Third-point flexural test on concrete-filled rectangular tubular flange girders

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Abstract. The influence of shear stud connectors on the horizontal displacement brought about by the occurrence of shear stress at the interface between the rectangular steel tube and in-filled concrete on Concrete-filled Rectangular Tubular Flange Girders (CFRTFG) was investigated. As a composite structure, providing shear stud connectors allow stress transfer between steel and concrete which may result for the two (2) components to work as a single unit. Accordingly, a three-dimensional finite element software called SOLIDWORKS® was employed. Static linear analysis was performed using the finite element (FE) models to study the effect of shear stud connectors on the resulting stresses and slip on CFRTFGs. Results showed that the maximum slip occurred at CFRTFG without shear stud connectors while CFRTFG under full composite action had the least slip. Correspondingly, the maximum shear stress for both CFRTFG under full and partial composite action occurred at the shear stud connectors, while the maximum shear stress for CFRTFG without shear connectors occurred at the supports. Conducting finite element analysis using SOLIDWORKS® proved to be theoretically accurate as in the case of this study.

Keywords: tubular flange girder, composite action, horizontal slip, shear stud connectors, finite element analysis

1. Introduction
Concrete-filled rectangular tubular flange girder (CFRTFG) is a type of composite structure with a concrete-filled rectangular top flange and a flat bottom flange. They have the beneficial merits of steel, such as high tensile strength and ductility, and of concrete, such as high compressive strength and stiffness [1]. Its design and proposed usage is attributed to its several advantages over steel I-girders. This includes having large local buckling resistance, large torsional stiffness, and reduced web slenderness [2] [3] [4]. Being a composite structure however, uncertainties in the composite action or interaction between the steel surface and in-filled concrete serves as a limitation in its use [5].

Ensuring proper stress transfer from a component to another is needed to achieve composite action. The connection of two parts of the composite structure is of vital importance; if there is no connection, then the two parts will behave independently [6]. Lack of composite action thereof, upon load application, causes significant slip due to the occurrence of horizontal shear stress. Such slip implies that the materials are resisting the loads individually, which in turn could affect its overall structural...
behaviour. In order to achieve composite action, supplemental devices such as shear stud connectors are used to allow stress transfer thus preventing slippage.

Prior to conducting actual experimental investigations, finite element analysis (FEA) have been widely practiced as it can provide approximate and valid results on understanding the behaviour of the structure (model) considered. In this study, finite element analysis using SOLIDWORKS® [7] was conducted to determine the effects of using shear stud connectors on CFRTFGs, particularly on the possible slip that may occur at the interface between the rectangular steel tube and in-filled concrete.

2. Methodology
2.1. Design Phase
W4x13, A36 steel I-beams were considered in the design of CFRTFGs. CFRTFGs were designed in such a way that the neutral axis is located directly below where concrete is placed. This is to ensure that the entire concrete section is subject to compression under load. Figure 1 shows the cross-sectional and isometric views, respectively, while Table 1 shows the cross-sectional dimensions.

\[
\text{Table 1. CFRTFG design dimensions.}
\]

| Flange Thickness \((t_f)\) | Concrete Thickness \((t_c)\) | I – beam Depth \((d)\) | Flange Width \((b_f)\) | Web Thickness \((t_w)\) | Shear Stud Connector Transverse Spacing \((s_t)\) | Shear Stud Height \((s_h)\) |
|--------------------------|---------------------------|----------------------|----------------------|----------------------|-----------------------------|----------------------|
| 8.76 mm                  | 63.50 mm                  | 105.66 mm            | 103.12 mm            | 7.11 mm              | 52 mm                       | 52 mm                |

Three (3) models were considered: CFRTFG without shear stud connectors, CFRTFG under full composite action, and CFRTFG under partial composite action. Full composite action provides full shear connection to carry the entire section capacity, whereas partial shear connection can only carry a portion of such.

As calculated, in accordance with the specifications from the National Structural Code of the Philippines 2015, CFRTFG under full composite action have ten (10) shear connectors with a center-to-center spacing of 240 mm. The corresponding number of shear stud connectors for CFRTFG under partial composite action is fixed to be at 60% of the number provided for CFRTFG under full composite action, thereby having six (6) shear connectors with a center-to-center spacing of 400 mm as shown in Figure 2. It should be noted that in going from a full composite to a partial composite beam, the number of shear studs can be reduced significantly which also reduces the stiffness of the beam and therefore increases deflections [8].
Figure 2. Design results for (a) CFRTFG under full composite action, and (b) CFRTFG under partial composite action

2.2. Finite Element Model
Simply-supported W4x13 CFRTFGs with a length (L) of 1.40-m were developed into three-dimensional models using SOLIDWORKS®. Properties for steel, concrete, and shear stud connectors were selected using the “Materials” option in SOLIDWORKS® as shown on Table 2. Curvature-based meshing was incorporated in simulating CFRTFGs since it primarily supports both multi-core surfaces and volume meshing for complex parts or assemblies [9]. It creates more elements in higher curvatures automatically. With the development of CFRTFG in SOLIDWORKS® involving three (3) parts: steel, concrete, and shear stud connectors; applying the curvature-based meshing for simulation after assembly allows for a tighter mesh generation in complex areas (e.g. shear stud connectors) which meant for more accurate results.

Table 2. Material properties applied in SOLIDWORKS®.

| Material                      | Yield Stress (MPa) | Modulus of Elasticity (MPa) | Poisson’s Ratio |
|-------------------------------|-------------------|----------------------------|----------------|
| Steel (A36)                   | 248.00            | 2.00x10^5                  | 0.26           |
| Concrete (Class AA)           | 33.81             | 2.73x10^4                  | 0.20           |
| Shear Stud Connectors (AISI 1020) | 3.52x10^2       | 2.00x10^5                  | 0.29           |

The default criterion considered was Maximum Shear Stress (Tresca) Criterion since it predicts failure to occur when the absolute maximum shear stress reaches the stress causing the material to yield in a simple tensile test [10].

2.3. Loading Set-up
The simply-supported CFRTFGs are supported 100 mm from both edges. Each sample was subjected to two-point loading at the first and middle-thirds of the supported length as shown in Figure 3.

Figure 3. Two-point loading set-up for CFRTFGs

The load applied was the lesser of the calculated theoretical maximum capacity (P) between steel and concrete.
\[
P = \text{less between} \begin{cases} 
F_b S_{TR(s)} = \frac{\omega_{DL}L^2}{8} + \frac{PL}{6} \\
0.85f'_c S_{TR(c)}n = \frac{\omega_{DL}L^2}{8} + \frac{PL}{6}
\end{cases}
\]

Where the theoretical maximum load capacity (P) is a function of the flexural stress (F_b), transformed section modulus (S_{TR}), total dead load carried by the structure (\omega_{DL}), and the supported length (L).

3. Results

3.1. Comparative Analysis

Generally, the moment of inertia is a measure on the level of force that has to be applied on a certain object at a given axis of rotation; an increase on such would imply that a greater force is needed to cause rotation.

In this study, the addition of concrete-filled tubular top flange brings about an increase on the moment of inertia. This results in a reduced flexural stress on beams as well as an increase on the overall capacity, which finally minimizes deflection.

Moreover, the moment of inertia directly affects the section modulus of the structure as in Equations (2) and (3). The section modulus, in turn, is then used in calculating the capacity of the structure as shown on Equation (1).

\[
I_{TR} = \left(\frac{1}{12}\right) \left(\frac{b_c}{n}\right) (t_c)^3 + (2) \left(\frac{1}{12}\right) (t_f)(t_c)^3 + \left(\frac{1}{12}\right) (b_f)(t_f)^3 + I_s
\]

\[
S_{TR} = \text{less between} \begin{cases} 
\frac{I_{TR}}{y} \\
\frac{I_{TR}}{H-y}
\end{cases}
\]

Where the transformed moment of inertia (I_{TR}) is a function of the dimensional properties of the structure. The transformed section modulus (S_{TR}) is a function of the transformed moment of inertia (I_{TR}), and the distance from the neutral axis to the extreme bottom fibers of the section (\bar{y}).

3.2. Effect of Shear Stud Connectors

Theoretically, the maximum shear force and corresponding stress occurs at the supports for simply-supported structures. Thus, in obtaining values for slip between the in-filled concrete and rectangular steel tube, the maximum slip for both steel and concrete were separately obtained. Shown are the summary of results for both slip and maximum shear stress, see Table 3.

| Table 3. Maximum relative slip and shear stress per sample. |
|----------------------------------------------------------|
| Sample | Maximum Shear Stress (Pa) | Location of Maximum Shear Stress |
|CFRTFG without shear stud connectors | 7.038x10^4 | At 96.078 mm from the edge, near the supports |
|CFRTFG under full composite action | 1.398x10^5 | At 224.178 mm from the edge, near the end welded shear stud connectors |
|CFRTFG under partial composite action | 1.380x10^5 | At 395.822 mm from the edge, near the end welded shear stud connectors |
Among the three (3) samples considered, CFRTFG under full composite action had the least slip. This is primarily due to the number of welded shear stud connectors which was designed to carry the entire section capacity. Consequently, CFRTFG without shear stud connectors had the largest slip due to the lack of means to allow shear stress transfer from one component to another.

Also, the location of maximum shear stress differs from CFRTFG with and without shear stud connectors. As shown on Figure 4, CFRTFGs under full and partial composite action experience maximum shear stress at the shear stud connectors near the supports while the maximum shear stress occurs at the supports for CFRTFG without shear stud connectors.

4. Conclusion
In this paper, the occurrence of slippage on CFRTFGs under varying conditions was investigated. Prior to developing finite element (FE) models of CFRTFGs thru SOLIDWORKS®, the theoretical maximum capacity of 1.40-m CFRTFG, and number of shear stud connectors for CFRTFGs under full and partial composite action were calculated. CFRTFG without shear stud connectors was also considered in the study. Each model were subjected under loading located at its third-points, and were designed to fail under the Max Shear Stress (Tresca) Criterion.

Among the three (3) sample conditions considered, it was concluded that providing shear stud connectors lessens the occurrence of slip between steel and concrete. Under full composite action, where the section is designed to carry its full capacity, slip is at its lowest, while CFRTFG without shear stud connectors experienced the maximum slip. A huge decrease on the slip can be noticed upon
the addition of shear stud connectors which implies that its purpose on transferring shear stress from one component (concrete) to another (steel) is effective.

In considering the occurrence of shear stress, CFRTFG under full composite action experienced the maximum shear stress at the studs near the supports, whereas CFRTFG without shear stud connectors had the least shear stress located at the supports. In this case, shear stress increases upon the addition of shear stud connectors, but it can be noticed that the maximum shear stress for the three (3) samples considered occurred near or at the supports.

It can be concluded that the finite element analysis (FEA) results was in line with the underlying principles of statics and shear stress. In the case of investigating slip, further study is needed to understand the bond stress and interaction among the three (3) materials comprising CFRTFGs. A part of proving the advantages of utilizing composite structures involve understanding its composition. Finally, in order to verify FEA results with regards to slip, experimental investigation must be conducted.

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