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# AXIAL AND FLEXURAL PERFORMANCE OF ADHESIVE CONNECTION ON COLD-FORMED STEEL STRUCTURES

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## ABSTRACT

In this paper, a research of new connection method on the cold-formed steel in civil engineering structures is presented. The study focuses on the axial and flexural performance on cold-formed steel structures. A cold-formed steel with screw, adhesive and combination connections that have been loaded in tension and flexure until rupture. A comparison strength in tensile and flexure between the joint types and screw joint on cold-formed steel were investigated. The use of adhesive as the joint (connection) be able to increase the structure capacity significantly. Combination joint between screw and adhesive on cold-formed steel structure could prevent premature collapse of the structure. Adhesive in the combination joints also could minimize the bearing failure of screw joint. It was caused by the rigidity cold-formed steel structure that has increased throughout the adhesive joint. The effect of local buckling could be minimized with increasing structural rigidity. The adhesively bonded joint strength is based on the type of adhesive. The joint failure was began at the end of an adhesively bonded area then it propagated to the middle until it was fully degraded.

*Keywords:* Adhesive; Axial strength; Cold-Formed Steel; Failure; Flexural strength; Joint/connection;

## 1. INTRODUCTION

Cold-Formed Steel (CSF) sections have been used in bridge construction, drainage facilities, metal building assemblies for industry, residential construction and many structural applications. Cold-form steel structures are made from flat sheets of steel bent at ambient temperatures, (Hancock, 2003). Cold-Rolled Steel (CRS) sections are made from bar stock and sheet which are used for durable goods, automobiles, and other applications.

Adhesive joints are also used in various industries because of its advantages over the mechanical fastening, such as riveting, welding and bolting (Kim & Brontman, 1971; Adam et al., 1997; Harris & Beevers, 1999; Adam, 2000; Knox et al., 2000; Naito et al., 2012). Adhesive joints distribute stresses uniformly; however, stress concentrations are at a lower level than those of mechanical fastening. For adhesive joints, the ultimate stress of joint which could be used will be lower than that of substrates (Brandon, 2010).

Generally, cold-form steel structures have mechanical fasteners, such as self-drilling screws for easy and rapid installation. A premature collapse of cold-formed steel structures could occur, even during the erection process, because of local buckling, torsional buckling, lateral buckling

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and residual stresses (Galambos, 1987; Dundu, 2012; Ganesan & Moen, 2012; Haidarali & Nethercot, Moen et al., 2008; Mutawalli, 2007; Young & Chen, 2008). During the process of connecting cold-formed structural steel members, two factors such as thin structural steel elements and/or a high stress gradient could lead to the premature collapse of cold-formed steel structures. Mechanical joints using connectors, such as bolts, rivets, screws and welded joints have disadvantages related to residual stress effects, corrosion, the type of connection, as well as the joint type and size. Residual stress effects surrounding the holes are a disadvantage for bolt and rivet joints. In addition to the effects of residual stress effect surrounding holes, screw joints can be applied for light loads only. Corrosion may occur as a potential side effect of welded joints. The limited size of cold-formed steel sections make it close to impossible to manufacture a welded joint.

One of the advantages in using cold-formed steel sections is in providing lightweight steel structures. Cold-formed steel sections are made from carbon or low alloy steel sheet, strip, plate or flat bar, which are formed in cold-rolling machines or by a press brake or brake press machine tool. The manufacturing process of thin cold-formed steel members causes residual stress and plastic strains throughout the sheet thickness. The plastic strains increase the yield stress in the sheets of cold-formed steel. Thin elements also may cause buckling and web crippling in the design structure. Cold-formed steel structures have a large cross-sectional width-to-thickness ratio, thus causing local buckling in the cross-sectional area below the melting point of steel, due to bending and compression loading. The width-to-thickness ratio has an extraordinary effect on the occurrence of local buckling before reaching the ultimate load. Attention should be directed to the cross section where the normal stress field in the plane perpendicular to the longitudinal axis of the structure varies due to local buckling (Setiyawan et al., 2012; Yu, 1999). Finite element modelling also has been developed to predict the flexural behavior of the adhesive joint (Anwar et al., 2013).

Another special problem of cold-formed steel structures is the sensitivity of the connection imperfections. Connection imperfections could lead to weakness in the connection area, thus reducing the load bearing capacity of the structure. The combined effect of element weakness and connection weakness on the cold-formed steel structure often leads to premature collapse of the structure. Consequently, in response to these combined weaknesses, adhesive joint connections for predicting the static strengths of cold-formed steel structures have been researched for development purposes. Design standards, material properties, element strength, member design, mechanical connections, and structural assemblies of cold formed steel are regulated by the American Iron and Steel Institute (AISI), under the Code of Standard Practice for Cold-Formed Steel Structural Framing, but there is no standard as yet for adhesive joints. To improve the performance of cold-formed steel structures, innovations in joint methodologies are needed to determine the best performance criteria for cold-formed steel joints to prevent the premature collapse of cold-formed steel structures. Adhesive joints for cold-formed steel connections potentially offer an increase in the incremental strength of the structure. The scope of the research in this paper concerns two types of structures, three types of connections, two types of adhesives and specifically, a substrate thickness of 0.75 mm. The point of the research is to investigate the capacity and variety of connections for cold-formed steel structures.

## 2. EXPERIMENTAL

Various test procedures were employed to obtain the mechanical properties of adhesives, namely an epoxy resin and a polyester resin. Experiments were conducted on bulk adhesives, on adhesively bonded Single Lap Joints (SLJs) and on flexural joints subjected to static loading.

### 2.1. Specimen Manufacture

Bulk adhesives, adhesively bonded single lap joints (SLJ) for cold-formed steel structures and flexural joints were analyzed in the experimental work. An epoxy resin and a polyester resin adhesives were utilized to make bulk adhesive specimens and joint specimens to measure axial and flexural forces. An epoxy resin adhesive and repair mortar is a structural two-part adhesive, which is solvent-free, moisture tolerant, designed for use at temperatures between 10°C and 30°C and is based on a combination of epoxy resins and special fillers. A polyester resin is a two-part epoxy system, solvent-free, with lasting repairs to metal and multiple surfaces, a curing time of 15–24 hours and it is designed for use in temperatures below of 288°C (550°F). Bulk adhesives of 0.75 mm thickness are manufactured for each type of adhesive to obtain the required tensile strength and compressive strength for an adhesive. Product data comparison was made between the type types of adhesive. A specimen thickness of 0.75 mm was maintained using steel spacers. To enhance the joint strength, the specimen's cold-formed steel surfaces were roughened, using maximum grade abrasive paper.

The joints tested in this research were made of cold-formed steel substrates of 0.75 mm thickness each. Each individual specimen was bonded with either an epoxy resin adhesive or a polyester resin of 0.75 mm thickness in order to manufacture the single lap joints (SLJs) and flexural beam joints. A screw joint with a 6 mm diameter, adhesive joint and a screw and adhesive combination joint were applied to the specimen joints. The dimensions of the joints are illustrated in Figures 1 and 2.

Figure 1 Single lap joint specimens of 42 mm width

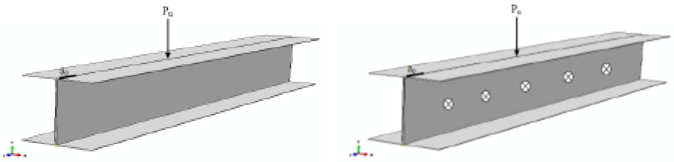


Figure 2 Flexural joint specimens of 250 mm length

A jig device was used to control the position of the SLJ substrates, the bond line thickness and the appropriate pressure for the joints. The substrates, adhesive layers and the spacers were pressed in the jig. The joints consisted of three types: screw joint, adhesive joint and a combination of screw with adhesive joint. The adhesive thickness was set to 0.75 mm. Figure 2 shows the flexural joints that consisted of a double lip channel of 76 mm × 36 mm × 0.75 mm × 0.75 mm. Similar to SLJs, the joints of the flexural beam consisted of three types. A simple beam was used to support the flexural joints.

### 2.2 Specimen Testing

Static testing was carried out on the bulk adhesive specimens and the joint specimens. The ultimate strength and strain, due to axial and flexural loading of the joints, were also measured. Visual investigation and a video microscope recorder were used to describe joint failure.

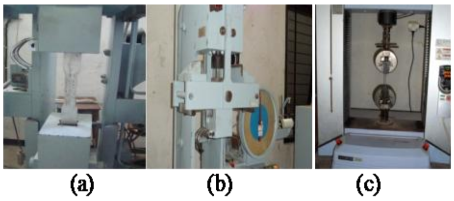


Figure 3 Materials testing: (a) Tensile test of cold-formed steel; (b) Compressive test of bulk Sikadur epoxy resin adhesive; (c) Tensile test of bulk adhesives

Figure 4 Axial testing of single lap joints (SLJs)

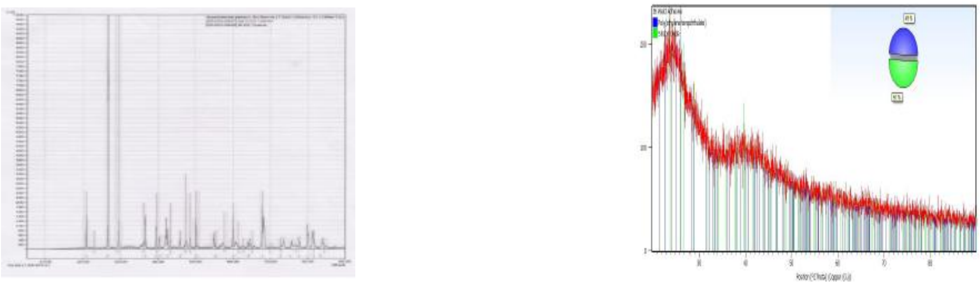
Figure 5 Flexural testing of cold-formed steel beams

## 3. RESULTS

Experimental results based on adhesive materials testing, bulk adhesive testing, static rupture test of joints, and investigation of progressive damage of the joints.

### 3.1. Materials Properties

The X-Ray Diffraction (XRD) testing was carried out on the adhesive materials of an epoxy resin and a polyester resin. The aim of XRD testing is to identify the chemical formula and to analyze the chemical composition. Based on the chemical formula and composition of chemical elements, the material characteristics of the adhesives could be obtained.



(a) (b)

Figure 6 The results of *X-Ray Defraction* (*XRD*) test: (a) an epoxy resin; (b) a polyester resin

Table 1 Chemical identification of an epoxy resin adhesive

| Chemical Formula | Composition of Chemical Elements (%) | Identification | Chemical Compound |
|---|---|---|---|
| $CaCO_3$ | 14 | Calcite | Calcium Carbonate |
| $SiO_2$ | 86 | Quartz | Silicon Dioxide |

Silicon is one of the complex compounds and mostly used as a material base for minerals, that is produced synthetically; whereas, calcite ($CaCO_3$) is a rock-forming mineral. Calcite is used widely for construction materials, abrasive materials, treatment of agricultural land, construction aggregate, pigments, pharmaceuticals and many more uses.

Table 2 Chemical identification of a polyester resin adhesive

| Chemical Formula | Composition of Chemical Elements (%) | Identification | Chemical Compound |
|---|---|---|---|
| $(C_{10}H_8O_4)_n$ | 49 | Polyester Polymer | Polyethylene Terephthalate (PET) |
| $SiO_2$ | 51 | Quartz | Silicon Dioxide |

The polyester resin adhesive is a polyester polymer, with a combination between a resin matrix and fiber in which the tensile strength is the dominant factor, instead of compressive strength. Generally, Polyethylene Terephthalate (PET) is spun and pressed into a high-strength sheet, then it is shaped into many kinds of objects.

The compressive strength test of an epoxy resin adhesive using the ASTM D695-15 Standard Test Method for Compressive Properties of Rigid Plastics. The cylindrical specimen dimension is 1 inch diameter, 2 inch height; or else a prism specimen, whose dimensions are half-inch width, half-inch height and 1-inch depth. The compressive strength of a polyester resin adhesive does not need to be tested because the material failure is a ductile failure, not a brittle failure.

Figure 7 Adhesive failure of cylindrical an epoxy resin specimens

Table 3 Compressive strength of an epoxy resin adhesive

| No | Diameter (mm) | Height (mm) | Area, (mm$^2$) | Ultimate Load (N) | Compressive Strength (N/mm$^2$) |
|---|---|---|---|---|---|
| 1 | 20.2 | 40.4 | 320.6 | 14,600 | 45.54 |
| 2 | 20.2 | 40.4 | 320.6 | 13,700 | 42.73 |
| 3 | 20.2 | 40.4 | 320.6 | 16,860 | 52.60 |
| 4 | 20.2 | 40.4 | 320.6 | 17,950 | 56.00 |

Table 4 Tensile strength of an epoxy resin and a polyester resin adhesive

| No | Adhesive | Thickness (mm) | Wide (mm) | Area (mm$^2$) | Ultimate Load (N) | Compressive Strength (N/mm$^2$) |
|---|---|---|---|---|---|---|
| 1 | Epoxy resin | 5 | 10 | 50 | 1,000 | 20 |
| 2 | | 5 | 10 | 50 | 800 | 16 |
| 3 | | 5 | 10 | 50 | 980 | 19.6 |
| 1 | Polyester resin | 2 | 5 | 10 | 265 | 26.5 |
| 2 | | 2 | 5 | 10 | 220 | 22 |
| 3 | | 2 | 5 | 10 | 250 | 25 |

Table 4 shows the tensile strength of an epoxy resin and a polyester resin adhesives. The values of fracture energy ($G_f$) and Poisson's ratio ($\nu$) of an epoxy resin and a polyester resin adhesives were 1.4 kJ(Nm); 0.28, and 2.5 kJ(Nm); 0.3, respectively.

Cold-formed steel plate, 0.75 mm thick was used as a substrate for the joints. For this research, cold-formed steel was produced by PT. Mulcindo Indonesia. Tensile strength of cold-formed steel refers to ASTM-E8 standards, and are as shown in Table 5. The tensile strength shown in the manufacturer's data is 0.7 mm × 1219 mm × the coil, which is 656 N/mm$^2$.

Table 5 Tensile strength of cold-formed steel

| No | Width (mm) | Thickness (mm) | Area (mm$^2$) | Ultimate Load (N) | Tensile Strength (N/ mm$^2$) |
|---|---|---|---|---|---|
| 1 | 29.85 | 0.75 | 22.39 | 11,025 | 492.5 |
| 2 | 29.85 | 0.75 | 22.39 | 11,250 | 502.5 |
| 3 | 29.95 | 0.75 | 22.46 | 11,150 | 496.4 |

### 3.2. Axial Strength of Single Lap Joint Specimens

Based on the static rupture test of the single lap joint specimens (SLJs), the load versus displacement curve is presented in Figure 8 below. Adhesive joints significantly increase the joint load capacity, exceeding that of the screw joint capacity.

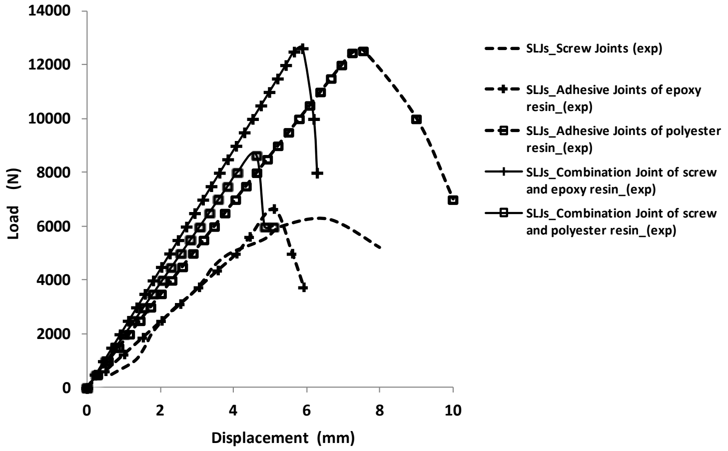


Figure 8 Load-displacement curve of SLJs tensile test

The dependency of the joint types on load capacity is shown in Table 6. The axial capacity of cold-formed steel has increased significantly with the screw and adhesive combination joint, compared to the screw connection. An anomaly occurred with the screw and a polyester resin adhesive combination joint, since the joint strength capacity was no higher than the individual polyester resin joint adhesive. The drilling action to install the screw may cause the polyester resin adhesive to move, resulting in fillet corners at the joint.

Table 6 Axial Joint Load Capacity

| Type of Joint | Ultimate Load (N) | Increment (%) |
|---|---|---|
| Screw | 6,240 | 0 |
| An epoxy resin adhesive | 6,650 | 7 |
| A polyester resin adhesive | 12,450 | 99 |
| Screw and an epoxy resin adhesive combination | 12,630 | 102 |
| Screw and a polyester resin adhesive combination | 8,650 | 39 |

### 3.3. Flexural Strength of Cold-Formed Steel Joint Specimens

The flexural capacity of cold-formed steel joint specimens also significantly increased for the screw and adhesive combination joint, compared to the screw-only connection. An anomaly occurred with the screw and a polyester resin adhesive combination joint, since the joint strength capacity was no higher than polyester resin joint's adhesive. There is a similar condition between the axial strength of the single joint specimen and the flexural strength of the cold-formed steel joint. The drilling action to install the screw might cause the polyester resin adhesive to move, resulting in fillet corners at the joint.

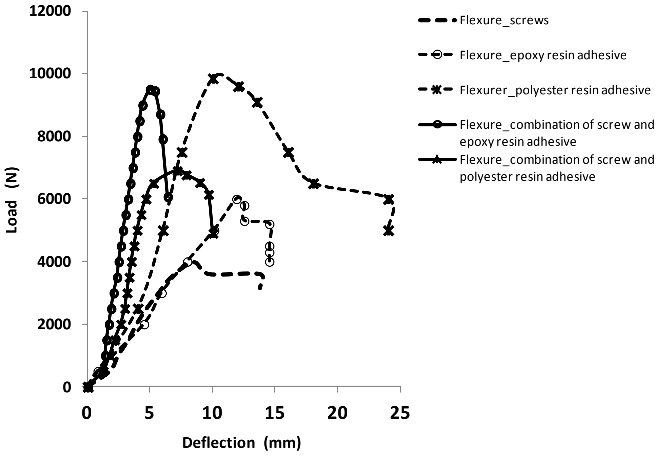


Figure 9 Load-displacement curve of the flexural joint

The capacity-enhanced flexural cold formed steel joints are presented in Table 7.

Table 7 Flexural Joint Load capacity

| Type of Joint | Ultimate Load (N) | Increment (%) |
|---|---|---|
| Screw | 3,980 | 0 |
| An epoxy resin adhesive | 6,000 | 51 |
| A polyester resin adhesive | 9,850 | 147 |
| Screw and an epoxy resin adhesive combination | 9,500 | 139 |
| Screw and a polyester resin adhesive combination | 6,900 | 76 |

## 4. DISCUSSION

### 4.1. Axial Performance of Cold-Formed Steel

In practice, the erection of a light steel structure is carried out by using a self-drilling screw between elements. The tensile strength of SLJs screw (self-drilling screw) is compared to adhesive SLJs and combination SLJs to obtain effective joint feasibility Tests were conducted on cold-formed steel SLJs with a length of 40 mm and a width overlap of 42 mm, resulting in a total joint area of $A_{tot}$ = 1,680 mm$^2$.

The capacity of the screw and adhesive connection cannot be compared in parallel, since the net connection area ($A_n$) is not the same. Considering their advantages, it is necessary to test the capacity of the connection between the combination joints. Moreover, considering the vibration effect of the screw connection, the adhesive can serve as a backup automatically, if dynamic screw resistance is weakened. Thus, premature collapse of cold-formed steel structural connections can be prevented, according to an increase in the stiffness ratio of the connection with the use of adhesive in the joint areas.

Figure 8 shows that the screw and adhesive combination joint. The load capacity is significantly affected by the types of joints, resulting in a more uniform stress distribution in the joint area. The load capacity is seen to increase separately in the combination joints, in either case of the screw joint or the adhesive joint. An anomaly occurred with the screw and adhesive combination joint as far as the polyester resin was concerned, so the incremental strength was not reached significantly. It was most likely caused by the different types of adhesive material. The polyester adhesive was not distributed uniformly in the joint area by screw drilling, which caused a dislocation of the adhesive connection, resulting in reduction in the maximum performance of joint strength.

## 4.2. Flexural Joint Performance of Cold-Formed Steel Joint Specimens

The flexural capacity of cold-formed steel joint specimens also increased for the screw and adhesive combination joint, compared with the screw joint connection. Adhesive on the connection area increases the stiffness element of the joint structure, thereby reducing web crippling strength and increasing local buckling. Web crippling at the flange (flens) cannot be avoided because of the thin cross-section and the ratio of web height to flange width (*h*/*b*), which is near 2.0.

## 4.3. Joint Failure in Cold-Formed Steel Structures

### *4.3.1. Axial joint failure*

Bearing failure of screw joint due axial load was occurred, as shown in Figure 9. Failure of screw connection was bearing failure, while the adhesive joint failure is a cohesive failure (CF). Adhesive failure was began by an initial crack, which was then propagated in the other direction at a constant speed. After the initial crack, the load versus deflection curve becomes non-linear and the strain increases rapidly until reaches a maximum point. Furthermore, the crack propagates at inconstant speed until reaches the center of the joint. The strain caused debonding of adhesive. Substrate pre-treatment affects the adhesive bonding and the load capacity of joints. Significant incremental loss in joint strength occurred on the screw and adhesive combination joint due axial loading. Joint failure was caused only by the crack propagation on adhesive layer as shown in Figure 11.

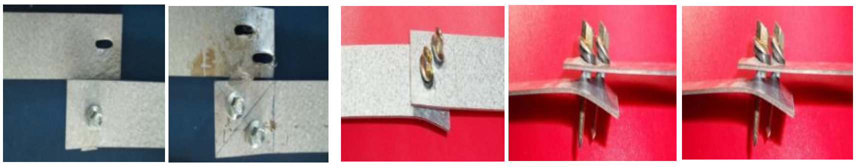
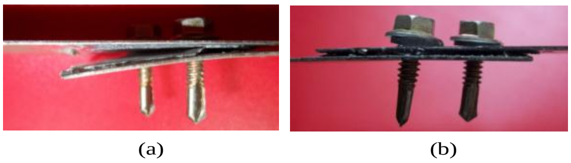


Figure 10 Axial joint failure of screw connection due axial loading



(a) (b)

Figure 11 Axial failure of combination joints: (a) screw and an epoxy resin adhesive; (b) screw and a polyester resin adhesive

### *4.3.2. Flexural joint failure*

Flexural joint failure is caused by combination effect between web buckling and web crippling at the flange. Failure of combination joints is most likely caused by adhesive debonding from the cohesive layer. Initial crack was began at the end of the adhesive around the pin support, then it was propagated towards to the middle. Furthermore, cracks around the center loading occurred as well and then spread to both edges until the adhesive bond fully degraded.

Figure 12 Flexural screw joint failure of cold-formed steel specimen

(a) (b)

Figure 13 Combination joint's failure of flexural cold-formed steel; (a) screw and an epoxy resin adhesive, (b) screw and a polyester resin adhesive

## 5. CONCLUSION

Six groups of single lap joints (SLJs) and flexural joints, manufactured from cold-formed steel and adhesive were tested. Screw and combination joints on cold-formed steel structures could prevent premature structural collapse. Adhesively bonded combination joints also could minimize bearing failure of screw joint. Cold-formed steel structure rigidity has been increased throughout the adhesively bonded joint. The effect of local buckling could be reduced with increasing structural rigidity. The adhesively bonded joint strength is based on the type of adhesive. The joint failure was began at the end of an adhesively bonded area then it propagated to the middle until it was fully degraded.

## 6. ACKNOWLEDGEMENT

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