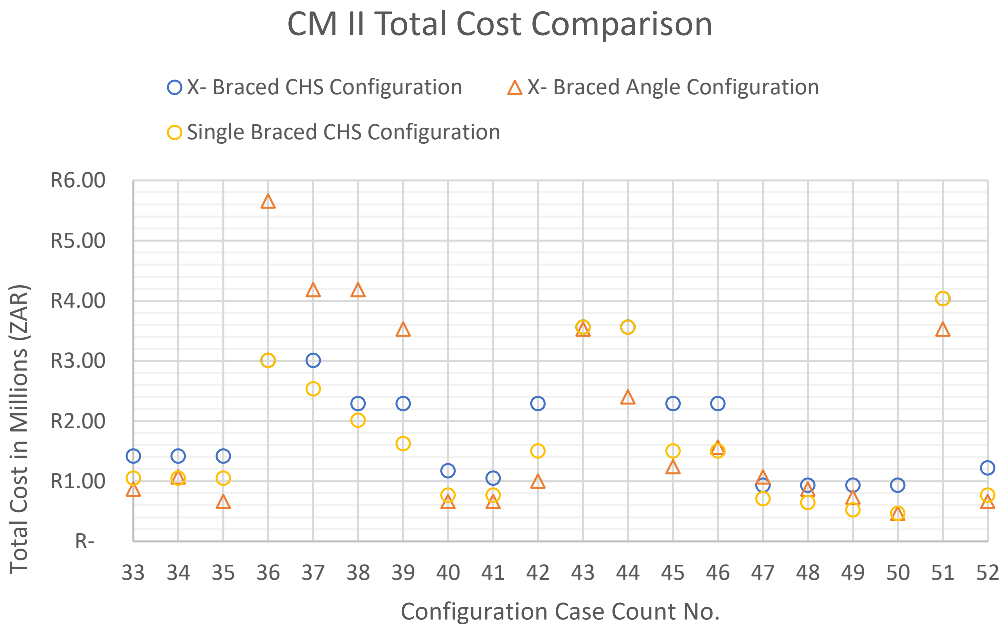


Figure 4-50 Built-site Configuration Total Cost Comparison for CM II

Total Cost Ratio - Crossed- CHS and Angle Configurations

Figure 4-51, Figure 4-52 and Figure 4-53 present the total cost ratios by different independent variables for the reference crossed CHS, and comparative crossed Angle, configurations.

The total cost ratio is calculated by dividing the total cost of the reference configuration by that of the comparative configuration. Figure 4-51 gives the total cost ratio as a function of the case count number. Figure 4-52 provides the total cost ratio as a function of the reference configuration CHS member slenderness ratio. Figure 4-53 shows the total cost ratio as a function of the comparative configuration design load.

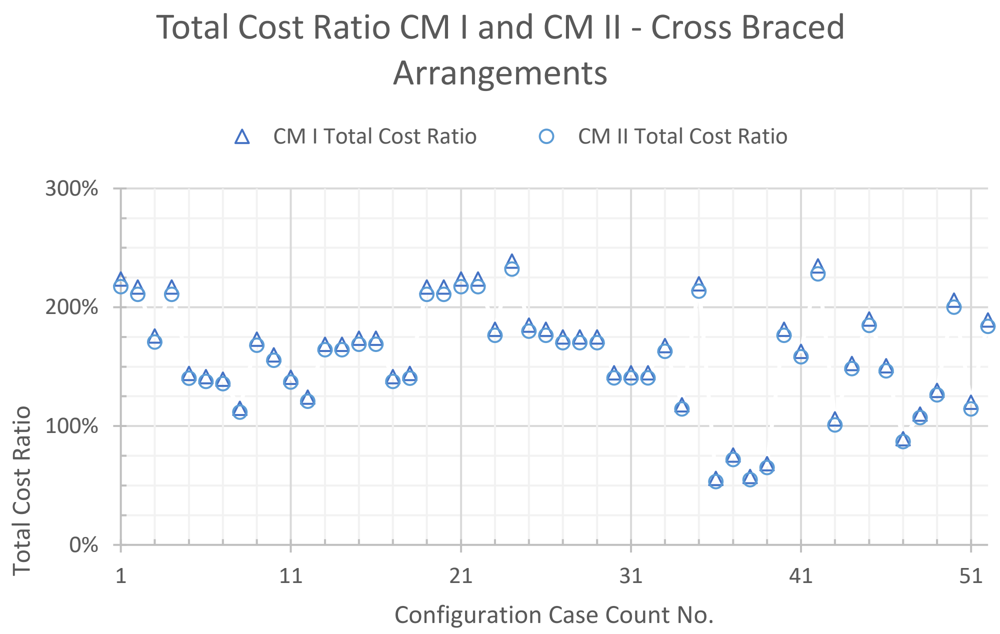


Figure 4-51 CM I and CM II Total Cost Ratio Comparison for Cross-braced CHS and Angle Arrangements by Case Count Number

Figure 4-51 points to limited deviation in terms of total cost ratio between the two costing models assessed. The figures shows that around 79% of cases analysed produce total cost ratios greater than 125%.

Figure 4-52 demonstrates a strong correlation between the reference configuration crossed CHS member slenderness ratio and the total cost ratio. A slenderness ratio limit of approximately 80 to 90 is noted where the total cost ratio tends below 100%.

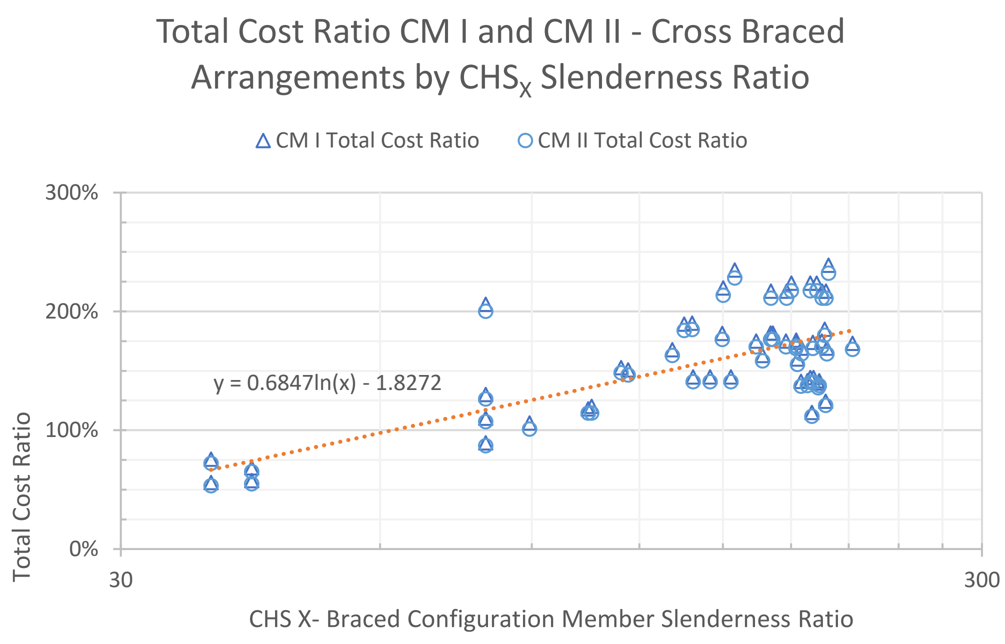


Figure 4-52 CM I and CM II Total Cost Ratio Comparison for Cross-braced CHS and Angle Arrangements by Cross-braced CHS Slenderness Ratio

Significant variability is noted in the presented data with a mean of 158% and standard deviation of 45%. The spread in the data points to further correlations as outlined in Figure 4-53. Figure 4-53 points to a reduction in total cost ratio as the configuration design load increases.

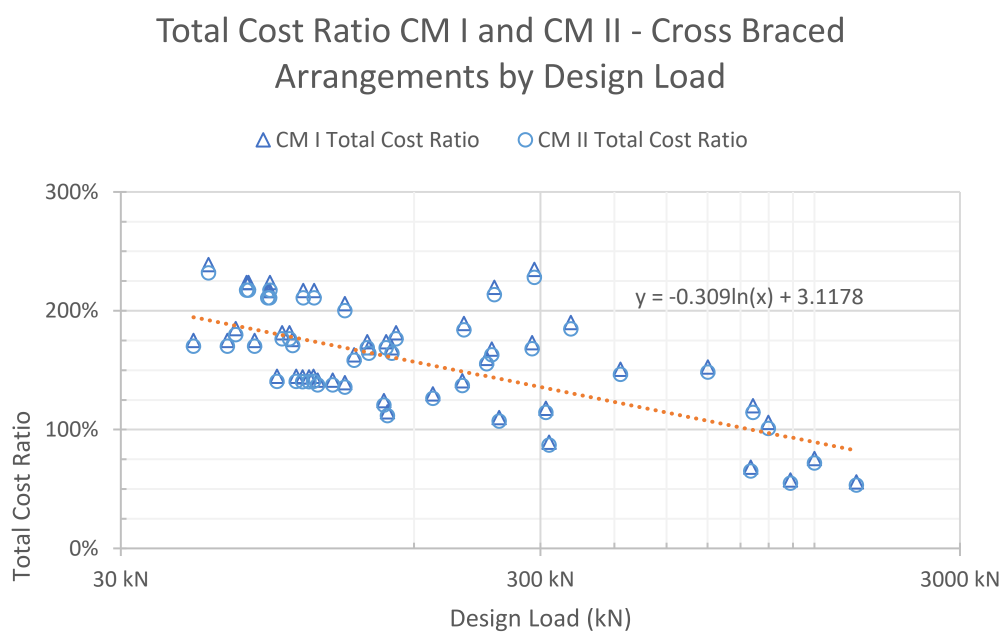


Figure 4-53 CM I and CM II Total Cost Ratio Comparison for Cross-braced CHS and Angle Arrangements by Design Load

Total Cost Ratio - Crossed- and Single- Braced CHS Configurations

Figure 4-54, Figure 4-55 and Figure 4-56 present the total cost ratios by different independent variables for the reference crossed CHS, and comparative single CHS, configurations. Figure 4-54 gives the total cost ratio as a function of the case count number. Figure 4-55 gives the total cost ratio as a function of the reference configuration CHS member slenderness ratio. Figure 4-56 gives the total cost ratio as a function of the comparative configuration design load.

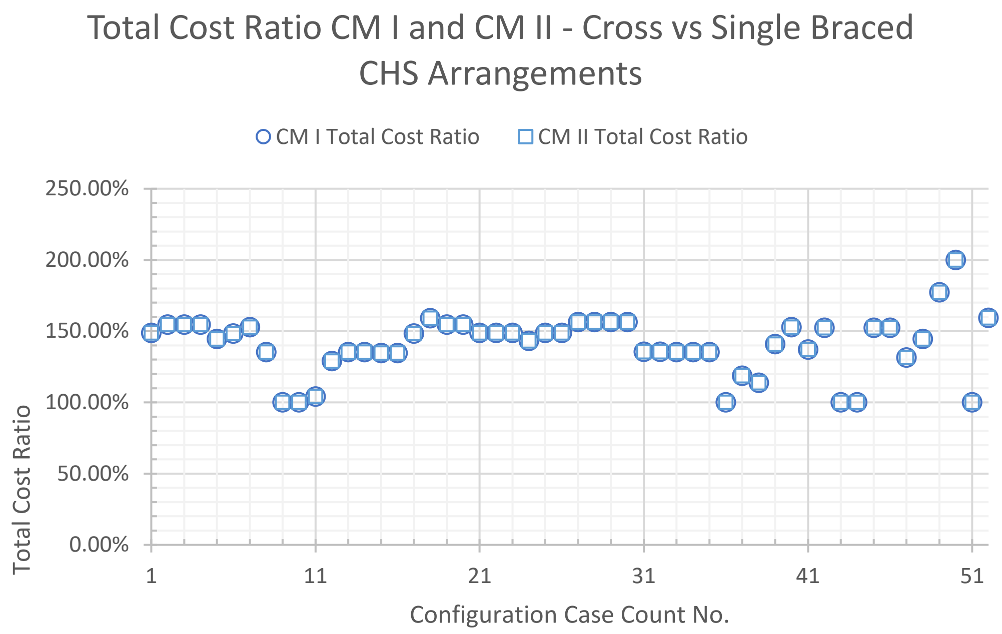


Figure 4-54 CM I and CM II Total Cost Ratio Comparison for Cross and Single-braced CHS Arrangements by Case Count Number

Figure 4-54 points to close correlation in terms of total cost ratio between the two analysed costing models. The figure shows that about 83% of cases analysed produce total cost ratios greater than 120%.

No clear correlation is noted between the total cost ratio and reference configuration slenderness ratio when examining Figure 4-55. The finding is expected as both reference and comparative configurations are comprised of CHS members. Both Figure 4-54 and Figure 4-55 indicate that single CHS braced configurations tend towards improved economy relative to cross-braced CHS configurations.

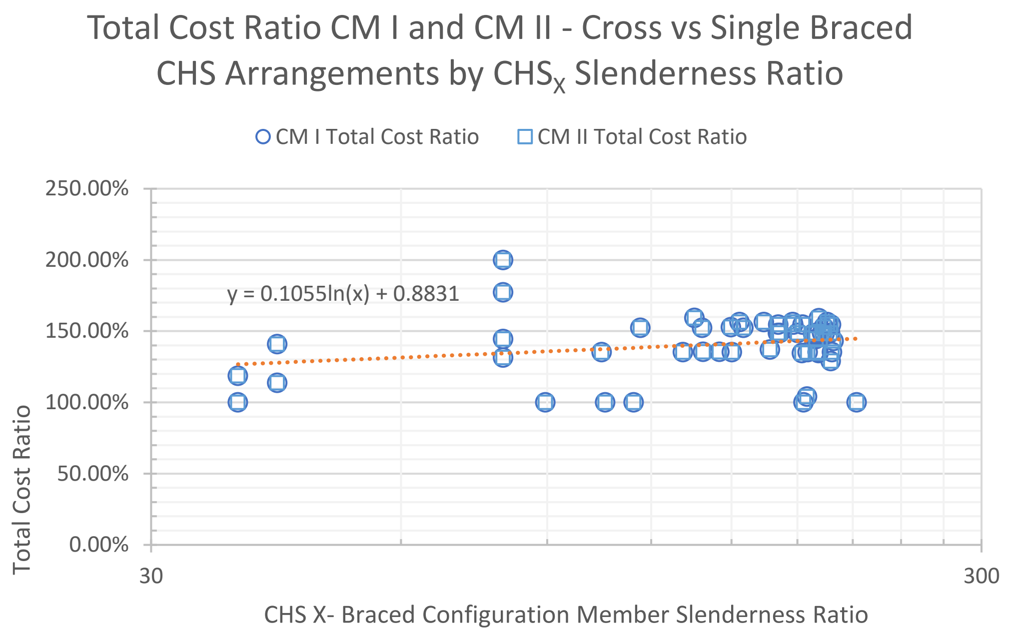


Figure 4-55 CM I and CM II Total Cost Ratio Comparison for Cross and Single-braced CHS Arrangements by Cross-braced CHS Slenderness Ratio

Figure 4-56 highlights a correlation between the comparative configuration design load and total cost ratio. Lower design loads appear to favour higher cost ratios. The finding is expected due to the study being limited to commercially available CHS cross sections (MacSteel, 2022). The CHS 219x6.0 is the largest cross section considered.

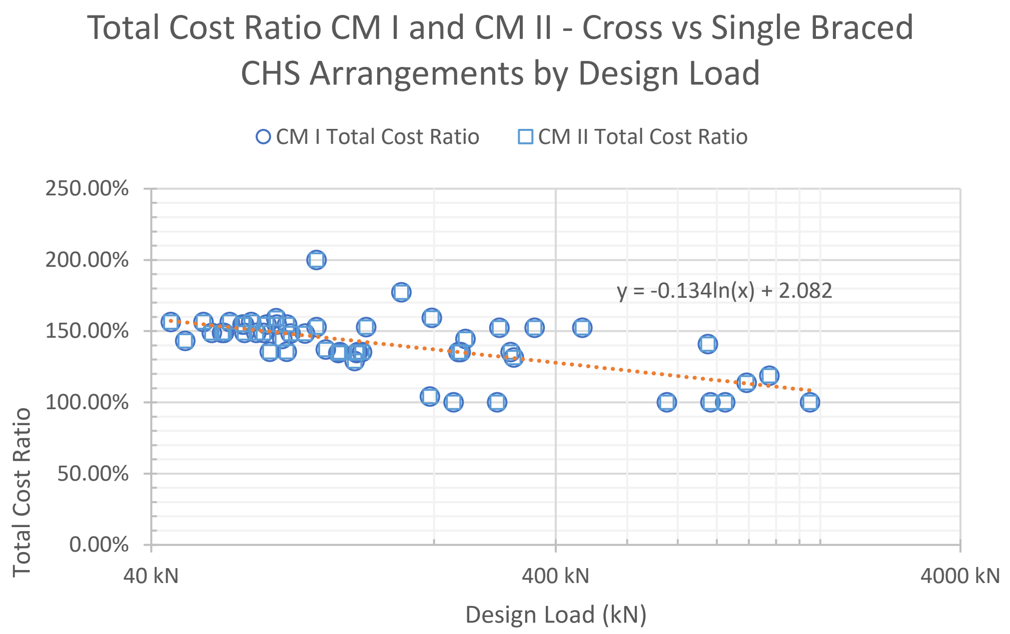


Figure 4-56 CM I and CM II Total Cost Ratio Comparison for Cross and Single-braced CHS Arrangements by Design Load

5. DISCUSSION

5.1. Introduction

The research hypothesis was:

Vertical cross-braced CHS configurations are less economical than traditionally designed comparative arrangements.

The hypothesis was investigated by evaluating key frame metrics between reference configurations and comparative configurations. Reference configurations consisted of vertically cross-braced CHS members. Comparative configurations consisted of:

i. Vertical cross-braced configurations with Angles sections implemented to resist tension only.
ii. Vertical single-brace configurations with CHS sections implemented to resist both compressive and tensile loads.

Key efficiency metrics evaluated for reference and comparative configurations were:

i. Configuration unit mass
ii. Raw materials cost
iii. Fabrication costs
iv. Erection costs.

Further research objectives identified included:

i. Determine industry motivations for the specification of CHS members in vertically cross-braced arrangements.

ii. Determine the design philosophy behind the use of CHS members in vertical cross-braced arrangements.
iii. Determine the proportion of load-share between tensile and compressive members when both are considered in a vertical cross-braced arrangement.
iv. Determine valid costing models for raw materials, fabrication, and erection costs.

5.2. Findings

5.2.1. Design Philosophy

The following summary of Table 4.1 offers reasons cited for the specification of CHS members in vertical cross-braced arrangements:

i. Client requirement or specification.
ii. Commercial availability of members.
iii. Lower member mass to facilitate on-site erection.
iv. Favourable cross-sectional geometry and slenderness compared to Angle sections.
v. Housekeeping – fine particulates less likely to accumulate on rounded CHS surfaces compared to Angle sections.
vi. Load-sharing between CHS members in a vertically cross-braced arrangement.
vii. Easier to retrofit larger CHS members to accommodate increased structural loading parameters.
viii. Robustness and redundancy seismic code requirements.
ix. Relatively high flexural buckling capacities comparted to Angle sections.

x. Subjective bias leading to preference for CHS members.

xi. Economy of transport.

A repeated motivation cited from interviews is the preference for CHS members based on their slenderness, buckling properties, and axial compressive capacities (Manthe, 2022) (Mostert, 2021) (Surat, 2022) (Waite, 2022) (Midgley, 2022).

From literature (Kanyilmaz, 2017), it is apparent that vertical cross-braced reference configuration arrangements do not have well formulated normative methodologies to characterise connection resistances, connection configurations, and connection stiffnesses. These configurations are subject to failure at member discontinuities (Gélinas, et al., 2012).

The discontinuous member and midspan plate connections act as a spring configuration (Davaran, 2001) with some unknown stiffness which must be estimated through numerical modelling and verified by experiment.

Cited reasons such as client specification (Anglo American, 2007) are not easy to argue against. Other motivations are questionable on further inspection. An example being that corrosion between back-to-back angle arrangements is listed as a risk (Anglo American, 2007) in Table 4.1. A counter point which may be argued are the difficulties associated with inspecting the interiors of CHS members for corrosion and quality of applied corrosion protection products. Moisture may become trapped inside sealed CHS member and drive corrosion from the interior of the section (Labuschagne, 2022) (Pereira, 2022).

5.2.2. Load Share Sensitivity Analysis

The average load-share factors found from the sensitivity analysis are summarised in Table 5.1. The average values of the compressive and tensile load-share factors were found to be close to equal. Greater variation was observed as the brace angle of inclination tended towards 30˚. Less variation was observed as the brace angle of inclination tended towards 65˚.

Table 5.1 Average Compressive (α_C) and Tensile (α_T) Load-Share Factors

Load-Share Factor	**Brace Angle of Inclination (θ_{br})**							
	30˚	**35˚**	**40˚**	**45˚**	**50˚**	**55˚**	**60˚**	**65˚**
α_C	52,7%	52,7%	52,4%	51,9%	51,7%	51,5%	51,1%	50,8%
α_T	47,3%	47,3%	47,6%	48,1%	48,3%	48,5%	48,9%	49,2%

5.2.3. Costing Models

Raw Materials Costs

Raw materials costing models were expressed on a per ton basis for each analysed case. Raw materials costs showed that reference configurations costs were greatest, followed by cross-braced Angle comparative configurations, with single-braced CHS comparative configurations the most economical.

Approximate average cost ratios between the reference and comparative configurations are summarised as follows:

i. Reference configurations had average raw materials costs 198% greater than comparative single-brace CHS configurations.

ii. Reference configurations had average raw materials costs 159% greater than comparative cross-braced Angle configurations.

iii. Comparative cross-braced Angle configurations had average raw materials cost 125% greater than comparative single-brace CHS configurations.

Fabrication and Erection Costs

Two costing models, referred to as CM I and CM II, were applied to determine fabrication and erection costs. The costing models differentiated between costing for CHS members and structural (or non-CHS) members. CM I differentiated structural steel costs into light- and medium- duty. CM II did not apply this differentiation.

Costing model findings are summarised as follows:

i. CM I labour costs for CHS members are approximately 35% and 23% higher for medium- and light- duty structural steel members, respectively.
ii. CM II labour costs for CHS member are approximately 28% higher than structural steel members.
iii. CM I materials costs excluding connecting plate for CHS members are approximately 61% and 59% higher than light- and medium- duty structural steel members, respectively.
iv. CM II materials costs excluding connecting plate for CHS members are approximately 23% higher than structural steel members.
v. CM I total fabrication costs excluding connecting plate for CHS members are approximately 44% and 48% higher than light- and medium- duty structural steel members, respectively.
vi. CM II total fabrication costs excluding connecting plate for CHS members are approximately 25% higher than structural steel members.

vii. CM I materials costs including connecting plate for CHS members are approximately 58% higher for both light- and medium- duty structural steel members.

viii. CM II materials costs excluding connecting plate for CHS members are approximately 28% higher than structural steel members.

ix. CM I total fabrication costs including connecting plate for CHS members are approximately 44% and 49% higher than light- and medium- duty structural steel members, respectively.

x. CM II total fabrication costs including connecting plate for CHS members are approximately 28% higher than structural steel members.

5.2.4. Efficiency Metrics

Unit Mass

The unite mass findings are summarised as follows:

i. From Figure 4-23 approximately 90% of analysed hypothetical cases resulted in unit masses for comparative cross-braced Angle and single-braced CHS configurations that were lower than for the reference configurations.

    a. Hypothetical case outliers are noted where compartment dimensions were large, necessitating large reference CHS cross-sections and concomitant high compressive resistances.

ii. From Figure 4-24 approximately 55% of analysed built-site cases resulted in unit masses for comparative cross-braced Angle and single-braced CHS configurations that were lower than for the reference configurations.

a. Referencing Figure 4-26 and Figure 4-27 built-site case outliers are correlated to either low reference configuration member slenderness ratio (< 80-90), high comparative configuration design load (> 225 kN), or both.

iii. From Figure 4-25 approximately 79% of all analysed cases resulted in relative mass ratios greater than 100% when considering reference configurations compared to cross-braced Angle configurations.

a. The implication is that 79% of comparative configurations have a lower unit mass than the reference configurations.

b. A direct correlation between reference section slenderness ratio and relative mass ratio is observed in Figure 4-26.

i. Significant spread is apparent in the relative mass ratio results pointing to additional contributing variables.

ii. A mean of 130% and standard deviation of 48% are observed.

c. An inverse correlation between comparative configuration design load and relative mass ratio is observed in Figure 4-27.

iv. From Figure 4-28 approximately 87% of all analysed cases resulted in relative mass ratios greater than 100% when considering reference configurations compared to single-braced CHS configurations.

a. The implication is that 87% of comparative configurations have a lower unit mass than the reference configurations.

b. No clearly discernible correlation between reference section slenderness ratio and relative mass ratio is observed in Figure 4-29.

c. A weak inverse correlation between comparative configuration design load and relative mass ratio is observed in Figure 4-30.

Raw Materials Costs

Raw materials costs closely reflected the findings of the unit mass metrics. Raw materials costs findings are summarised as follows:

i. Approximately 90% of analysed hypothetical cases in Figure 4-31 resulted in comparative configurations that were more economical by way of raw materials cost per unit mass when compared to the reference configurations.
    a. Comparative cross-brace Angle configurations were on average 45% more efficient than reference configurations.
    b. Comparative single-brace CHS configurations were on average 30% more efficient than reference configurations.

ii. Approximately 80% of analysed built-site cases in Figure 4-32 resulted in comparative configurations that were more economical by way of raw materials cost per unit mass when compared to the reference configurations.

iii. Approximately 92% of all analysed cases in Figure 4-33 resulted in raw materials cost ratios greater than 100% when considering reference configurations compared to cross-braced Angle configurations.
    a. From Figure 4-34 an inflection point is observed at an approximate reference configuration member slenderness ratio of 80.

i. Reference configurations are more efficient than comparative cross-brace Angle configurations below this point.

b. From Figure 4-35 a strong inverse correlation is apparent between design load and comparative configuration cost efficiency.

i. Comparative configuration design loads greater than approximately 1200 kN are less efficient than reference configurations.

ii. Significant spread is observed in the data evidencing the statement that configuration efficiency is a function of both slenderness and design load when comparing cross-braced Angle arrangements to reference configurations.

iv. Approximately 88% of all analysed cases in Figure 4-36 resulted in raw materials cost ratios greater than 100% when considering reference configurations compared to single-braced CHS configurations.

a. High design loads resulted in a 1:1 correlation in efficiency metrics, as expected.

b. This finding is due to specified CHS members upper bound being controlled by commercially available cross-sections.

c. The largest commercially available cross-sections are CHS 219x6.0

Total Costs

Total costs derived from CM I and CM II comprise of the sum of fabrication and erection costs and include the contribution of plate connections. Only total costs are summarised for the dual reasons of brevity and that these provide a holistic view of the comparative efficiencies.

Total costs are summarised as follows:

i. For both CM I and CM II approximately 96% of analysed hypothetical cases from Figure 4-47 and Figure 4-48 resulted in comparative configurations that were more economical by way of total cost per unit mass when compared to the reference configurations.
    a. Results for cases 9 and 10 in both figures show comparative single-brace CHS and reference configurations being equal.
    b. Comparative single-braced CHS configurations were less efficient than comparative cross-braced Angle configurations in 69% of analysed cases.
    c. Comparative cross-braced Angle configurations were most efficient in 75% of analysed cases.

ii. For both CM I and CM II approximately 55% of analysed hypothetical cases from Figure 4-49 and Figure 4-50 resulted in comparative cross-braced Angle configurations that were more economical by way of total cost per unit mass when compared to the reference configurations.
    a. Reference configurations were most efficient in 5% of the analysed cases.
        i. These instances produced equal cost results with the comparative single-brace CHS configurations.
    b. Comparative single-braced CHS configurations proved most efficiencies in 40% of analysed cases.

iii. For both CM I and CM II approximately 90% of all analysed cases from Figure 4-51 resulted in total cost ratios greater than 100% when considering reference configurations compared to cross-braced Angle configurations.

   a. Close correlation for total cost ratios expressed in Figure 4-51 is observed between CM I and CM II.
      i. Results from CM I produce a mean value of 158% and a standard deviation of 45%.
      ii. Results from CM II produce a mean value of 156% and a standard deviation of 44%.
   b. Figure 4-52 shows a strong direct correlation between reference configuration member slenderness ratio and total cost ratio.
      i. An inflection point is observed at an approximate reference member slenderness ratio of 80-90.
      ii. Below this point reference configurations are more efficient than comparative cross-braced configurations.
      iii. Significant variability is observed referring to mean and standard deviation values quoted above.
      iv. The observed variability supports the statement that configuration efficiency is controlled by multiple variables.
   c. From Figure 4-53 a strong inverse correlation is apparent between design load and comparative configuration cost efficiency.

        i. Comparative configuration design loads greater than approximately 1500 kN are less efficient than reference configurations.

iv. For both CM I and CM II approximately 88% of all analysed cases from Figure 4-54Figure 4-51 resulted in total cost ratios greater than 100% when considering reference configurations compared to single-braced CHS configurations.

    a. An exact correlation for total cost ratios expressed in Figure 4-54 is observed between CM I and CM II.

        i. Results from both CM I and CM II produced a mean value of 140% and a standard deviation of 20%.

    b. No clearly discernible correlation between reference section slenderness ratio and relative mass ratio is observed in Figure 4-55.

    c. A weak inverse correlation between comparative configuration design load and relative mass ratio is observed in Figure 4-56.

5.3. Implications

Vertical brace system configuration, design and member specification should be carefully considered. The use of CHS members in cross-braced arrangements are readily motivated under high design loads and where long span compressive members are needed.

Drawing on the results of the presented study, cross-braced CHS configurations were not the most efficient form of bracing for the majority of analysed cases when considering all analysed efficiency metrics. Cross-braced Angle configurations proved the most efficient in the majority of analysed cases, dependent on efficiency parameter. Single-braced CHS configurations were the second most efficient of the configurations and cases analysed. Improved efficiencies carry direct savings to the end user and reduce environmental impact.

Low-rise light-industrial, residential and commercial structures using traditional cross-braced arrangements with Angle sections designed as tension only members would trump cross-braced CHS configurations in terms of mass and cost efficiency metrics as moderate lateral loads are expected. Cross-braced CHS configurations efficiencies would exceed in heavy industrial structures and high-rise structures where lateral loading is extreme. The above conclusions are supported by the results discussion of Figure 4-56, among others. Lower design loads equate to a high cost ratio, conversely higher design loads correlate to a lower cost ratio. The total cost efficiency metric of cross-braced CHS configurations improve with higher design load relative to equivalent cross-braced Angle arrangements.

A caveat to using cross-braced CHS configurations is that the design of these arrangements and their connections are a well-researched and formulated topics and do not appear in most normative references. Experimental research characterising the behaviour of these systems is generally lacking.

5.4. Limitations

Limitations to this research include:

i. Built-site sample size.

ii. Assumptions relating to the design philosophy for built-sites.

    a. No sample design calculations were ever supplied or could be verified from conducted interviews.
    b. Assumptions were taken that reference configuration capacities were based on either:
        i. Continuous CHS member out-of-plane buckling capacity.
        ii. Shear capacity of the connection bolt group.

iii. Considered cross-sections and configurations.
    a. Only commercially available Angle and CHS cross-sections considered.
    b. Only cross-braced and single-braced configurations considered.

iv. Efficiency metrics considered.
    a. Only mass, raw materials cost, fabrication costs, and erection costs considered.

v. Design of connections.
    a. Connection capacity generally ignored.
    b. Where considered based on bolt group shear capacity.

vi. Conservative effective length factors applied.
    a. K = 0.85 and K = 1

vii. Slenderness ratios applied as per code.
    a. Compression: SR < 200
    b. Tension: SR < 300

5.5. Future Research

Future research topics may include:

i. Experimental characterisation of reference configurations:

a. Global stiffnesses and capacities.

b. Connection stiffnesses and capacities.

c. Member effective lengths.

ii. Investigation of the suitability of code specified member slenderness ratios.

iii. Impact of other cross-sections on efficiency parameters.

iv. Impact of other types of comparative configurations (K-, V-, Chevron, etc.) on efficiency parameters.

v. Expand efficiency metrics evaluated.

   a. For example, to include corrosion protection and transport costs.

5.6. Concluding Remarks

Comparative configurations were more efficient than reference configurations in 80%-90% of analysed cases, dependent on the configuration, cross-section and efficiency metric considered. Care and consideration should be taken when specifying vertical bracing configurations. Efficiency produces savings to the end user and carries a lower environmental impact.

The presented study was limited in terms of number of built-sites evaluated. Built-sites provided a greater spread of results than hypothetical cases. Conservative assumptions were taken in the evaluation of the reference member design.

6. CONCLUSION

The presented research paper sought to test the hypothesis that Vertical cross-braced CHS configurations are less economical than traditionally designed comparative arrangements.

The study found that CHS member compressive resistance was a strong motivator, inter-alia, for their use in cross-braced configurations. The load-share factor was then derived from a sensitivity analysis to evaluate in what proportion tensile and compressive loads are shared in reference cross-braced configurations. The load-share factor in compression varied from 52.7% to 50.8% of total cross-brace configuration load. Conversely, a tensile load-share factor from 47.3% to 49.2% was observed.

The raw materials costing model showed that reference configuration raw material costs exceeded those of the comparative configurations by 159% for cross-braced Angle arrangements and 198% for single-brace CHS arrangements.

Total costs were defined as the sum of fabrication and erection, including plate connections. Fabrication, erection and total costing models showed that total costs associated with CHS members were 28% higher than structural steel members for CM II, and 44% and 49% higher than light- and medium- duty structural members, respectively, according to CM I.

Considering the configuration unit mass metric, it was found that in 79% of investigated cases comparative cross-brace Angle configurations were more efficient than the reference cases; and in 87% of analysed cases the single-braced CHS comparative configurations were more efficient than the reference.

Considering the raw materials cost metric, it was found that in 92% of investigated cases comparative cross-brace Angle configurations were more efficient than the reference cases; and in 88% of analysed cases the single-braced CHS comparative configurations were more efficient than the reference.

Considering the total cost metric, it was found that in 90% of investigated cases comparative cross-brace Angle configurations were more efficient than the reference cases; and in 88% of analysed cases the single-braced CHS comparative configurations were more efficient than the reference.

Efficiency parameters were observed to be influenced by reference configuration slenderness ratio and comparative configuration design load. Inversions of the efficiency parameter findings, with reference configurations proving more efficient than comparative configurations, were observed when:

i. Reference configuration CHS member slenderness ratios were less than 80-90.
ii. Comparative configuration design loads were greater than:
    a. 225 kN for the mass efficiency metric.
    b. 1200 kN for the raw materials cost efficiency metric.
    c. 1500 kN the total cost efficiency metric.

The efficiency findings are important from a financial and environmental perspective. Greater efficiencies translate to savings to the client and a lower environmental impact associated with the structure. Both reference and comparative configurations have applications and conditions to which they are best suited. The role of the engineer is to ensure that the most efficient, safe, and reliable solution is implemented.

The study was limited by conservative assumptions relating to determining the capacity of CHS members in reference configurations. These were taken in lieu of being able to procure sample design calculations form conducted interviews. Further limitations include the built-site sample size, efficiency metrics evaluated, cross-sections considered, and vertical braced configurations considered.

Future research may focus on several topics including:

i. Experimental characterisation of reference configurations:
    a. Global stiffnesses and capacities.
    b. Connection stiffnesses and capacities.
    c. Member effective lengths.
ii. Investigation of the suitability of code specified member slenderness ratios.
iii. Impact of other cross-sections on efficiency parameters.
iv. Impact of other types of comparative configurations (K-, V-, Chevron, etc.) on efficiency parameters.
v. Expand efficiency metrics evaluated.
    a. For example, to include corrosion protection and transport costs.

To conclude cross-braced Angle comparative configurations proved to be the most economical in 80%-90% of analysed cases compared to reference configurations, efficiency metric dependent. Single-brace CHS comparative configurations proved to be the most economical in 87%-88% of analysed cases compared to reference configurations, efficiency metric dependent.

Efficiency parameters had a strong direct correlation to reference configuration CHS slenderness ratio, and strong inverse correlation to comparative configuration design load, when considering the cross-braced Angle comparison to reference.

Efficiency parameters had no clear correlation to reference configuration CHS slenderness ratio and a weak inverse correlation to comparative configuration design load when considering the single-braced CHS comparison to reference.

References

Abbassi, S. K., 2009. *The Weight Efficiency of Steel Framed Buildings with Various Wind Bracing Systems,* Gazimagusa: Eastern Mediterranean Universtiy.

Anglo American, 2007. *AA Specification - Design of Steel Structures Issue 11.* Johannesburg: Anglo American.

Ballio, G., Castiglioni, C. & Perotti, F., 1998. Numerical models for simulating the cyclic behavior and the seismic response of steel structures. *Proceedings of the ninth world conference on earthquake engineering,* pp. 231-236.

Brown, G. D., King, M. C., Rackham, J. W. & Way, A., 2001. *Design of Multi-Storey Braced Frames.* 1st ed. Ascot: The Steel Construction Institute.

Davaran, ,. A., 2001. Effective Length Factor for Discontinuous X-Bracing Systems. *Journal of Engineering Mechanics,* 127(2), pp. 106-112.

de Clercq, H., 2012. *The Green Book Structural Steel Connections.* 1st ed. Johannesburg: Southern African Institue of Steel Construction.

Gélinas, A., Tremblay, R. & Davaran, A., 2012. Seismic behavior of steel HSS X-bracing of the conventional construction category. *Structures Congress,* pp. 1649-1660.

Kanyilmaz, A., 2017. Role of compression diagonals in concentrically braced frames in moderate seismicity: A full scale experimental study. *Journal of Constructional Steel Research,,* Volume 133, pp. 1-18.

Labuschagne, M., 2022. *CHS, Light, Medium and Heavy Duty Steel Costing* [Interview] (23 May 2022).

Limited, P. S., 2022. *Prokon.* Pretoria: Prokon Software Limited.

MacSteel, 2022. *Selling Price List Germiston South.* Germiston: MacSteel.

Mahachi, J., 2004. *Design of Structural Steelwork to SANS 10162.* s.l.:South African Institute for Civil Engineering (SAICE).

Manthe, M., 2022. *Circular Hollow Sections as Structural Bracing Members* [Interview] (14 January 2022).

McRae-Samuel, G., 2022. *Circular Hollow Sections as Structural Bracing Members* [Interview] (2 March 2022).

Midgley, M., 2022. *Circular Hollow Sections as Structural Bracing Members* [Interview] (04 February 2022).

Mohanraj, E. K., Kandasamy, S. & Malathy, R., 2011. Behaviour of steel tubular stub and slender columns filled with concrete using recycled aggregates. *Journal of the South African Institution of Civil Engineering,* 53(2), pp. 31-38.

Mostert, M., 2021. *Circular Hollow Sections as Structural Bracing Members* [Interview] (08 October 2021).

NSC Technical, 2019. Cross-braced lateral load-resisting systems. *New Steel Construction,* 11 September, pp. 24-27.

Pereira, M., 2022. *CHS, Light, Medium and Heavy Duty Steel Costing* [Interview] (17 May 2022).

Razak, S. et al., 2018. A Review of Influence of Various Types of Structural Bracing to the Structural Performance of Buildings. *E3S Web of Conferences ,* 34(Interncation Conference on Civil & Environmental Engineering (CENVIRON 2017)), p. 01010.

SABS, 2011. *SANS10162-1:2011 Limit-states design of hot-rolled steelwork.* Pretoria: SABS.

Southern African Institute for Steel Construction, 2010. *Southern African Steel Construction Handbook (The Red Book).* 7th ed. Johannesburg: Southern African Institute for Steel Construction.

StonCor Africa, 2022. *Carboline Price List.* Johannesburg: StonCor Africa.

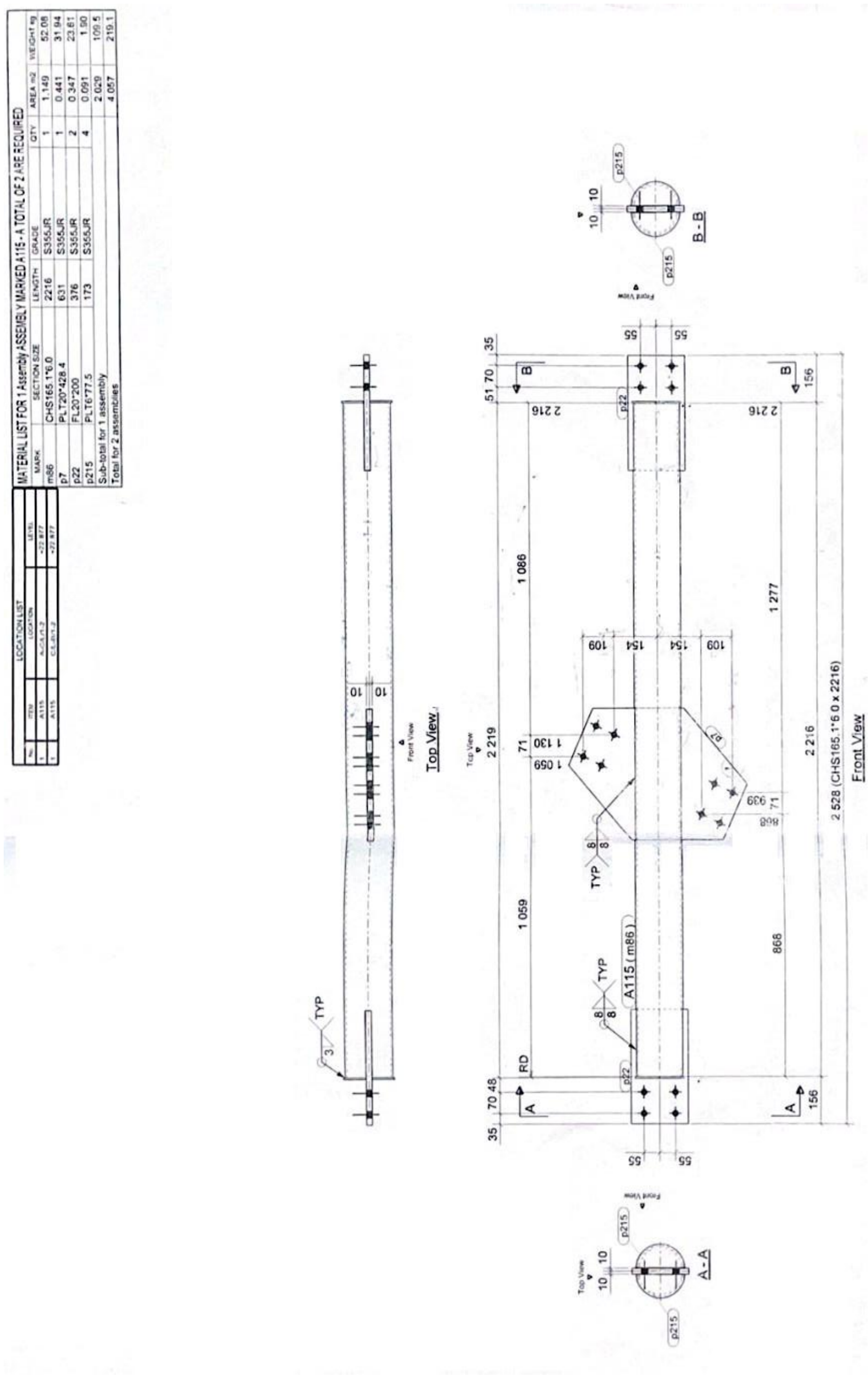
Surat, D., 2022. *Circular Hollow Sections as Structural Bracing Members* [Interview] (20 April 2022).

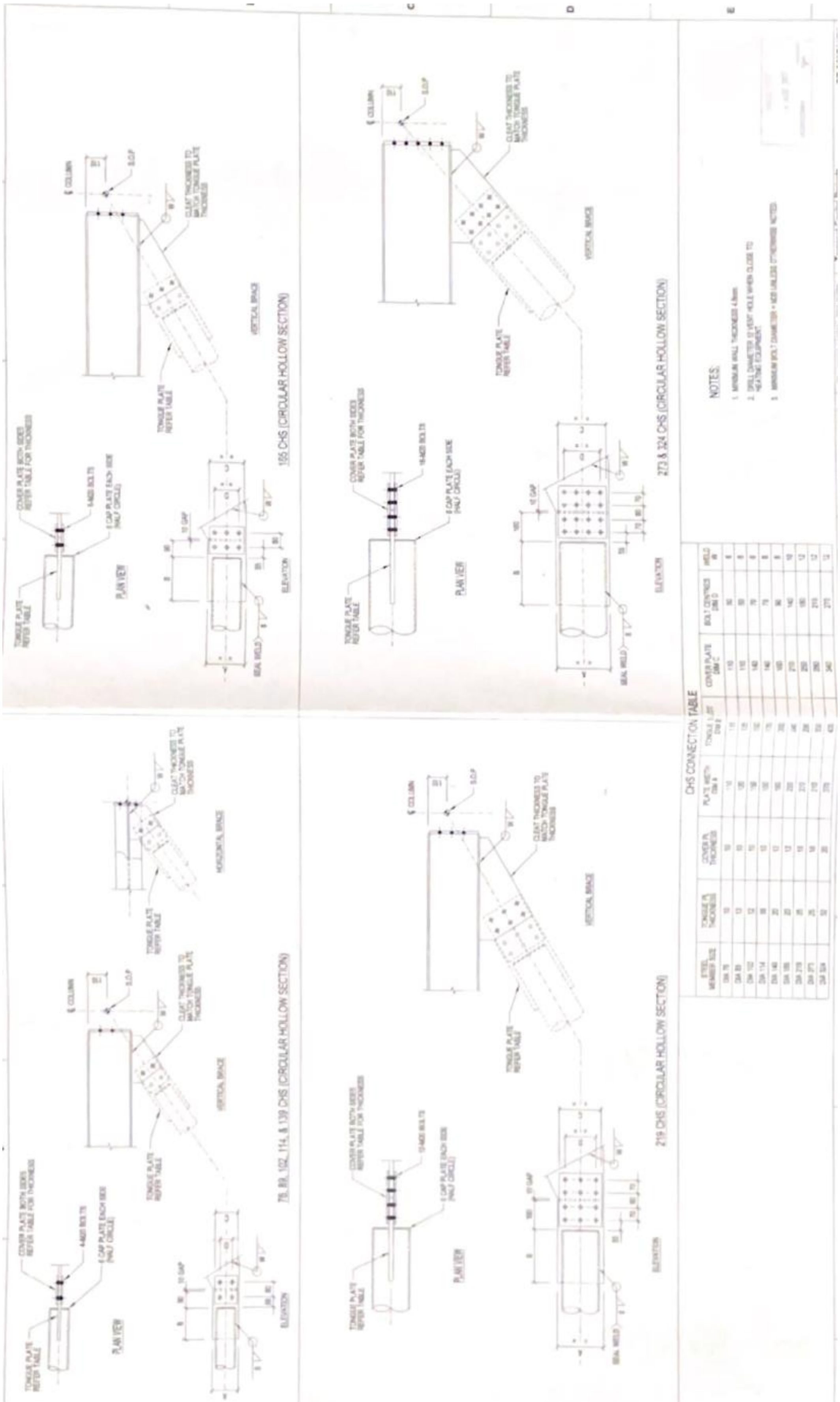
Swann, C., 2021. *Circular Hollow Sections as Structural Bracing Members* [Interview] (08 December 2021).

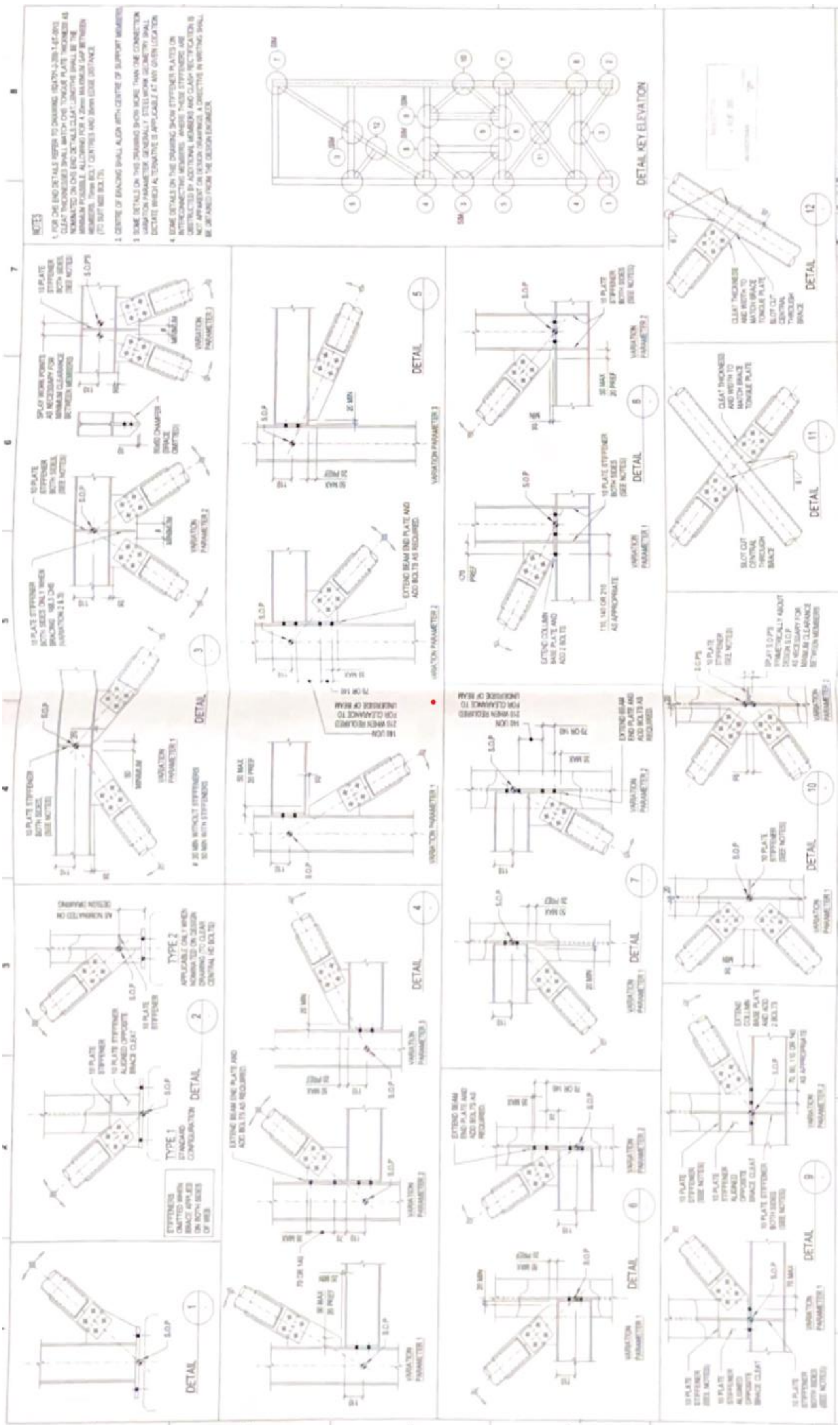
Waite, C., 2022. *Circular Hollow Sections as Structural Bracing Members* [Interview] (04 February 2022).

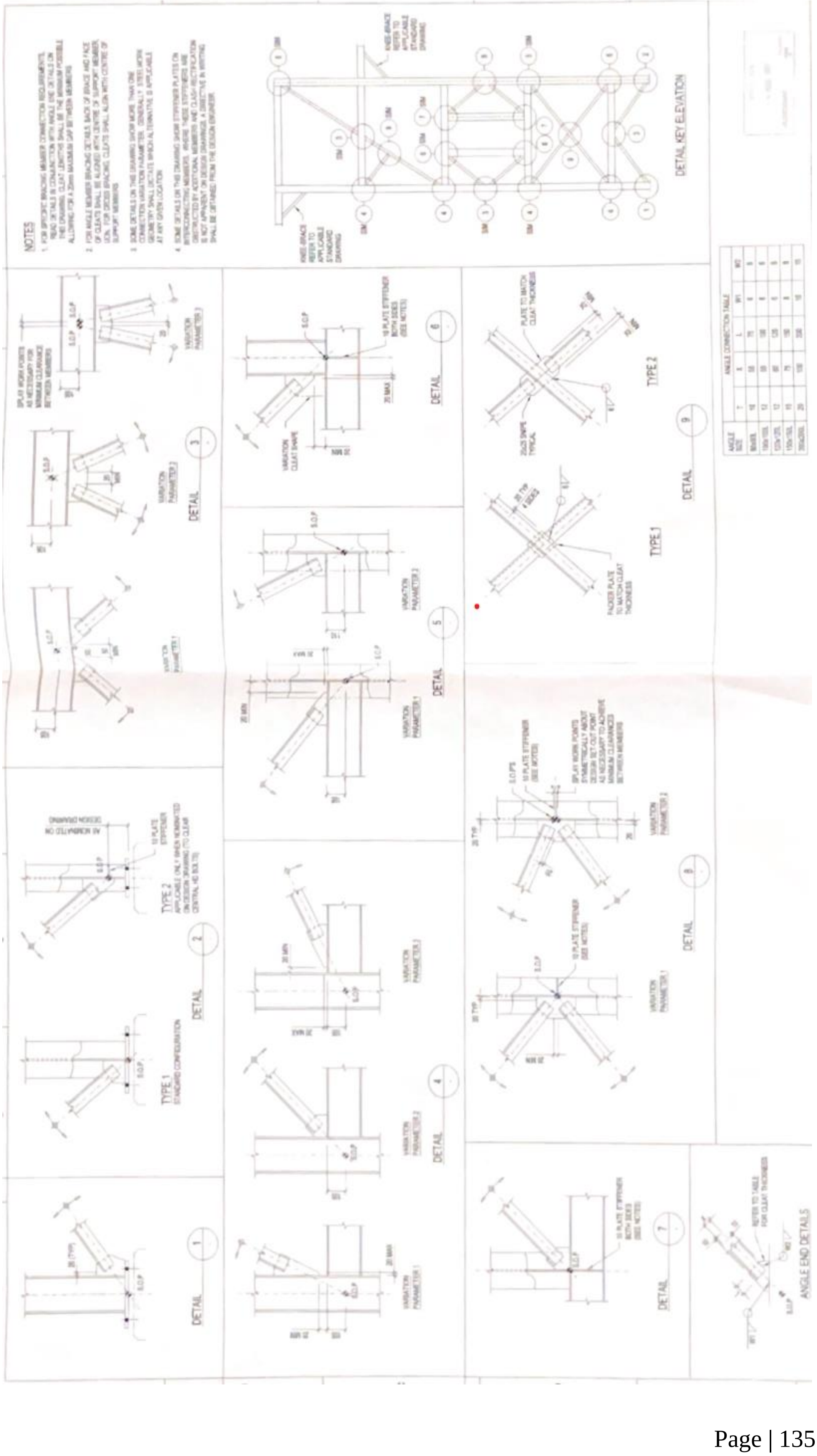
Wardenier, J., J.A., P., -L., Z. X. & G.J., v. d. V., 2010. *Hollow Sections in Structural Applications.* 2nd ed. Geneva: CIDECT.

APPENDIX A – SITE C DRAWINGS

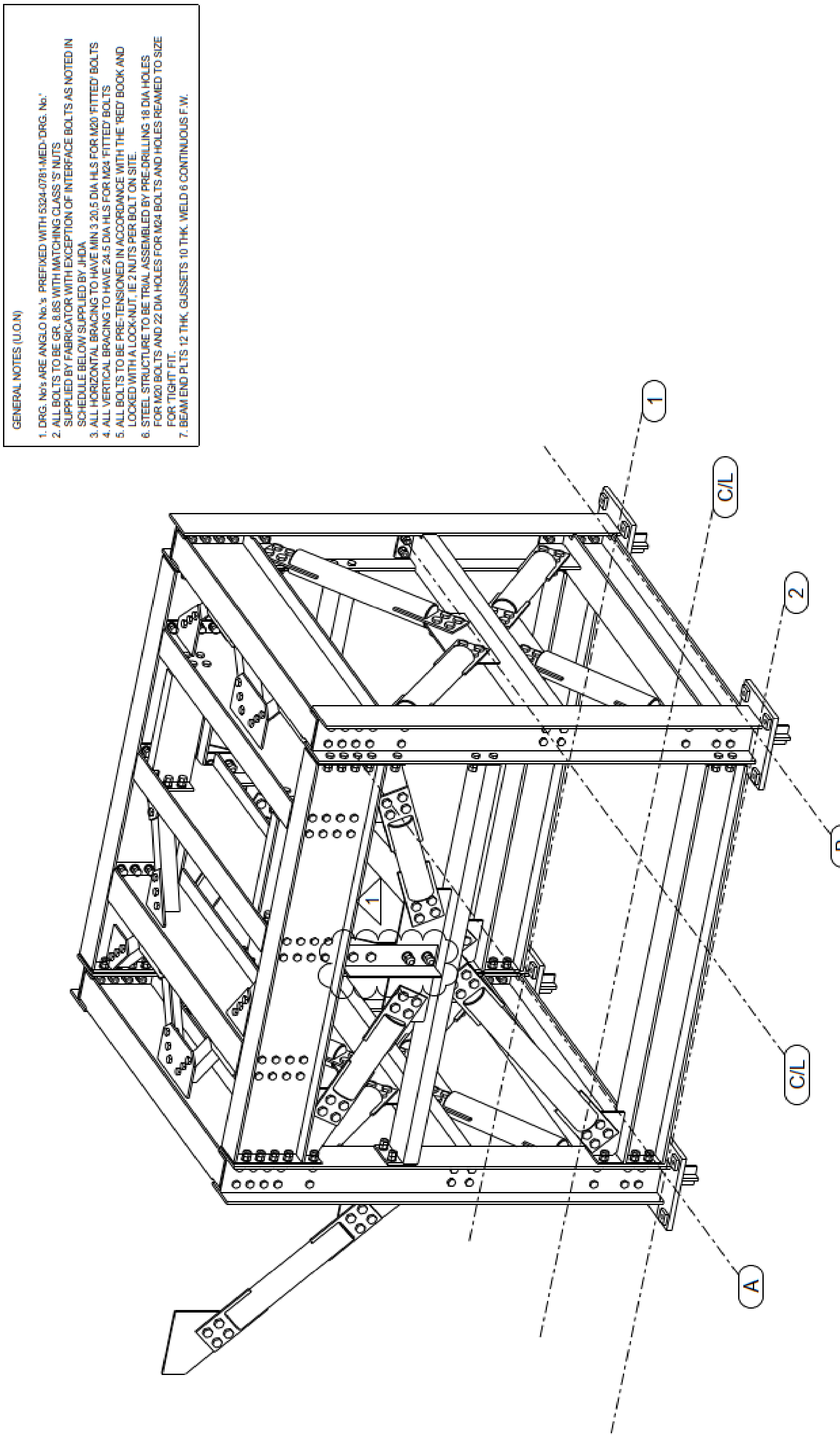



155 CHS (CIRCULAR HOLLOW SECTION)
273 & 324 CHS (CIRCULAR HOLLOW SECTION)
76, 89, 102, 114, & 139 CHS (CIRCULAR HOLLOW SECTION)
219 CHS (CIRCULAR HOLLOW SECTION)
CHS CONNECTION TABLE
NOTES:

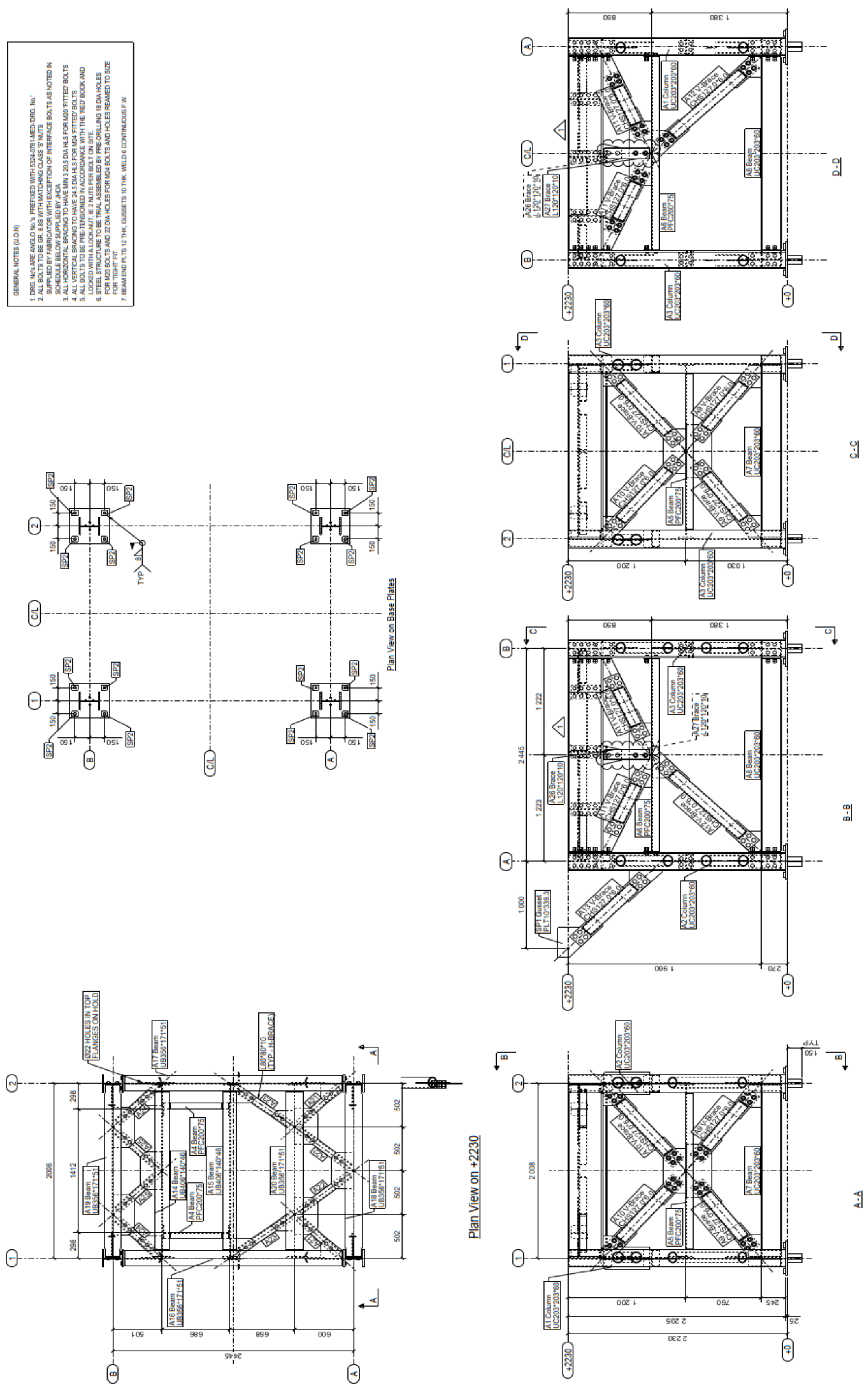



NOTES
DETAIL KEY ELEVATION
TYPE 1
TYPE 2
ANGLE END DETAILS

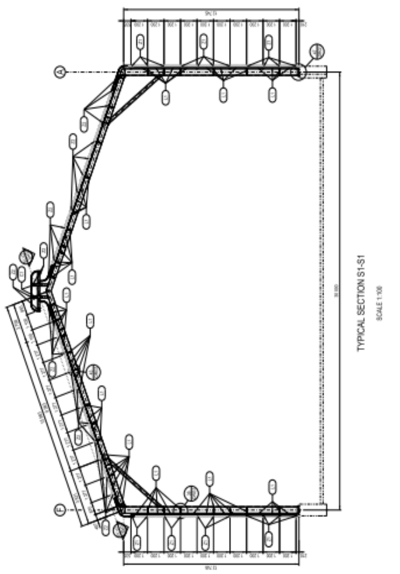
APPENDIX B – SITE D DRAWINGS

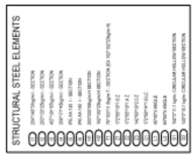


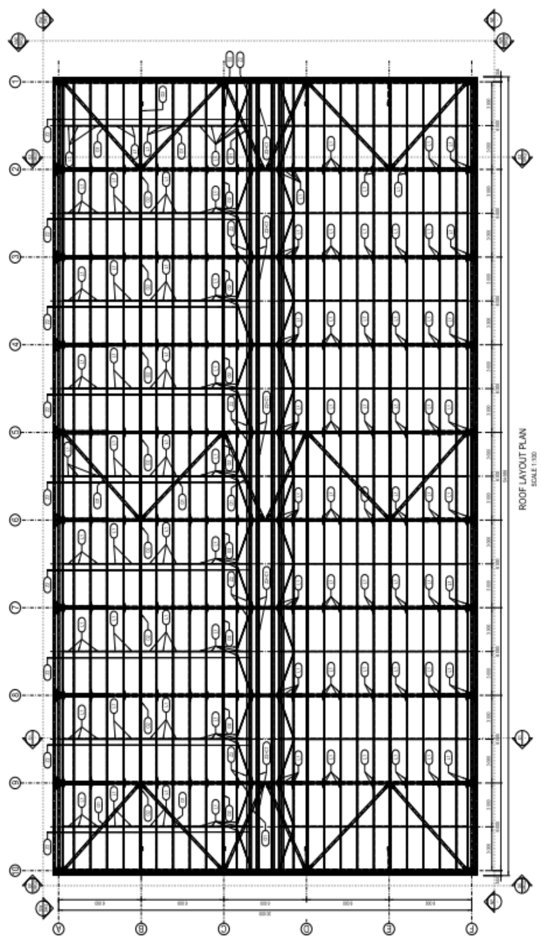
3D View

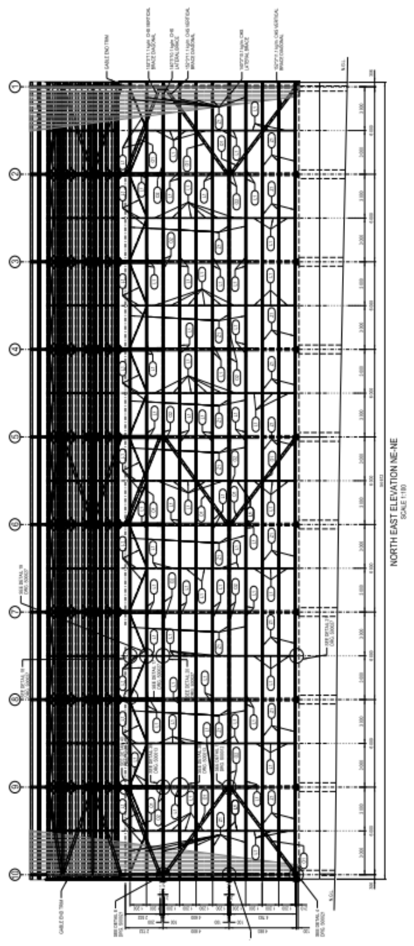

GENERAL NOTES (U.O.N)
Plan View on Base Plates
Plan View on +2230
A - A
B - B
C - C
D - D

APPENDIX C – SITE E DRAWINGS

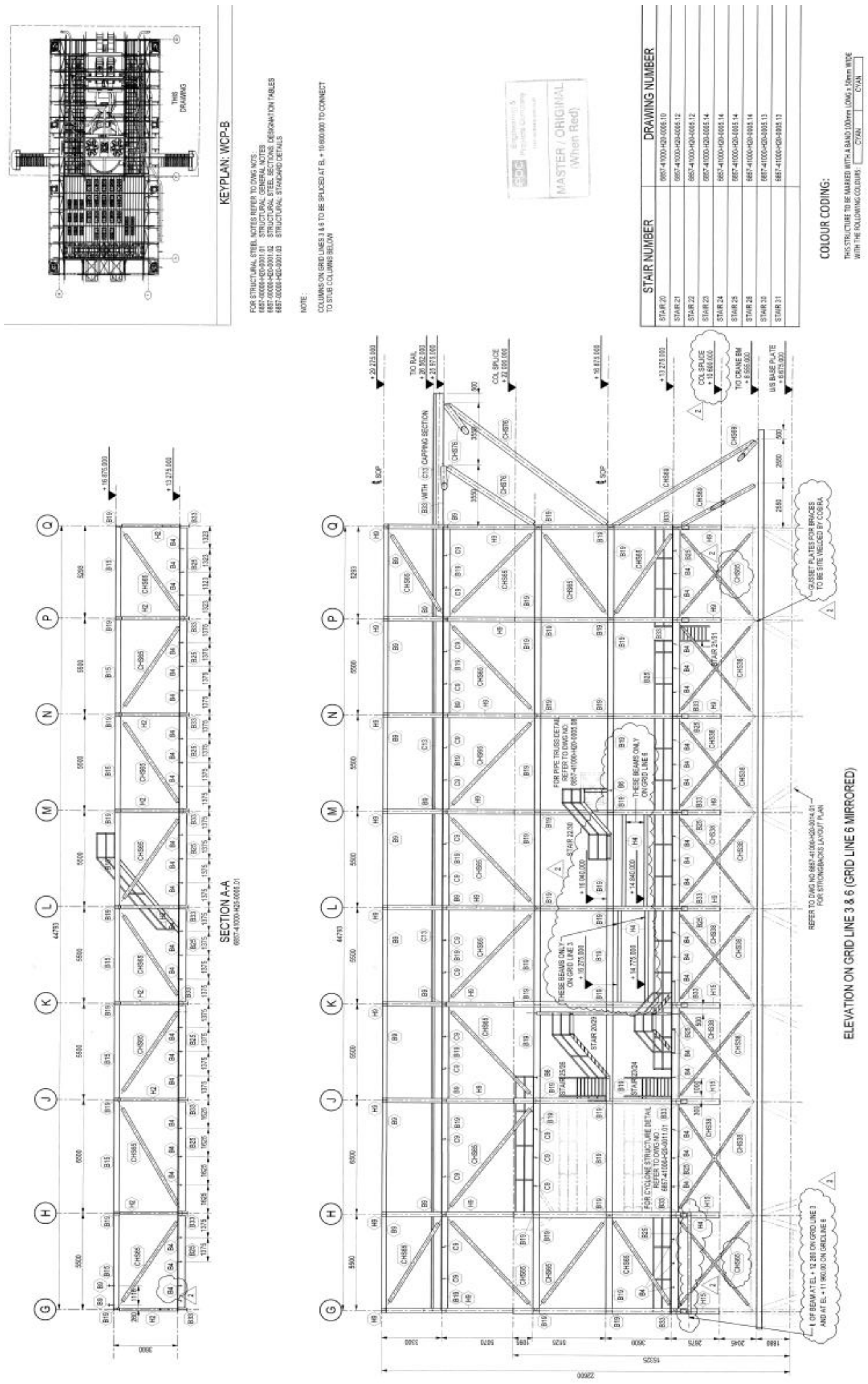


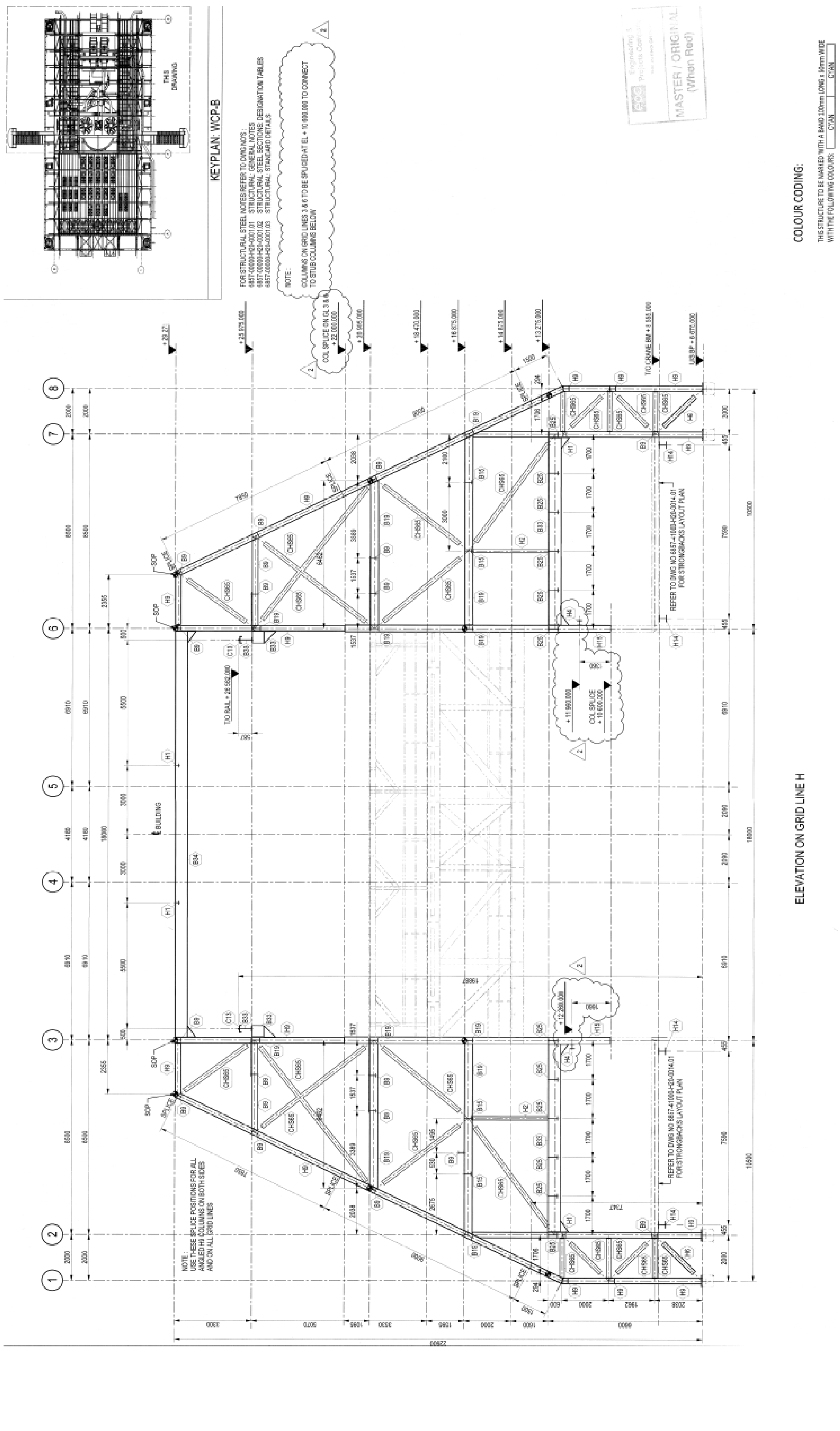


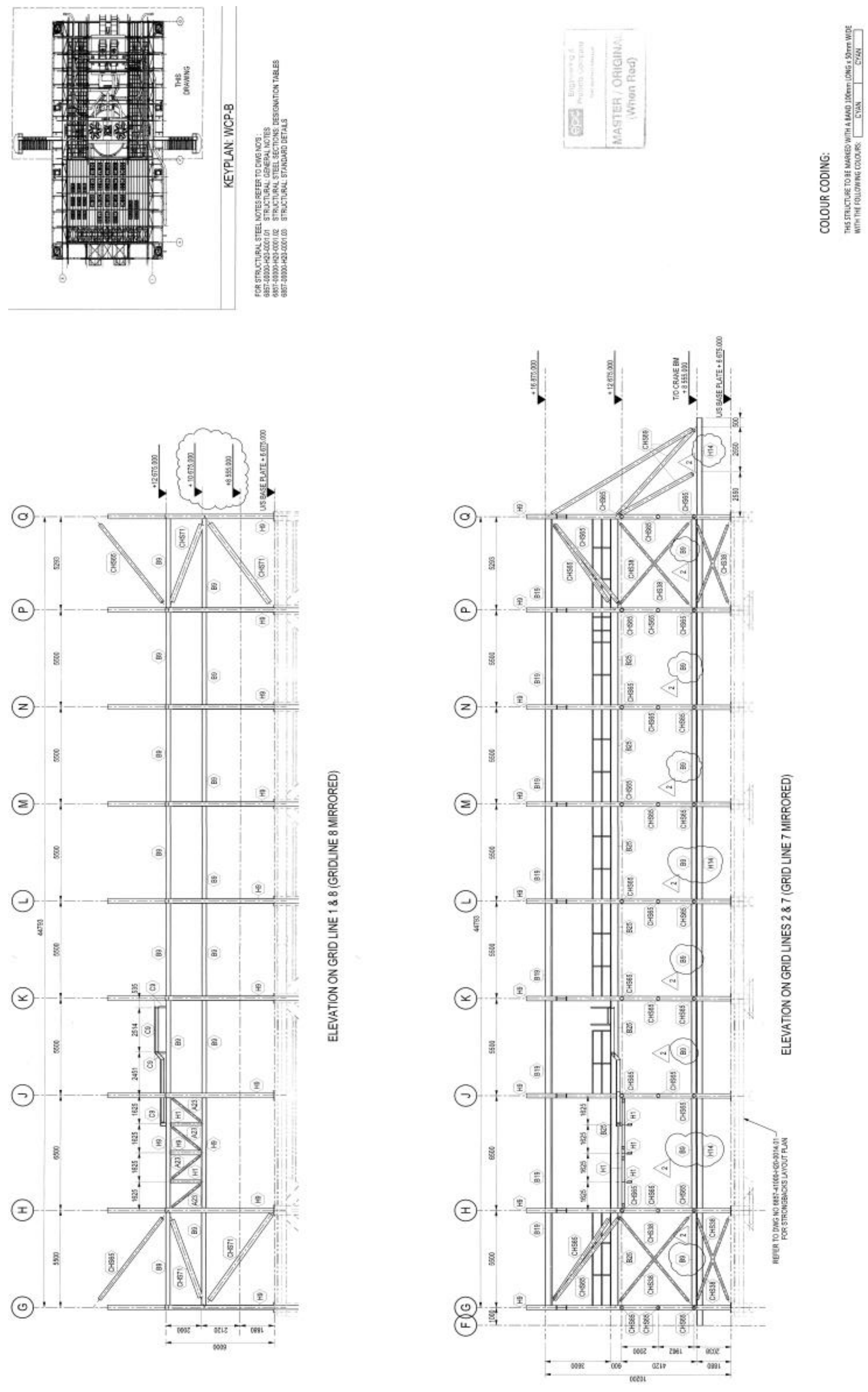




APPENDIX D – SITE F DRAWINGS

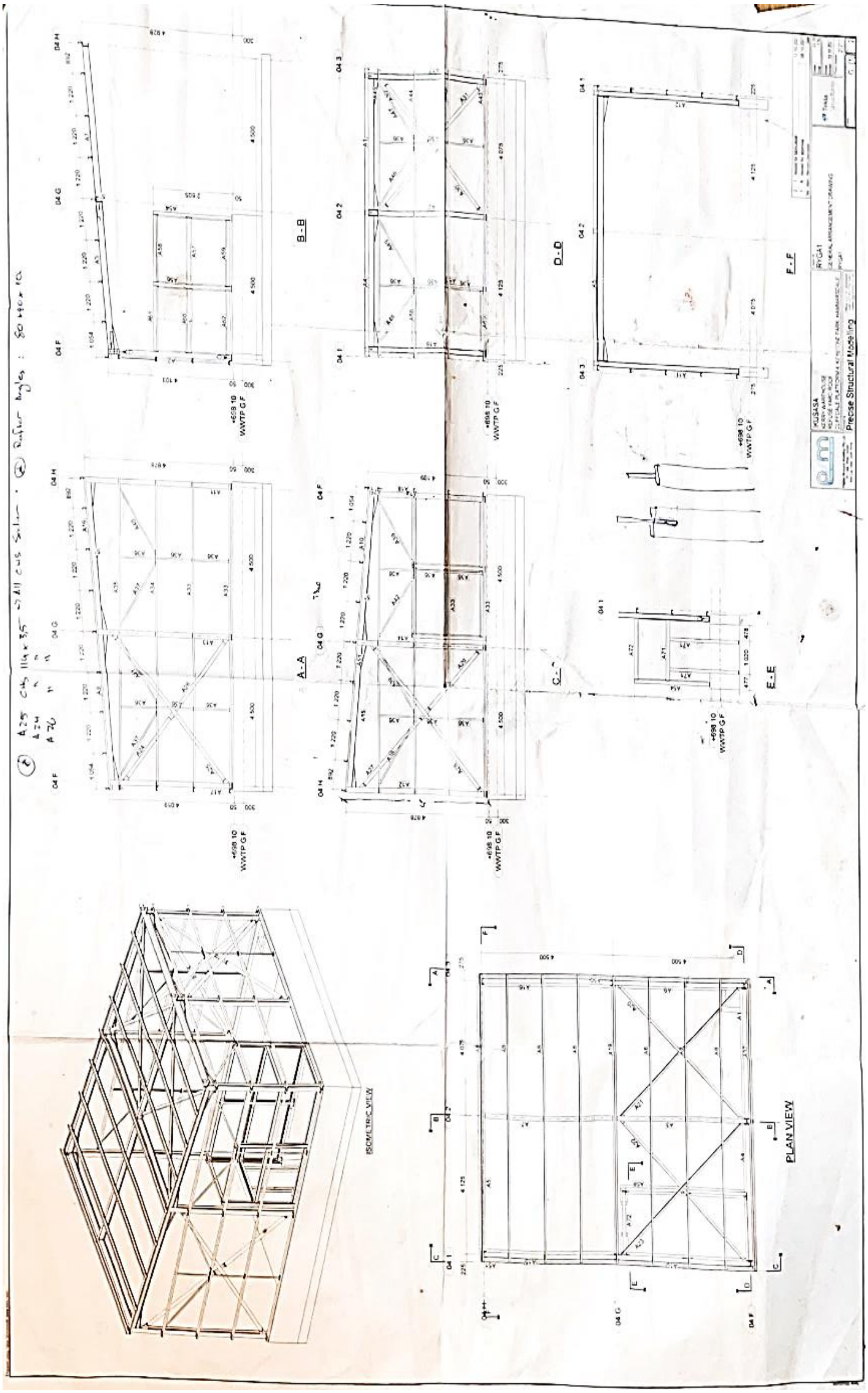



KEYPLAN: WCP-B
ELEVATION ON GRID LINE H
COLOUR CODING:



KEYPLAN: WCP-B
ELEVATION ON GRID LINE 1 & 8 (GRIDLINE 8 MIRRORED)
ELEVATION ON GRID LINES 2 & 7 (GRID LINE 7 MIRRORED)
COLOUR CODING:

APPENDIX E – SITE I DRAWINGS



APPENDIX F – SENSITIVITY ANALYSIS DATA

1. Fixed Width (5m) Variable Height Two Vertical Bay Configuration							
10 kN Load Applied at Top Left Corner of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Lower	5,74	-5,82	49,7%	50,3%	98,6%
35º	10	Lower	6,06	-6,15	49,6%	50,4%	98,5%
40º	10	Lower	6,50	-6,56	49,8%	50,2%	99,1%
45º	10	Lower	7,05	-7,09	49,9%	50,1%	99,4%
50º	10	Lower	7,77	-7,80	49,9%	50,1%	99,6%
55º	10	Lower	8,71	-8,73	49,9%	50,1%	99,8%
60º	10	Lower	10,00	-10,01	50,0%	50,0%	99,9%
65º	10	Lower	11,83	-11,84	50,0%	50,0%	99,9%
30º	10	Upper	6,24	-5,32	54,0%	46,0%	117,3%
35º	10	Upper	6,58	-5,62	53,9%	46,1%	117,1%
40º	10	Upper	6,95	-6,10	53,3%	46,7%	113,9%
45º	10	Upper	7,43	-6,71	52,5%	47,5%	110,7%
50º	10	Upper	8,11	-7,44	52,2%	47,8%	109,0%
55º	10	Upper	9,03	-8,39	51,8%	48,2%	107,6%
60º	10	Upper	10,26	-9,73	51,3%	48,7%	105,4%
65º	10	Upper	12,05	-11,58	51,0%	49,0%	104,1%

2. Fixed Width (5m) Variable Height Two Vertical Bay Configuration							
10 kN Load Applied at Middle & Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Lower	11,97	-11,13	51,8%	48,2%	107,5%
35º	10	Lower	12,64	-11,76	51,8%	48,2%	107,5%
40º	10	Lower	13,45	-12,66	51,5%	48,5%	106,2%
45º	10	Lower	14,48	-13,80	51,2%	48,8%	104,9%
50º	10	Lower	15,87	-15,24	51,0%	49,0%	104,1%
55º	10	Lower	17,73	-17,12	50,9%	49,1%	103,6%
60º	10	Lower	20,25	-19,73	50,7%	49,3%	102,6%
65º	10	Lower	23,87	-23,41	50,5%	49,5%	102,0%
30º	10	Upper	6,68	-4,91	57,6%	42,4%	136,0%
35º	10	Upper	7,03	-5,19	57,5%	42,5%	135,5%
40º	10	Upper	7,35	-5,72	56,2%	43,8%	128,5%
45º	10	Upper	7,78	-6,37	55,0%	45,0%	122,1%
50º	10	Upper	8,43	-7,13	54,2%	45,8%	118,2%
55º	10	Upper	9,35	-8,10	53,6%	46,4%	115,4%
60º	10	Upper	10,53	-9,48	52,6%	47,4%	111,1%
65º	10	Upper	12,31	-11,37	52,0%	48,0%	108,3%

3. Fixed Width (5m) Variable Height Single Vertical Bay Configuration							
10 kN Load Applied at Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Lower	6,34	-5,22	54,8%	45,2%	121,5%
35º	10	Lower	6,67	-5,54	54,6%	45,4%	120,4%
40º	10	Lower	7,02	-6,04	53,8%	46,2%	116,2%
45º	10	Lower	7,54	-6,60	53,3%	46,7%	114,2%
50º	10	Lower	8,16	-7,40	52,4%	47,6%	110,3%
55º	10	Lower	9,05	-8,39	51,9%	48,1%	107,9%
60º	10	Lower	10,31	-9,69	51,6%	48,5%	106,4%
65º	10	Lower	12,13	-11,53	51,3%	48,7%	105,2%

4. Fixed Height (8m) Variable Width Single Vertical Bay Configuration							
10 kN Load Applied at Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Lower	6,13	5,42	53,1%	46,9%	113,1%
35º	10	Lower	6,44	-5,77	52,7%	47,3%	111,6%
40º	10	Lower	6,94	-6,11	53,2%	46,8%	113,6%
45º	10	Lower	7,36	-6,79	52,0%	48,0%	108,4%
50º	10	Lower	8,05	-7,51	51,7%	48,3%	107,2%
55º	10	Lower	9,02	-8,41	51,7%	48,3%	107,3%

4. Fixed Height (8m) Variable Width Single Vertical Bay Configuration							
10 kN Load Applied at Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
60º	10	Lower	10,22	-9,76	51,2%	48,8%	104,7%
65º	10	Lower	12,02	-11,63	50,8%	49,2%	103,4%

5. Fixed Height (16m) Variable Width Two Vertical Bay Configuration							
10 kN Load Applied at Middle & Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Lower	11,96	-11,13	51,8%	48,2%	107,5%
35º	10	Lower	12,53	-11,87	51,4%	48,6%	105,6%
40º	10	Lower	13,44	-12,67	51,5%	48,5%	106,1%
45º	10	Lower	14,40	-13,88	50,9%	49,1%	103,7%
50º	10	Lower	15,93	-15,18	51,2%	48,8%	104,9%
55º	10	Lower	17,72	-17,15	50,8%	49,2%	103,3%
60º	10	Lower	20,90	-19,79	51,4%	48,6%	105,6%
65º	10	Lower	23,89	-23,41	50,5%	49,5%	102,1%
30º	10	Upper	6,65	-4,90	57,6%	42,4%	135,7%
35º	10	Upper	6,79	-5,42	55,6%	44,4%	125,3%
40º	10	Upper	7,33	-5,73	56,1%	43,9%	127,9%
45º	10	Upper	7,61	-6,53	53,8%	46,2%	116,5%

5. Fixed Height (16m) Variable Width Two Vertical Bay Configuration							
10 kN Load Applied at Middle & Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
50º	10	Upper	8,55	-7,01	54,9%	45,1%	122,0%
55º	10	Upper	9,30	-8,14	53,3%	46,7%	114,3%
60º	10	Upper	10,42	-9,52	52,3%	47,7%	109,5%
65º	10	Upper	12,32	-11,34	52,1%	47,9%	108,6%

6. Fixed Height (16m) Variable Width Two Vertical Bay Configuration							
10 kN Load Applied at Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Lower	5,73	-5,81	49,7%	50,3%	98,6%
35º	10	Lower	6,08	-6,13	49,8%	50,2%	99,2%
40º	10	Lower	6,50	-6,56	49,8%	50,2%	99,1%
45º	10	Lower	7,06	-7,08	49,9%	50,1%	99,7%
50º	10	Lower	7,76	-7,80	49,9%	50,1%	99,5%
55º	10	Lower	8,71	-8,73	49,9%	50,1%	99,8%
60º	10	Lower	10,00	-10,01	50,0%	50,0%	99,9%
65º	10	Lower	11,83	-11,85	50,0%	50,0%	99,8%
30º	10	Upper	6,23	-5,32	53,9%	46,1%	117,1%
35º	10	Upper	6,46	-5,75	52,9%	47,1%	112,3%

6. Fixed Height (16m) Variable Width Two Vertical Bay Configuration							
10 kN Load Applied at Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
40º	10	Upper	6,94	-6,11	53,2%	46,8%	113,6%
45º	10	Upper	7,34	-6,79	51,9%	48,1%	108,1%
50º	10	Upper	8,17	-7,38	52,5%	47,5%	110,7%
55º	10	Upper	9,01	-8,42	51,7%	48,3%	107,0%
60º	10	Upper	10,20	-9,78	51,1%	48,9%	104,3%
65º	10	Upper	12,06	-11,57	51,0%	49,0%	104,2%

7. Fixed Width (5m) Variable Height Three Vertical Bay Configuration							
10 kN Load Applied at Lower, Middle & Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Lower	17,76	-16,91	51,2%	48,8%	105,0%
35º	10	Lower	18,75	-17,87	51,2%	48,8%	104,9%
40º	10	Lower	19,98	-19,20	51,0%	49,0%	104,1%
45º	10	Lower	21,56	-20,85	50,8%	49,2%	103,4%
50º	10	Lower	23,68	-23,00	50,7%	49,3%	103,0%
55º	10	Lower	26,46	-25,83	50,6%	49,4%	102,4%
60º	10	Lower	30,27	-29,72	50,5%	49,5%	101,9%
65º	10	Lower	35,70	-35,25	50,3%	49,7%	101,3%

7. Fixed Width (5m) Variable Height Three Vertical Bay Configuration							
10 kN Load Applied at Lower, Middle & Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Middle	12,37	-10,74	53,5%	46,5%	115,2%
35º	10	Middle	13,05	-11,35	53,5%	46,5%	115,0%
40º	10	Middle	13,82	-12,29	52,9%	47,1%	112,4%
45º	10	Middle	14,83	-13,44	52,5%	47,5%	110,3%
50º	10	Middle	16,21	-14,89	52,1%	47,9%	108,9%
55º	10	Middle	18,03	-16,79	51,8%	48,2%	107,4%
60º	10	Middle	20,50	-19,42	51,4%	48,6%	105,6%
65º	10	Middle	24,10	-23,18	51,0%	49,0%	104,0%
30º	10	Upper	6,65	-4,94	57,4%	42,6%	134,6%
35º	10	Upper	7,00	-5,22	57,3%	42,7%	134,1%
40º	10	Upper	7,33	-5,74	56,1%	43,9%	127,7%
45º	10	Upper	7,80	-6,37	55,0%	45,0%	122,4%
50º	10	Upper	8,47	-7,11	54,4%	45,6%	119,1%
55º	10	Upper	9,37	-8,11	53,6%	46,4%	115,5%
60º	10	Upper	10,59	-9,49	52,7%	47,3%	111,6%
65º	10	Upper	12,30	-11,37	52,0%	48,0%	108,2%

8. Fixed Width (5m) Variable Height Three Vertical Bay Configuration							
10 kN Load Applied at Top Left Corner of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Lower	5,79	-5,78	50,0%	50,0%	100,2%
35º	10	Lower	6,11	-6,10	50,0%	50,0%	100,2%
40º	10	Lower	6,53	-6,53	50,0%	50,0%	100,0%
45º	10	Lower	7,08	-7,08	50,0%	50,0%	100,0%
50º	10	Lower	7,79	-7,79	50,0%	50,0%	100,0%
55º	10	Lower	8,73	-8,73	50,0%	50,0%	100,0%
60º	10	Lower	10,02	10,02	50,0%	50,0%	100,0%
65º	10	Lower	11,83	-11,84	50,0%	50,0%	99,9%
30º	10	Middle	5,74	-5,81	49,7%	50,3%	98,8%
35º	10	Middle	6,06	-6,14	49,7%	50,3%	98,7%
40º	10	Middle	6,50	-6,55	49,8%	50,2%	99,2%
45º	10	Middle	7,04	-7,09	49,8%	50,2%	99,3%
50º	10	Middle	7,76	-7,79	49,9%	50,1%	99,6%
55º	10	Middle	8,69	-8,72	49,9%	50,1%	99,7%
60º	10	Middle	9,97	-9,99	49,9%	50,1%	99,8%
65º	10	Middle	11,81	-11,82	50,0%	50,0%	99,9%
30º	10	Upper	6,24	-5,32	54,0%	46,0%	117,3%
35º	10	Upper	6,58	-5,62	53,9%	46,1%	117,1%

8. Fixed Width (5m) Variable Height Three Vertical Bay Configuration							
10 kN Load Applied at Top Left Corner of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
40º	10	Upper	6,95	-6,11	53,2%	46,8%	113,7%
45º	10	Upper	7,45	-6,69	52,7%	47,3%	111,4%
50º	10	Upper	8,13	-7,42	52,3%	47,7%	109,6%
55º	10	Upper	9,04	-8,38	51,9%	48,1%	107,9%
60º	10	Upper	10,28	-9,71	51,4%	48,6%	105,9%
65º	10	Upper	12,06	-11,59	51,0%	49,0%	104,1%

9. Fixed Height (9m) Variable Width Two Vertical Bay Configuration							
10 kN Load Applied at Middle & Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Lower	11,82	-11,27	51,2%	48,8%	104,9%
35º	10	Lower	12,60	-11,81	51,6%	48,4%	106,7%
40º	10	Lower	13,37	-12,74	51,2%	48,8%	104,9%
45º	10	Lower	14,41	-13,86	51,0%	49,0%	104,0%
50º	10	Lower	15,84	-15,24	51,0%	49,0%	103,9%
55º	10	Lower	17,77	-17,09	51,0%	49,0%	104,0%
60º	10	Lower	20,30	-19,66	50,8%	49,2%	103,3%
65º	10	Lower	23,84	-23,39	50,5%	49,5%	101,9%

9. Fixed Height (9m) Variable Width Two Vertical Bay Configuration							
10 kN Load Applied at Middle & Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Upper	6,34	-5,21	54,9%	45,1%	121,7%
35º	10	Upper	6,93	-5,29	56,7%	43,3%	131,0%
40º	10	Upper	7,19	-5,88	55,0%	45,0%	122,3%
45º	10	Upper	7,63	-6,51	54,0%	46,0%	117,2%
50º	10	Upper	8,39	-7,71	52,1%	47,9%	108,8%
55º	10	Upper	9,43	-8,02	54,0%	46,0%	117,6%
60º	10	Upper	10,65	-9,35	53,3%	46,8%	113,9%
65º	10	Upper	12,33	-11,34	52,1%	47,9%	108,7%

10. Fixed Height (9m) Variable Width Two Vertical Bay Configuration							
10 kN Load Applied at Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Lower	5,76	-5,79	49,9%	50,1%	99,5%
35º	10	Lower	6,07	-6,14	49,7%	50,3%	98,9%
40º	10	Lower	6,51	-6,55	49,8%	50,2%	99,4%
45º	10	Lower	7,06	-7,09	49,9%	50,1%	99,6%
50º	10	Lower	7,76	-7,79	49,9%	50,1%	99,6%
55º	10	Lower	8,71	-8,74	49,9%	50,1%	99,7%

10. Fixed Height (9m) Variable Width Two Vertical Bay Configuration							
10 kN Load Applied at Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
60º	10	Lower	9,99	-10,02	49,9%	50,1%	99,7%
65º	10	Lower	11,84	-11,85	50,0%	50,0%	99,9%
30º	10	Upper	6,06	-5,48	52,5%	47,5%	110,6%
35º	10	Upper	6,53	-5,67	53,5%	46,5%	115,2%
40º	10	Upper	6,86	-6,19	52,6%	47,4%	110,8%
45º	10	Upper	7,35	-6,78	52,0%	48,0%	108,4%
50º	10	Upper	8,08	-7,46	52,0%	48,0%	108,3%
55º	10	Upper	9,07	-8,35	52,1%	47,9%	108,6%
60º	10	Upper	10,31	-9,65	51,7%	48,3%	106,8%
65º	10	Upper	12,05	-11,55	51,1%	48,9%	104,3%

11. Fixed Height (9m) Variable Height Three Vertical Bay Configuration							
10 kN Load Applied at Lower, Middle & Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Lower	17,66	-16,98	51,0%	49,0%	104,0%
35º	10	Lower	18,69	-17,94	51,0%	49,0%	104,2%
40º	10	Lower	19,95	-19,19	51,0%	49,0%	104,0%
45º	10	Lower	21,60	-20,83	50,9%	49,1%	103,7%

11. Fixed Height (9m) Variable Height Three Vertical Bay Configuration							
10 kN Load Applied at Lower, Middle & Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
50º	10	Lower	23,70	-22,94	50,8%	49,2%	103,3%
55º	10	Lower	26,53	-25,79	50,7%	49,3%	102,9%
60º	10	Lower	30,30	-29,74	50,5%	49,5%	101,9%
65º	10	Lower	35,65	-35,26	50,3%	49,7%	101,1%
30º	10	Middle	12,20	-10,89	52,8%	47,2%	112,0%
35º	10	Middle	12,94	-11,48	53,0%	47,0%	112,7%
40º	10	Middle	13,78	-12,31	52,8%	47,2%	111,9%
45º	10	Middle	14,90	-13,38	52,7%	47,3%	111,4%
50º	10	Middle	16,29	-14,79	52,4%	47,6%	110,1%
55º	10	Middle	18,16	-16,69	52,1%	47,9%	108,8%
60º	10	Middle	20,57	-19,42	51,4%	48,6%	105,9%
65º	10	Middle	24,02	-23,19	50,9%	49,1%	103,6%
30º	10	Upper	6,45	-5,09	55,9%	44,1%	126,7%
35º	10	Upper	6,87	-5,35	56,2%	43,8%	128,4%
40º	10	Upper	7,29	-5,76	55,9%	44,1%	126,6%
45º	10	Upper	7,86	-6,29	55,5%	44,5%	125,0%
50º	10	Upper	8,55	-7,00	55,0%	45,0%	122,1%
55º	10	Upper	9,48	-7,96	54,4%	45,6%	119,1%

11. Fixed Height (9m) Variable Height Three Vertical Bay Configuration							
10 kN Load Applied at Lower, Middle & Top Left Corners of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
60º	10	Upper	10,59	-9,42	52,9%	47,1%	112,4%
65º	10	Upper	12,24	-11,40	51,8%	48,2%	107,4%

12. Fixed Height (9m) Variable Height Three Vertical Bay Configuration							
10 kN Load Applied at Top Left Corner of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
30º	10	Lower	5,77	-5,77	50,0%	50,0%	100,0%
35º	10	Lower	6,11	-6,11	50,0%	50,0%	100,0%
40º	10	Lower	6,53	-6,52	50,0%	50,0%	100,2%
45º	10	Lower	7,07	-7,07	50,0%	50,0%	100,0%
50º	10	Lower	7,77	-7,78	50,0%	50,0%	99,9%
55º	10	Lower	8,72	-8,72	50,0%	50,0%	100,0%
60º	10	Lower	10,01	-10,02	50,0%	50,0%	99,9%
65º	10	Lower	11,82	-11,83	50,0%	50,0%	99,9%
30º	10	Middle	5,75	-5,80	49,8%	50,2%	99,1%
35º	10	Middle	6,08	-6,13	49,8%	50,2%	99,2%
40º	10	Middle	6,50	-6,55	49,8%	50,2%	99,2%
45º	10	Middle	7,04	-7,09	49,8%	50,2%	99,3%

12. Fixed Height (9m) Variable Height Three Vertical Bay Configuration							
10 kN Load Applied at Top Left Corner of Structure							
θ_{brace}	**$F_{horiz.}$ (kN)**	**Comp. Location**	**Member F_C (kN)**	**Member F_T (kN)**	**F_C %**	**F_T %**	**F_C:F_T %**
50º	10	Middle	7,75	-7,79	49,9%	50,1%	99,5%
55º	10	Middle	8,69	-8,73	49,9%	50,1%	99,5%
60º	10	Middle	9,98	-10,01	49,9%	50,1%	99,7%
65º	10	Middle	11,79	-11,80	50,0%	50,0%	99,9%
30º	10	Upper	6,13	-5,41	53,1%	46,9%	113,3%
35º	10	Upper	6,51	-5,70	53,3%	46,7%	114,2%
40º	10	Upper	6,93	-6,12	53,1%	46,9%	113,2%
45º	10	Upper	7,49	-6,65	53,0%	47,0%	112,6%
50º	10	Upper	8,18	-7,36	52,6%	47,4%	111,1%
55º	10	Upper	9,11	-8,32	52,3%	47,7%	109,5%
60º	10	Upper	10,30	-9,70	51,5%	48,5%	106,2%
65º	10	Upper	12,03	-11,60	50,9%	49,1%	103,7%

APPENDIX G – CONFIGURATION ANALYSIS AND MEMBER SPECIFICATION SUPPLEMENTARY DATA

Reference Configuration Cross-braced CHS Hypothetical Cases					
Case Count No.	**CHS Section**	**L_{eff} (mm)**	**$C_{r,X\text{-}CHS}$ (kN)**	**$(KL/r)_{CHS}$**	**Controlling Design Variable**
1	76,2x3,0	4909	31,9 kN	190	Cross Sectional Capacity
2	88,9x3,0	5188	45,7 kN	171	Cross Sectional Capacity
3	88,9x3,0	5551	40,4 kN	183	Cross Sectional Capacity
4	88,9x3,0	6010	34,9 kN	198	Cross Sectional Capacity
5	101,6x3,0	6613	43,6 kN	189	Cross Sectional Capacity
6	114,3x3,0	7409	49,4 kN	188	Cross Sectional Capacity
7	127x3,0	8500	52,4 kN	194	Cross Sectional Capacity
8	152,4x3,0	10055	64,9 kN	190	Cross Sectional Capacity
9	219,1x6,0	16003	151 kN	212	Cross Sectional Capacity
10	219,1x3,5	13952	117,8 kN	183	Cross Sectional Capacity
11	193,7x3,5	12443	102,4 kN	185	Cross Sectional Capacity
12	165,1x3,0	11314	66 kN	197	Cross Sectional Capacity
13	152,4x3,0	10441	60,5 kN	198	Cross Sectional Capacity
14	152,4x3,0	9765	68,4 kN	185	Cross Sectional Capacity
15	139,7x3,0	9238	59,3 kN	191	Cross Sectional Capacity

Reference Configuration Cross-braced CHS Hypothetical Cases					
Case Count No.	**CHS Section**	**L_{eff} (mm)**	**$C_{r,X\text{-}CHS}$ (kN)**	**$(KL/r)_{CHS}$**	**Controlling Design Variable**
16	139,7x3,0	8827	64,5 kN	182	Cross Sectional Capacity
17	114,3x3,0	7647	46,6 kN	194	Cross Sectional Capacity
18	101,6x3,0	6671	42,9 kN	191	Cross Sectional Capacity
19	88,9x3,0	5949	35,6 kN	196	Cross Sectional Capacity
20	88,9x3,0	5409	42,4 kN	178	Cross Sectional Capacity
21	76,2x3,0	4995	30,9 kN	193	Cross Sectional Capacity
22	76,2x3,0	4669	35 kN	180	Cross Sectional Capacity
23	76,2x3,0	4417	38,7 kN	171	Cross Sectional Capacity
24	63,5x3,0	4221	24,3 kN	199	Cross Sectional Capacity
25	76,2x3,0	5103	29,7 kN	197	Cross Sectional Capacity
26	76,2x3,0	4443	38,3 kN	172	Cross Sectional Capacity
27	60,0x3,0	3970	23,4 kN	196	Cross Sectional Capacity
28	60,0x3,0	3607	27,9 kN	178	Cross Sectional Capacity
29	60,0x3,0	3330	32,3 kN	164	Cross Sectional Capacity
30	60,0x3,0	3113	36,4 kN	153	Cross Sectional Capacity
31	60,0x3,0	2944	40,1 kN	145	Cross Sectional Capacity
32	60,0x3,0	2814	43,3 kN	139	Cross Sectional Capacity

Reference Configuration Cross-braced CHS Built-Site Cases					
Case Count No.	**CHS Section**	**L_{eff} (mm)**	**$C_{r,X\text{-}CHS}$ (kN)**	**$(KL/r)_{CHS}$**	**Controlling Design Variable**
33	152,4x3,0	6918	120 kN	131	Bolt Group Shear Capacity
34	152,4x3,0	5525	176,9 kN	105	Cross Sectional Capacity
35	152,4x3,0	7927	99,4 kN	150	Cross Sectional Capacity
36	165,1x6,0	2149	882,4 kN	38	Cross Sectional Capacity
37	165,1x6,0	2149	700 kN	38	Bolt Group Shear Capacity
38	127x6,0	1822	627,3 kN	43	Cross Sectional Capacity
39	127x6,0	1822	504 kN	43	Bolt Group Shear Capacity
40	127x3,0	6575	59,1 kN	150	Cross Sectional Capacity
41	114,3x3,0	6575	47 kN	167	Bolt Group Shear Capacity
42	127x6,0	6631	153 kN	155	Cross Sectional Capacity
43	193,7x6,0	5942	550,4 kN	89	Cross Sectional Capacity
44	193,7x6,0	7592	392,1 kN	114	Cross Sectional Capacity
45	127x6,0	5914	186,2 kN	138	Cross Sectional Capacity
46	127x6,0	4986	245,2 kN	116	Cross Sectional Capacity
47	101,6x3,0	2779	165,8 kN	79	Cross Sectional Capacity
48	101,6x3,0	2779	126 kN	79	Bolt Group Shear Capacity
49	101,6x3,0	2779	87,6 kN	79	Bolt Group Shear Capacity
50	101,6x3,0	2779	54 kN	79	Bolt Group Shear Capacity
51	219,1x6,0	7966	498,2 kN	106	Cross Sectional Capacity

Reference Configuration Cross-braced CHS Built-Site Cases					
Case Count No.	**CHS Section**	**L_{eff} (mm)**	**$C_{r,X\text{-}CHS}$ (kN)**	**$(KL/r)_{CHS}$**	**Controlling Design Variable**
52	114,3x3.5	5302	102,6 kN	136	Cross Sectional Capacity

Comparative Configuration Cross-braced Angle Hypothetical Cases				
Case Count No.	**N_{design} (kN)**	**Angle Section**	**$T_{r,X\text{-}L}$ (kN)**	**Connection Spec.**
1	**60,5 kN**	50x50x4	69 kN	1 Line x 4 Rows (4x) Gr8.8 M16
2	**86,7 kN**	60x60x4	87 kN	1 Line x 4 Rows (4x) Gr8.8 M16
3	**77,1 kN**	60x60x5	108 kN	1 Line x 4 Rows (4x) Gr8.8 M16
4	**67,2 kN**	60x60x4	87 kN	1 Line x 4 Rows (4x) Gr8.8 M16
5	**84,3 kN**	70x70x6	132 kN	1 Line x 2 Rows (2x) Gr8.8 M16
6	**95,9 kN**	80x80x6	132 kN	1 Line x 2 Rows (2x) Gr8.8 M20
7	**102,5 kN**	90x90x6	132 kN	1 Line x 2 Rows (2x) Gr8.8 M20
8	**129,5 kN**	100x100x8	175 kN	1 Line x 2 Rows (2x) Gr8.8 M20
9	**286,5 kN**	150x150x10	350 kN	2 Lines x 2 Rows (4x) Gr8.8 M20
10	**223,5 kN**	120x120x8	263 kN	1 Line x 3 Rows (3x) Gr8.8 M20
11	**195,4 kN**	120x120x8	263 kN	1 Line x 3 Rows (3x) Gr8.8 M20
12	**127,2 kN**	100x100x8	175 kN	1 Line x 2 Rows (2x) Gr8.8 M20
13	**117 kN**	90x90x6	132 kN	1 Line x 2 Rows (2x) Gr8.8 M20
14	**132,8 kN**	90x90x6	132 kN	1 Line x 2 Rows (2x) Gr8.8 M20

Comparative Configuration Cross-braced Angle Hypothetical Cases				
Case Count No.	**N_{design} (kN)**	**Angle Section**	**$T_{r,X-L}$ (kN)**	**Connection Spec.**
15	**116 kN**	80x80x6	132 kN	1 Line x 2 Rows (2x) Gr8.8 M20
16	**128,7 kN**	80x80x6	132 kN	1 Line x 2 Rows (2x) Gr8.8 M20
17	**88,4 kN**	80x80x6	132 kN	1 Line x 2 Rows (2x) Gr8.8 M20
18	**81,4 kN**	70x70x6	132 kN	1 Line x 2 Rows (2x) Gr8.8 M16
19	**67,9 kN**	60x60x4	87 kN	1 Line x 4 Rows (4x) Gr8.8 M16
20	**81,7 kN**	60x60x4	87 kN	1 Line x 4 Rows (4x) Gr8.8 M16
21	**59,8 kN**	50x50x4	69 kN	1 Line x 4 Rows (4x) Gr8.8 M16
22	**68 kN**	50x50x4	69 kN	1 Line x 4 Rows (4x) Gr8.8 M16
23	**75,7 kN**	50x50x5	84,9 kN	1 Line x 4 Rows (4x) Gr8.8 M16
24	**48,5 kN**	50x50x3	53,2 kN	1 Line x 4 Rows (4x) Gr8.8 M16
25	**56,4 kN**	60x60x4	65,5 kN	1 Line x 3 Rows (3x) Gr8.8 M16
26	**72,7 kN**	50x50x5	84,9 kN	1 Line x 4 Rows (4x) Gr8.8 M16
27	**44,7 kN**	50x50x4	48,9 kN	1 Line x2 Rows (2x) Gr8.8 M16
28	**53,8 kN**	50x50x4	69 kN	1 Line x 4 Rows (4x) Gr8.8 M16
29	**62,5 kN**	50x50x4	69 kN	1 Line x 4 Rows (4x) Gr8.8 M16
30	**70,7 kN**	60x60x4	87 kN	1 Line x 4 Rows (4x) Gr8.8 M16
31	**78,5 kN**	60x60x4	87 kN	1 Line x 4 Rows (4x) Gr8.8 M16
32	**86,4 kN**	60x60x4	87 kN	1 Line x 4 Rows (4x) Gr8.8 M16

Comparative Configuration Cross-braced Angle Built-Site Cases				
Case Count No.	**N_{design} (kN)**	**Angle Section**	**$T_{r,X-L}$ (kN)**	**Connection Spec.**
33	**229,9 kN**	70x70x8	255 kN	1 Line x 4 Rows (4x) Gr8.8 M20
34	**309,3 kN**	80x80x10	350 kN	1 Line x 4 Rows (4x) Gr8.8 M20
35	**232,8 kN**	70x70x6	192 kN	1 Lines x 3 Rows (3x) Gr8.8 M20
36	**1700,2 kN**	200x200x18	1698 kN	2 Lines x 7 Rows (14x) Gr8.8 M24
37	**1348,7 kN**	150x150x18	1350 kN	1 Lines x 11 Rows (11x) Gr8.8 M24
38	**1183,6 kN**	150x150x18	1190 kN	2 Lines x 6 Rows (12x) Gr8.8 M20
39	**950,9 kN**	150x150x15	1030 kN	2 Lines x 7 Rows (14x) Gr8.8 M20
40	**135,9 kN**	70x70x6	144 kN	1 Lines x 3 Rows (3x) Gr8.8 M20
41	**108 kN**	70x70x6	144 kN	1 Lines x 3 Rows (3x) Gr8.8 M20
42	**290,3 kN**	80x80x8	308 kN	1 Lines x 4 Rows (4x) Gr8.8 M20
43	**1048,4 kN**	150x150x15	1114 kN	1 Lines x 10 Rows (10x) Gr8.8 M24
44	**752,6 kN**	150x150x10	762 kN	1 Lines x 7 Rows (7x) Gr8.8 M24
45	**354,7 kN**	80x80x10	365 kN	1 Lines x 5 Rows (5x) Gr8.8 M20
46	**465,3 kN**	100x100x10	483 kN	1 Lines x 6 Rows (6x) Gr8.8 M20
47	**314,6 kN**	70x70x10	314 kN	1 Lines x 4 Rows (4x) Gr8.8 M20
48	**239,1 kN**	70x70x8	250 kN	1 Line x 4 Rows (4x) Gr8.8 M20
49	**166,2 kN**	60x60x8	165 kN	1 Line x 6 Rows (6x) Gr4.8 M16
50	**102,5 kN**	50x50x6	100 kN	1 Line x 4 Rows (4x) Gr8.8 M20
51	**963,6 kN**	150x150x15	1030 kN	2 Lines x 6 Rows (12x) Gr8.8 M20

Comparative Configuration Cross-braced Angle Built-Site Cases				
Case Count No.	**N_{design} (kN)**	**Angle Section**	**$T_{r,X-L}$ (kN)**	**Connection Spec.**
52	**197,3 kN**	70x70x6	197 kN	1 Lines x 4 Rows (4x) Gr8.8 M20

Comparative Configuration Single CHS Braced Hypothetical Cases			
Case Count No.	**Single CHS Section**	**CHS Effective Length (mm)**	**$C_{r,S-CHS}$ (kN)**
1	101,6x3,0	4909	85,1 kN
2	114,3x3,0	5188	92,4 kN
3	114,3x3,0	5551	82,5 kN
4	114,3x3,0	6010	72 kN
5	139,7x3,0	6613	107,2 kN
6	152,4x3,0	7409	111,7 kN
7	165,1x3,0	8500	110,5 kN
8	193,7x3,5	10055	149,8 kN
9	2x Bays 219,1x6,0	16003	151,2 kN
10	2x Bays 219,1x3,5	13952	235,6 kN
11	219,1x6,0	12443	240,4 kN
12	219,1x3,5	11314	171,2 kN
13	193,7x3,5	10441	140,3 kN
14	193,7x3,5	9765	157,6 kN

Comparative Configuration Single CHS Braced Hypothetical Cases			
Case Count No.	**Single CHS Section**	**CHS Effective Length (mm)**	**$C_{r,S\text{-}CHS}$ (kN)**
15	177,8x3,5	9238	136,4 kN
16	177,8x3,5	8827	147,5 kN
17	152,4x3,0	7647	105,8 kN
18	127x3,0	6671	81,1 kN
19	114,3x3,0	5949	73,3 kN
20	114,3x3,0	5409	86,2 kN
21	101,6x3,0	4995	71,8 kN
22	101,6x3,0	4669	80,4 kN
23	101,6x3,0	4417	88,1 kN
24	76,2x3,5	4221	48,4 kN
25	101,6x3,0	5103	69,3 kN
26	101,6x3,0	4443	87,2 kN
27	76,2x3,0	3970	46,8 kN
28	76,2x3,0	3607	55,2 kN
29	76,2x3,0	3330	63 kN
30	76,2x3,0	3113	70,2 kN
31	76,2x3,5	2944	88,2 kN
32	76,2x3,5	2814	94,3 kN

Comparative Configuration Single CHS Braced Built-Site Cases			
Case Count No.	**Single CHS Section**	**CHS Effective Length (mm)**	**$C_{r,S\text{-}CHS}$ (kN)**
33	193,7x3,5	6918	270,8 kN
34	193,7x3,5	5525	464,1 kN
35	193,7x3,5	7927	221,5 kN
36	2x Bays 165,1x6,0	2149	1764,8 kN
37	2x Bays 139,7x6,0	2149	1418,6 kN
38	219,1x6,0	1822	1238,4 kN
39	177,8x6,0	1822	972,3 kN
40	152,4x3,0	6575	135,9 kN
41	152,4x3,0	6575	135,9 kN
42	165,1x6,0	6631	316,9 kN
43	2x 193,7x6,0	5942	1100,8 kN
44	2x 193,7x6,0	7592	784,2 kN
45	165,1x6,0	5914	375,8 kN
46	165,1x6,0	4986	417,7 kN
47	152,4x3,0	2779	315,2 kN
48	139,7x3,0	2779	262,2 kN
49	114,3x3,0	2779	1177,7 kN
50	101,6x3,0	2779	136,7 kN
51	2x Bays 219,1x6,0	7966	996,4 kN

Comparative Configuration Single CHS Braced Built-Site Cases			
Case Count No.	**Single CHS Section**	**CHS Effective Length (mm)**	**$C_{r,S\text{-}CHS}$ (kN)**
52	165,1x3,0	5302	227,4 kN

ANNEX H – MEMBER DESIGN

The results of the braced frame analysis are outlined in the subsequent section. The results are divided between the hypothetical and built-site configurations and reference by case count number. Hypothetical configurations constitute cases 1-32 and built-site configurations are referenced as cases 33-52.

Summary of Cross-braced CHS Reference Configurations by Reference Number showing Brace Inclination Angle, Cross Section and Calculated Compressive Resistance				
Case Count No.	**Brace Inclination Angle.**	**$SR_{X\text{-}CHS}$ = (KL/r)**	**CHS Section**	**$C_{r,X\text{-}CHS}$ (kN)**
1	30º	190	76,2x3,0	31,9 kN
2	35º	171	88,9x3,0	45,7 kN
3	40º	183	88,9x3,0	40,4 kN
4	45º	198	88,9x3,0	34,9 kN
5	50º	189	101,6x3,0	43,6 kN
6	55º	188	114,3x3,0	49,4 kN
7	60º	194	127x3,0	52,4 kN
8	65º	190	152,4x3,0	64,9 kN
9	30º	212	219,1x6,0	151 kN
10	35º	183	219,1x3,5	117,8 kN
11	40º	185	193,7x3,5	102,4 kN
12	45º	197	165,1x3,0	66 kN
13	50º	198	152,4x3,0	60,5 kN

Summary of Cross-braced CHS Reference Configurations by Reference Number showing Brace Inclination Angle, Cross Section and Calculated Compressive Resistance				
Case Count No.	**Brace Inclination Angle.**	**$SR_{X\text{-}CHS}$ = (KL/r)**	**CHS Section**	**$C_{r,X\text{-}CHS}$ (kN)**
14	55º	185	152,4x3,0	68,4 kN
15	60º	191	139,7x3,0	59,3 kN
16	65º	182	139,7x3,0	64,5 kN
17	30º	194	114,3x3,0	46,6 kN
18	35º	191	101,6x3,0	42,9 kN
19	40º	196	88,9x3,0	35,6 kN
20	45º	178	88,9x3,0	42,4 kN
21	50º	193	76,2x3,0	30,9 kN
22	55º	180	76,2x3,0	35 kN
23	60º	171	76,2x3,0	38,7 kN
24	65º	199	63,5x3,0	24,3 kN
25	30º	197	76,2x3,0	29,7 kN
26	35º	172	76,2x3,0	38,3 kN
27	40º	196	60,0x3,0	23,4 kN
28	45º	178	60,0x3,0	27,9 kN
29	50º	164	60,0x3,0	32,3 kN
30	55º	153	60,0x3,0	36,4 kN
31	60º	145	60,0x3,0	40,1 kN

Summary of Cross-braced CHS Reference Configurations by Reference Number showing Brace Inclination Angle, Cross Section and Calculated Compressive Resistance				
Case Count No.	**Brace Inclination Angle.**	**$SR_{X\text{-}CHS}$ = (KL/r)**	**CHS Section**	**$C_{r,X\text{-}CHS}$ (kN)**
32	65º	139	60,0x3,0	43,3 kN

Summary of Cross-braced Angle Comparative Configurations by Reference Number showing Design Load, Cross Section and Calculated Tensile Resistance			
Case Count No.	**Design Load (kN)**	**Required Angle Section**	**$T_{r,X\text{-}L}$ (kN)**
1	**60,5 kN**	50x50x4	69 kN
2	**86,7 kN**	60x60x4	87 kN
3	**77,1 kN**	60x60x5	108 kN
4	**67,2 kN**	60x60x4	87 kN
5	**84,3 kN**	70x70x6	132 kN
6	**95,9 kN**	80x80x6	132 kN
7	**102,5 kN**	90x90x6	132 kN
8	**129,5 kN**	100x100x8	175 kN
9	**286,5 kN**	150x150x10	350 kN
10	**223,5 kN**	120x120x8	263 kN
11	**195,4 kN**	120x120x8	263 kN
12	**127,2 kN**	100x100x8	175 kN
13	**117 kN**	90x90x6	132 kN

Summary of Cross-braced Angle Comparative Configurations by Reference Number showing Design Load, Cross Section and Calculated Tensile Resistance			
Case Count No.	**Design Load (kN)**	**Required Angle Section**	**$T_{r,X\text{-}L}$ (kN)**
14	**132,8 kN**	90x90x6	132 kN
15	**116 kN**	80x80x6	132 kN
16	**128,7 kN**	80x80x6	132 kN
17	**88,4 kN**	80x80x6	132 kN
18	**81,4 kN**	70x70x6	132 kN
19	**67,9 kN**	60x60x4	87 kN
20	**81,7 kN**	60x60x4	87 kN
21	**59,8 kN**	50x50x4	69 kN
22	**68 kN**	50x50x4	69 kN
23	**75,7 kN**	50x50x5	84,9 kN
24	**48,5 kN**	50x50x3	53,2 kN
25	**56,4 kN**	60x60x4	65,5 kN
26	**72,7 kN**	50x50x5	84,9 kN
27	**44,7 kN**	50x50x4	48,9 kN
28	**53,8 kN**	50x50x4	69 kN
29	**62,5 kN**	50x50x4	69 kN
30	**70,7 kN**	60x60x4	87 kN
31	**78,5 kN**	60x60x4	87 kN
32	**86,4 kN**	60x60x4	87 kN

Summary of Single-braced CHS Comparative Configurations by Reference Number showing Design Load, Cross Section and Calculated Compressive Resistance			
Case Count No.	**Design Load (kN)**	**Required Single CHS Section**	**$C_{r,S\text{-}CHS}$ (kN)**
1	**60,5 kN**	101,6x3,0	85,1 kN
2	**86,7 kN**	114,3x3,0	92,4 kN
3	**77,1 kN**	114,3x3,0	82,5 kN
4	**67,2 kN**	114,3x3,0	72 kN
5	**84,3 kN**	139,7x3,0	107,2 kN
6	**95,9 kN**	152,4x3,0	111,7 kN
7	**102,5 kN**	165,1x3,0	110,5 kN
8	**129,5 kN**	193,7x3,5	149,8 kN
9	**286,5 kN**	2x Bays 219,1x6,0	151,2 kN
10	**223,5 kN**	2x Bays 219,1x3,5	235,6 kN
11	**195,4 kN**	219,1x6,0	240,4 kN
12	**127,2 kN**	219,1x3,5	171,2 kN
13	**117 kN**	193,7x3,5	140,3 kN
14	**132,8 kN**	193,7x3,5	157,6 kN
15	**116 kN**	177,8x3,5	136,4 kN
16	**128,7 kN**	177,8x3,5	147,5 kN
17	**88,4 kN**	152,4x3,0	105,8 kN
18	**81,4 kN**	127x3,0	81,1 kN

Summary of Single-braced CHS Comparative Configurations by Reference Number showing Design Load, Cross Section and Calculated Compressive Resistance			
Case Count No.	**Design Load (kN)**	**Required Single CHS Section**	**$C_{r,S\text{-}CHS}$ (kN)**
19	**67,9 kN**	114,3x3,0	73,3 kN
20	**81,7 kN**	114,3x3,0	86,2 kN
21	**59,8 kN**	101,6x3,0	71,8 kN
22	**68 kN**	101,6x3,0	80,4 kN
23	**75,7 kN**	101,6x3,0	88,1 kN
24	**48,5 kN**	76,2x3,5	48,4 kN
25	**56,4 kN**	101,6x3,0	69,3 kN
26	**72,7 kN**	101,6x3,0	87,2 kN
27	**44,7 kN**	76,2x3,0	46,8 kN
28	**53,8 kN**	76,2x3,0	55,2 kN
29	**62,5 kN**	76,2x3,0	63 kN
30	**70,7 kN**	76,2x3,0	70,2 kN
31	**78,5 kN**	76,2x3,5	88,2 kN
32	**86,4 kN**	76,2x3,5	94,3 kN

Summary of Cross-braced CHS Reference Configurations by Reference Number showing Brace Inclination Angle, Cross Section and Calculated Compressive Resistance				
Case Count No.	**Brace Inclination Angle**	**$SR_{X\text{-}CHS}$ = (KL/r)**	**CHS Section**	**$C_{r,X\text{-}CHS}$ (kN)**
33	42,5º	131	152,4x3,0	120 kN
34	22,6º	105	152,4x3,0	176,9 kN
35	36,0º	150	152,4x3,0	99,4 kN
36	45º	38	165,1x6,0	882,4 kN
37	45º	38	165,1x6,0	700 kN
38	20,8º	43	127x6,0	627,3 kN
39	20,8º	43	127x6,0	504 kN
40	39,1º	150	127x3,0	59,1 kN
41	39,1º	167	114,3x3,0	47 kN
42	33,6º	155	127x6,0	153 kN
43	38,1º	89	193,7x6,0	550,4 kN
44	43,6º	114	193,7x6,0	392,1 kN
45	37,8º	138	127x6,0	186,2 kN
46	20,3º	116	127x6,0	245,2 kN
47	35,5º	79	101,6x3,0	165,8 kN
48	35,5º	79	101,6x3,0	126 kN
49	35,5º	79	101,6x3,0	87,6 kN
50	35,5º	79	101,6x3,0	54 kN

Summary of Cross-braced CHS Reference Configurations by Reference Number showing Brace Inclination Angle, Cross Section and Calculated Compressive Resistance				
Case Count No.	**Brace Inclination Angle**	**SR_{X-CHS} = (KL/r)**	**CHS Section**	**$C_{r,X-CHS}$ (kN)**
51	50,2º	106	219,1x6,0	498,2 kN
52	43,8º	136	114,3x3.5	102,6 kN

Summary of Cross-braced Angle Comparative Configurations by Reference Number showing Design Load, Cross Section and Calculated Tensile Resistance			
Case Count No.	**Design Load (kN)**	**Required Angle Section**	**$T_{r,X-L}$ (kN)**
33	**229,9 kN**	70x70x8	255 kN
34	**309,3 kN**	80x80x10	350 kN
35	**232,8 kN**	70x70x6	192 kN
36	**1700,2 kN**	200x200x18	1698 kN
37	**1348,7 kN**	150x150x18	1350 kN
38	**1183.6 kN**	150x150x18	1190 kN
39	**950.9 kN**	150x150x15	1030 kN
40	**135,9 kN**	70x70x6	144 kN
41	**108 kN**	70x70x6	144 kN
42	**290,3 kN**	80x80x8	308 kN
43	**1048,4 kN**	150x150x15	1114 kN
44	**752,6 kN**	150x150x10	762 kN

Summary of Cross-braced Angle Comparative Configurations by Reference Number showing Design Load, Cross Section and Calculated Tensile Resistance			
Case Count No.	**Design Load (kN)**	**Required Angle Section**	**$T_{r,X-L}$ (kN)**
45	**354,7 kN**	80x80x10	365 kN
46	**465,3 kN**	100x100x10	483 kN
47	**314,6 kN**	70x70x10	314 kN
48	**239,1 kN**	70x70x8	250 kN
49	**166,2 kN**	60x60x8	165 kN
50	**102,5 kN**	50x50x6	100 kN
51	**963,6 kN**	150x150x15	1030 kN
52	**197,3 kN**	70x70x6	197 kN

Summary of Single-braced CHS Comparative Configurations by Reference Number showing Design Load, Cross Section and Calculated Compressive Resistance			
Case Count No.	**Design Load (kN)**	**Required Single CHS Section**	**$C_{r,S-CHS}$ (kN)**
33	**229,9 kN**	193,7x3,5	270,8 kN
34	**309,3 kN**	193,7x3,5	464,1 kN
35	**232,8 kN**	193,7x3,5	221,5 kN
36	**1700,2 kN**	2x Bays 165,1x6,0	1764,8 kN
37	**1348,7 kN**	2x Bays 139,7x6,0	1418,6 kN
38	**1190,3 kN**	219,1x6,0	1238,4 kN
39	**956,4 kN**	177,8x6,0	972,3 kN

Summary of Single-braced CHS Comparative Configurations by Reference Number showing Design Load, Cross Section and Calculated Compressive Resistance			
Case Count No.	**Design Load (kN)**	**Required Single CHS Section**	**$C_{r,S\text{-}CHS}$ (kN)**
40	**135,9 kN**	152,4x3,0	135,9 kN
41	**108 kN**	152,4x3,0	135,9 kN
42	**290,3 kN**	165,1x6,0	316,9 kN
43	**1048,4 kN**	2x 193,7x6,0	1100,8 kN
44	**752,6 kN**	2x 193,7x6,0	784,2 kN
45	**354,7 kN**	165,1x6,0	375,8 kN
46	**465,3 kN**	165,1x6,0	417,7 kN
47	**314,6 kN**	152,4x3,0	315,2 kN
48	**239,1 kN**	139,7x3,0	262,2 kN
49	**166,2 kN**	114,3x3,0	1177,7 kN
50	**102,5 kN**	101,6x3,0	136,7 kN
51	**963,6 kN**	2x Bays 219,1x6,0	996,4 kN
52	**197,3 kN**	165,1x3,0	227,4 kN