HYBRID CONNECTION OF COLD FORMED STEEL PLATES UTILIZING ADHESIVE AND SELF-DRILLING SCREWS

RACKFORD BONG

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Faculty of Engineering
Universiti Teknologi Malaysia

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DEDICATION

Thank GOD for giving me the strength, guidance and opportunity to complete this study.

This thesis is dedicated to my beloved wife, Falinah Misol, my children, Ryan Joshua, Fharelyne Joeyna, Eddy Isaiah, Nicholas Paul, Adrian James and my family for their love and sacrifice.

To my beloved parents and in laws, thank for your prayers and support, and for always being there for me through happiness and sadness.

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ABSTRACT

The application of cold-formed steel (CFS) on roof structures has become popular in construction practices in Malaysia. Generally, CFS structure joints use self-drilling screws (SdS) for easy and fast installation purpose. However, a premature collapse of a CFS structure may occur due to connection failure. Therefore, in order to avoid and better prepare for such an eventuality, a study to overcome the failure of the connection on CFS structures is needed. Research suggests that a combined joint (connection) between SdS and adhesive (Hybrid connection) on CFS structures could prevent premature collapse. Informed by past and current research developments, this study therefore investigated the behaviour and failure modes of CFS connections with three different types of connection methods; adhesive, SdS and hybrid connection. Shear test was conducted to determine the ultimate failure load, where the connection failed as a result of direct shear acting on it. The effect of adhesive thickness, number of screws, bonded area, plate thickness and screw arrangement on connection strength was also studied and reviewed through experiment and statistical analyses using Pearson Correlation. The results demonstrated the existence of statistically significant correlation between the bonded area and bonding strength for C-section of CFS. Specifically, an increase in the bonded area provides an increase in bonding strength. In this study it is also found that with an increase of screw quantities and plate thickness, the connection strength increased. Comparisons on the connection strength between adhesive, SdS and hybrid connections was carried out and statistical analysis using ANOVA test prove that the strength of hybrid connections is statistically significantly higher compared to adhesive connection and SdS connection. It was found that hybrid connection specimen utilising 0.5mm adhesive thickness, 4 screws connection, with a web depth of 100mm, plate thickness of 1.20mm and lapping length of 80mm, has the highest connection strength, specifically at 66% higher than adhesive connection, and 46% higher than SdS connection. Based on the regression analysis, this research proposed an empirical formula to calculate the hybrid connection strength. A comparison of hybrid connection strength between the experimental result and predicted connection strength (proposed empirical formula) was conducted and generally the predicted connection strength is in accordance with the experimental result. Therefore, the proposed empirical formula is considered ideal for calculating the connection strength of the hybrid connection limited to plate thickness range 0.75mm – 1.20mm.

ABSTRAK

Aplikasi keluli berbentuk sejuk (CFS) pada struktur bumbung telah menjadi popular dalam amalan pembinaan di Malaysia. Secara amnya, sambungan struktur CFS menggunakan skru self-drilling (SdS) untuk tujuan pemasangan yang mudah dan cepat. Walau bagaimanapun, keruntuhan struktur CFS pramatang mungkin berlaku kerana kegagalan sambungan. Oleh itu, untuk mengelakkan dan mempersiapkan diri dengan lebih baik untuk kemungkinan seperti itu, kajian diperlukan untuk mengatasi kegagalan sambungan pada struktur CFS. Penyelidikan menunjukkan bahawa gabungan SdS dan pelekat (sambungan hibrid) pada struktur CFS dapat mencegah keruntuhan pramatang. Oleh itu, berdasarkan perkembangan penyelidikan masa lalu dan semasa, kajian ini menyiasat tingkah laku dan mod kegagalan sambungan CFS dengan tiga jenis kaedah sambungan; sambungan pelekat, SdS dan hibrid. Ujian ricih dilakukan untuk menentukan beban kegagalan akhir, di mana sambungannya gagal akibat ricih langsung yang bertindak padanya. Pengaruh ketebalan pelekat, jumlah skru, luas ikatan, ketebalan plat dan susunan skru pada kekuatan sambungan juga dikaji melalui analisis eksperimen dan statistik menggunakan Korelasi Pearson. Hasilnya menunjukkan adanya hubungan yang signifikan secara statistik antara kawasan terikat dan kekuatan ikatan untuk bahagian C-seksyen dari CFS. Secara khusus, peningkatan di kawasan ikatan memberikan peningkatan kekuatan ikatan. Dalam kajian ini juga didapati bahawa dengan peningkatan kuantiti skru dan ketebalan plat, kekuatan sambungan bertambah. Perbandingan kekuatan sambungan antara sambungan pelekat, SdS dan hibrid dilakukan dan analisis statistik menggunakan ujian ANOVA membuktikan bahawa kekuatan sambungan hibrid secara statistik jauh lebih tinggi berbanding dengan sambungan pelekat dan sambungan SdS. Didapati bahawa spesimen sambungan hibrid yang menggunakan ketebalan pelekat 0.5mm, sambungan 4 skru, dengan kedalaman web 100mm, ketebalan plat 1.20mm dan panjang putaran 80mm, mempunyai kekuatan sambungan tertinggi, khususnya pada tahap 66% lebih tinggi daripada sambungan pelekat, dan 46% lebih tinggi daripada sambungan SdS. Berdasarkan analisis regresi, penyelidikan ini mencadangkan formula empirik untuk mengira kekuatan sambungan hibrid. Perbandingan kekuatan sambungan hibrid antara hasil eksperimen dan kekuatan sambungan yang diramalkan (formula empirik yang dicadangkan) telah dilakukan dan umumnya kekuatan sambungan yang diramalkan sesuai dengan hasil eksperimen. Oleh itu, formula empirik yang dicadangkan dianggap sesuai untuk mengira kekuatan sambungan sambungan hibrid yang terhad kepada julat ketebalan plat 0.75mm - 1.20mm.

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LIST OF ABBREVIATIONS

A	-	Adhesive
A’	-	Glued Area
AISI	-	American Ion Steel Institute
ANOVA	-	Analysis of Variance
ASD	-	Allowable Stress Design
Avg	-	Average
C	-	C-section
Cal		Calculate
CFS		Cold-Formed Steel
Cont’d	-	Continued
EN	-	Euro Number
exp	-	Experimental
F	-	Flat-plate
GPa	-	Giga Pascal
G-CFS		Cold-formed steel + Galvanized Ion
H	-	Hybrid
I	-	Parallel
II	-	Perpendicular
LRFD	-	Load Resistance for Design
MPa	-	Mega Pascal
N	-	Normal
r	-	Pearson Correlation Coefficient
S	-	Screws
S-CFS	-	Cold-formed steel + Cold-formed Steel
SdS	-	Self-drilling Screws
S1	-	Specimen
UTM	-	Universal Testing Machine
vs	-	versus

LIST OF SYMBOLS

A, A_s	-	Area of section
A_{net}	-	Net cross-sectional area
B	-	Width
$D, d, \varnothing$	-	Diameter
e	-	Edge distance
f	-	Estimated tensile strength
F	-	Maximum load
f_{ba}	-	Bearing adhesive
F_{Avg}	-	Maximum load average
F_b	-	Bonding strength theory/experimental
F_{bcp}	-	Bearing of composite
$F_{b,Rd}$	-	Shear strength calculate
F_c, F_{cp}	-	Capacity of section
F_s	-	Direct shear
$F_{t,Rd}$	-	Tension resistance
F_u, f_u	-	Tensile strength
F_y, f_y	-	Yield strength
H_0	-	Null hypothesis
H_a	-	Alternative hypothesis
L	-	Length
m_f	-	Modification factor
P_{exp}	-	Shear strength experiment
P_{ns}	-	Nominal shear strength per screw
P_{nt}	-	Nominal tension strength per screw
P_{not}	-	Nominal pull-out strength per screw
P_{nov}	-	Nominal pull-over strength per screw
R^2	-	Regression
t	-	Thickness
t_a	-	Thickness of the adhesive
t_p	-	Thickness of the plate

Y - Dependent variable

α - Bearing resistance factor

σ - Shear stress

σ_b - Ultimate bearing stress

ϵ - Residual (additive error)

γ_{M2} - Gamma factor

Δ_A, Δ_B - Deformation

Δu - Displacement

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The increase in recent research and the diversity of commercial applications dealing with the use of Cold-formed steel (CFS) structures in the construction industry was initiated at the end of the 1990s with the introduction of a roofing steel frame system for residential buildings. Nowadays, the channel (C) and zee (Z) section of (CFS) are commonly used for homes, roofing, wall frames, railings, purlins and cladding (see Figure 1.1). Some of the various needs could not be satisfied only by restructuring techniques using the current CFS, particularly in connection part. As the main connection for the CFS is screws and bolts, the study and development of the alternative connection of the CFS section must be carried out.

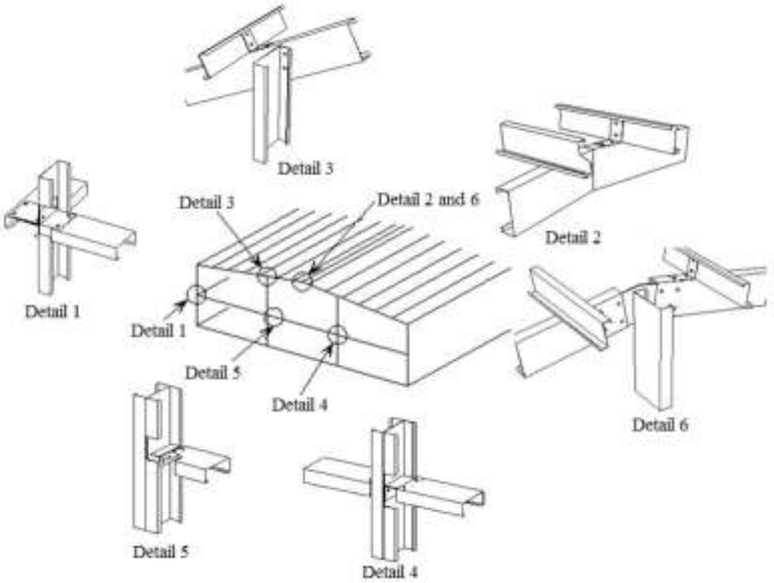

Figure 1.1 Cold-formed steel sections used as column, rafters, and purlin (ECCS, 1987)

The increasing application of CFS in the construction field is due to its advantageous characteristics. CFS is lightweight with high durability and high strength, and it is also made with solid material consistency, with corrosion-free properties (Probowo, 2012). Although CFS sections are increasingly being utilised, numerous concerns are associated with them, which include thin-walled sections and connection failure. For instance, thin-walled sections present a structural issue as they restrict the structural performance of CFS sections due to premature buckling and instability. Meanwhile, a connection failure takes place when the main support component that mechanically tightens the structural elements together are not properly secured.

Common joining techniques for CFS connections such as welded, the mechanical fastener, and adhesive have been studied by researchers around the world (Billah *et al.,* 2019; Saipee, 2013; Hongthong *et al.,* 2019). To achieve maximum strength of the connection, builders such as contractor need to improvise on this joining technique. Nevertheless, research on joining technique for CFS connection using adhesive and screws has not been explored much. The behaviour and performance of such connections need to be further investigated in order to accurately determine the strength of the connection.

1.2 Background of Study

The housing construction industry has introduced the first truss system using wood for the roofing of terrace houses and shop houses. The use of wood to produce truss systems has had implications for the environment, such as greenhouse gas emissions, air and water pollution. Furthermore, it in recent years, it has become a challenge to procure good timber with the right maturity and treatment. Researchers, therefore, need to find an alternative to address the growing building materials shortage. The discovery of an alternative material comes at a critical time, as poor project management have caused an overzealous consumption of wood in the construction industry, which in turn have contributed to the pollution problem by creating waste.

As was iterated earlier, CFS is increasingly being used in construction due to its light weight, high durability, high strength, and material consistency. Therefore, the use of CFS is the best alternative construction material for residential and commercial buildings. Apart from the outlined advantages, the CFS truss system is also able to employ semi-skilled workers, as its installation work does not typically require high skills compared to the conventional wood-based truss system. Additionally, compared with the conventional steel truss system, the CFS truss system is more economical because the steel raw materials used are of different grades, weights, and sizes.

Figure 1.2 shows the connection lapped joints which is an important structural element whose function is to transfer load from one member to another. In construction projects where CFS is used, fasteners such as bolts and nuts, screws, among other special devices like the adhesive bonding are commonly used (Daudet and Roger, 1996).

Figure 1.2 A commonly used connection device used in the structural system

Other commonly utilised fasteners are self-drilling screws, which are used to make connections to metal cladding roofs, as well as specialty roofs such as framing members. According to Daudet and Roger (1996), the self-drilling screw is an externally threaded fastener, meaning that they can drill holes through and from their internal threads. Therefore, in one simple operation, the self-drilling screw is effective in clamping two or more pieces of thin steel sheets, offering a more secure clamp and improved thread engagement. Moreover, the self-drilling screw can be used to determine correct hole sizes on a connection (Daudet and Roger, 1996). This significantly reduces the fabrication time taken to pre-drill holes during the installation stage. The economical factor also makes the self-drilling screw a sound choice, especially for use in fastening processes that do not require power drills and drill bits, costly press tools, machine taps, and high maintenance. Daudet and Roger (1996), therefore conclude that for fastening thin-walled steel members, such as CFS structural members, self-drilling screws can provide the fastest, most efficient, and economical method.

Naito *et al.* (2012) state that, adhesive joints are also used in various industries because of their advantages over mechanical fasteners such as riveting, welding, and bolting. In general, adhesive joints distribute stress uniformly; however, stress concentrations are at relatively lower levels than those of mechanical fasteners (Siti Nur Rahmah *et al.,* 2015). According to Daudet ad Roger (1996), the process of fabrication of a connection is the most labour-intensive aspect. As such, a deep understanding of hybrid connection behaviour can contribute to the optimum connection design and potentially reduces the cost of fabrication. A hybrid connection refers to self-drilling screws that are combined with adhesives, and which provide links between structural elements through the use of screws. In hybrid connection, if the force direction on the connection is parallel to the screw axis then it is said to be loaded in tension. However, if the direction of the external load or force acting on the connection is parallel to the cross-sectional surface, the screw connection is said to be loaded in shear (see Figure 1.3).

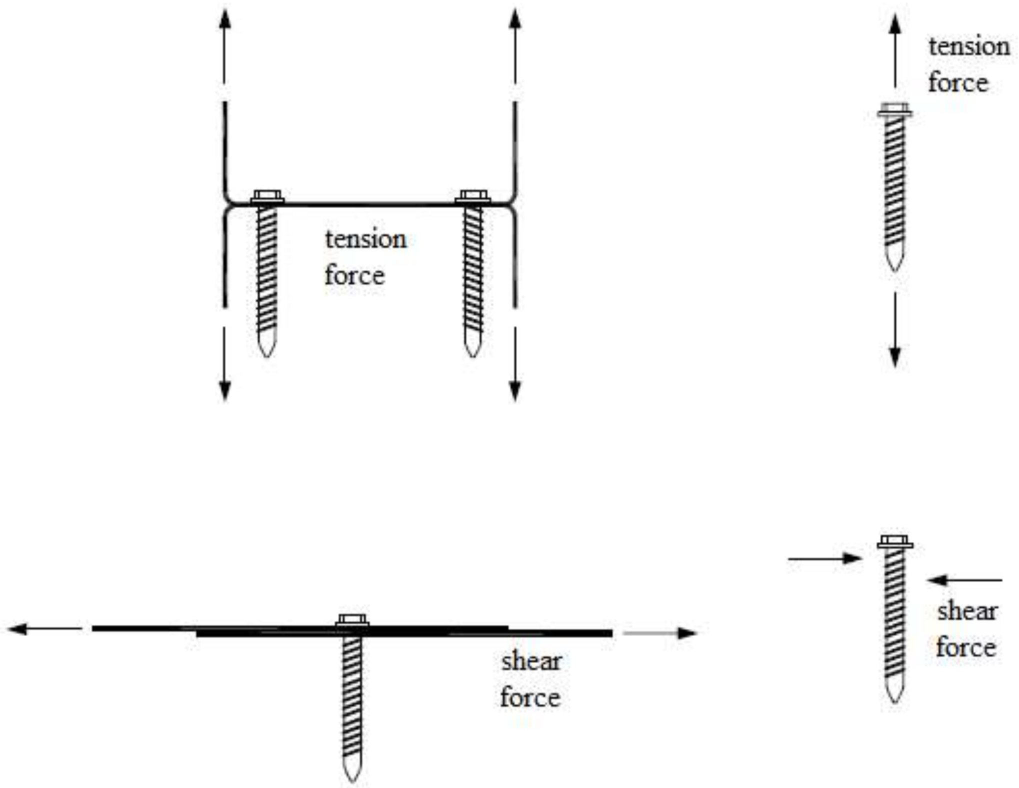

Figure 1.3 Screw loaded in shear or tension (Serrette *et al.,* 2009)

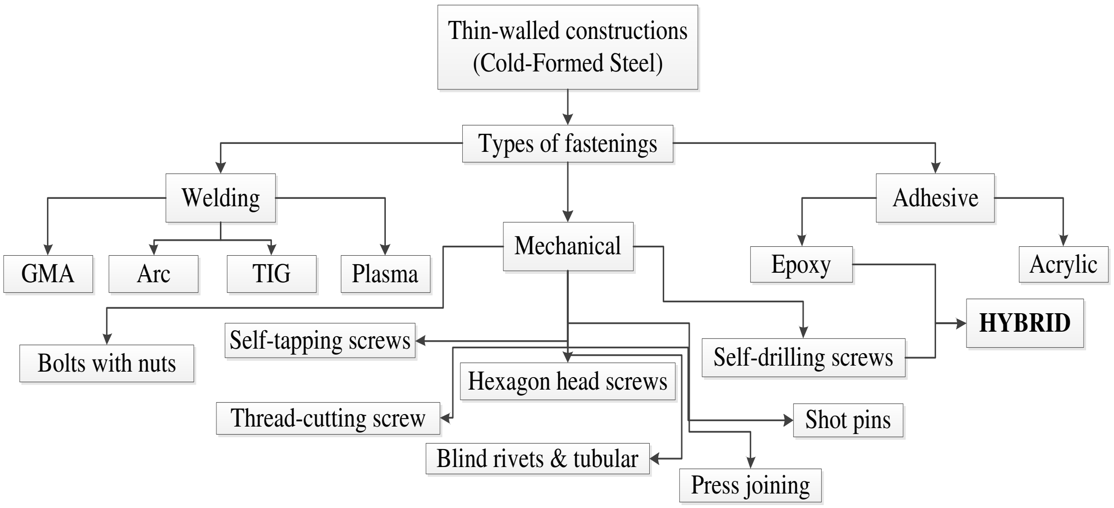

Figure 1.4 CFS Connections (Billah *et al*., 2019)

The application of hybrid connections is a growing area of interest among researchers. Nevertheless, limited studies have been conducted on utilising combined adhesives with self-drilling screws (hybrid), especially for CFS connections (see Figure 1.4). Therefore, this study aims to investigate the connectivity behaviour regarding CFS trusses by utilising combined adhesives with self-drilling screws, besides also to provide relevant design guidance for industry professionals.

1.3 Problem Statement

Despite its wide use, of the application of CFS sections as an alternative for building materials remains a secondary choice among professionals in the construction industry, as the use of traditional materials is still preferred. For example, the use of wood truss structure for the construction of terraced houses and shop houses. Wood potentially invites numerous problems in the roof system itself, as the wood that was installed during the construction process may be left by the contractor, without any shelter. Over time, the wood used to build the truss structure will decay due to environmental factors.

To overcome this issue, the introduction of alternative materials such as CFS sections to replace wood for building truss structure, is therefore deemed necessary. In recent years, the housing industry in Peninsular Malaysia has been using CFS in its truss system, although CFS use has yet to achieve a nationwide reach. Truss system uses screw type connections for its fabrication process, which offers much better quality compared to the wood truss system. As was stated earlier, the lightweight, thin, and portable nature of CFS makes it’s a practical choice for the construction sector yet, connection flaws in CFS structures could lead to weaknesses in the connection area, thus reducing the load-bearing capacity of the structure. The combined effect of element weakness and connection weakness on the CFS structure often leads to a premature collapse of the structure. To avoid such damaging outcomes, a better understanding of the behaviour of screw connections is thus critical, to help in optimal connection design.

As the connection behaviour in CFS truss structure is key to ensure the safety of the structure under loading conditions, it is therefore necessary to study the adhesive connections to improve the static strengths of CFS structures. Although the design standards, material properties, element strength, member design, mechanical connections, and structural assemblies of CFS are regulated by the American Iron and Steel Institute (AISI), under the code of Standard Practice for CFS structural framing, there is no standard as yet for adhesive joints. Thus, an improved understanding of the behaviour of adhesive connections that is compatible with CFS material could lead to effectiveness of connection design.

To improve the performance of CFS structures, innovations in connection design are needed. A new connection method on CFS that combines self-drilling screws and adhesives for CFS connections or hybrid connection potentially offers an increase in connection strength. Thus, development and design analysis of the CFS hybrid connection and its stability are the focus of this study.

1.4 Research objectives

The objective of the research was to study the behaviour of hybrid connection of CFS utilising adhesive and self-drilling screws. To address the problem statements discussed previously, the following research objectives were outlined:

i. To experimentally assess the performance of adhesives that is compatible with CFS material and mode of failure.
ii. To experimentally assess the behaviour and strength of self-drilling screws connection and mode of failure.
iii. To experimentally assess the behaviour and strength of hybrid connection and mode of failure.
iv. To compare experimental results between adhesive, self-drilling screws, and hybrid connection.

v. To conduct an analytical study and propose an empirical formula for the strength of hybrid connection, and to compare experimental and calculated data from empirical formula.

1.5 Research scope and limitations

This study covered the performance and behaviour of CFS connections with three types of connection methods – the adhesive connection, self-drilling screws connection, and hybrid connection. The following lists the scope of the study;

i. A total of 90 adhesive connection specimens were tested in the laboratory subject to thickness of plate range from 0.75mm – 1.20mm for C-section and Flat-plate. Then, difference on adhesive thickness between 0.5mm - 0.7mm for Flat-plate connection also studied.
ii. A total of 108 self-drilling screws connection specimens comprising of different numbers of screws (2, 3, 4 screws) and different screw arrangement (parallel and perpendicular) were tested in the laboratory.
iii. A total of 36 hybrid connection specimens were tested in the laboratory. and connection strength.
iv. The connection strength between adhesive connection, self-drilling screw connection, and a hybrid connection was compared in this study through experimental results and statistical analysis results using ANOVA.
v. An analytical study and regression test was conducted. An empirical formula was proposed for hybrid connection strength subject to thickness of plate range from 0.75mm – 1.20mm for C-section and Flat-plate.

In this study, only Pioneer All-purpose epoxy was used as adhesive in this study, with one self-drilling screw type measuring one diameter. The design capacity of each section or the resistance capacities of each joint were calculated according to EN1993-1-3: Cold-formed thin gauge members and sheeting.

1.6 Significance of the study

This research is a significant endeavour in the improvement of CFS connection by combining adhesive and self-drilling screws. The empirical equation proposed for the strength of hybrid connection in this study is a helpful guide to develop CFS truss structures utilising hybrid connection, besides providing information on reducing fabrication costs.

1.7 Thesis Outline

This thesis is structured in seven chapters:

Chapter 1 introduces the overview of the research background, problem statement, objective, scope, research methodology, and significance of the study.

Chapter 2 reviews literature encompassing basic theories on CFS materials, CFS connection on self-drilling screws, adhesive, and hybrid.

Chapter 3 describes the experimental study on CFS adhesive connection performance. The first experiment was conducted on S-CFS: C-section and G-CFS: C-section specimen, which was then followed by CFS: Flat-section. Adhesives of differing thickness were focused on in this chapter. Besides, statistical analysis was also conducted.

Chapter 4 then discusses the performance of self-drilling screws in CFS connection. The first experiment on CFS: C-section specimen was conducted, which was then followed by CFS: Flat-section specimen. Varied numbers of self-drilling screws and arrangements were highlighted in this chapter. Besides, statistical analysis was also conducted.

Chapter 5 discusses the performance of hybrid CFS connection, outlined in the experimental study of hybrid connections, using the shear test method to collect data on the bearing capacity. CFS: Flat-section was used for the experiment. Besides, statistical analysis was also conducted.

Chapter 6 examines the analytical study and theory of structural mechanics involved in the calculation of CFS connection.

Chapter 7 concludes the thesis by providing a summary of research, conclusion, and recommendations for further studies.

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LIST OF PUBLICATION

1. Publish eBook THE ISSUES IN TECHNOLOGIES: APPLICATION AND DEVELOPMENT (2020). Statistical Analysis on the Behaviour and Strength of Cold-Formed Steel Hybrid Connection.
   E-ISBN: 978-967-17718-7-7. https://kaizentrenovationpublishing.com/e-book
2. Malaysian Journal of Civil Engineering 27 Special Issue (1): 57-67(2015) Performance of connections adhesive-bonded for cold-formed steel.
3. Malaysia Journal of Civil Engineering 28 Special Issue (2): 88-101(2016) Performance of single lap joints using adhesive and self-drilling screw for cold-formed steel under tensile loading.