AN EVALUATION OF THE FLEXURAL BEHAVIOUR OF CONCRETE-FILLED RECTANGULAR FLANGE GIRDERS

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Abstract. *This paper presents a detailed study into the flexural behaviour of concrete filled rectangular flange girders (CFRFG's). These are steel beams in which the top flange plate is replaced with a concrete filled hollow steel section. A key advantage of these members is the increased torsional stability, which reduces the need for bracing under construction loading conditions. The tubular section can be any shape (e.g. circular, rectangular, and pentagonal) and the focus in the current paper is on simply supported girders with a rectangular section for the top flange, and stiffened webs. These are complex members and their behaviour is governed by several inter-related parameters which are studied herein. A nonlinear three-dimensional finite element model is developed and validated using available experimental data from the literature. A parametric study is then carried out focussing on the most salient properties such as web height, tubular flange dimensions as well as the width of the bottom flange. Finally, the paper presents a detailed discussion on the appropriate applications and design methods for these types of section, based on the results of the numerical analysis.*

1. INTRODUCTION

Steel–concrete composite structures are very popular in construction because they exploit the positive attributes of both of the constituent materials to create an efficient and effective load-carrying system. A new type of steel-concrete composite beam has recently been developed called a tubular flange girder (TFG). These have a similar shape to conventional steel beams, but the top flange plate is replaced with a hollow steel section. The tube may be infilled with concrete to create a concrete filled tubular flange girder (CFTFG). Various shapes of top flange tube have been proposed (e.g. circular, rectangular, pentagonal, etc.), and their usage has increased in buildings and bridges, particularly for heavily loaded scenarios. The main advantages of tubular flange girders compared with regular steel I-beams have been described by Wassef et al. [1] and include excellent local buckling resistance, large torsional stiffness, and relatively low web slenderness.

In this context, several researchers have studied the behaviour of CFTFGs in recent years. Wimer and Sause [2] performed a design study for a four girder prototype bridge which included two large-scale experiments on 18 m long CFTFGs. These girders had a rectangular concrete-filled tube as the compression flange and a flat plate as the tension flange, as shown in Fig. 1(a). The study found that the large torsional stiffness of the tubular flange permits the use of large unbraced lengths in the bridge framing system. Kim et al. [3,4] investigated the lateral–torsional buckling flexural strength of CFTFGs with a circular concrete-filled tube as the compression flange and a flat plate as the tension flange, shown in Fig. 1(b). The results indicated that fewer intermediate members are needed for CFTFGs to maintain lateral–torsional stability compared with conventional I-beams of a similar depth, which reduces the fabrication and erection effort required during construction. In addition, they provided formulas for determining the lateral–torsional buckling flexural strength of CFTFGs. Sause [5] carried out a further investigation on curved CFTFGs, and it was found that these members have high torsional stiffness, and also a significantly greater load carrying capacity compared with curved I-beams.

In this paper, the flexural behaviour of concrete filled rectangular flange girders (CFRFGs) is investigated through numerical modelling. This work follows on from previous studies in which the authors have developed a series of analytical expressions for predicting the ultimate bending capacity (M_u) of CFTFGs with a circular top flange [6]. The current article begins with a description of the finite element (FE) model which is validated against test data available in the literature. A parametric study is then conducted using the validated model to investigate the effect of key parameters and to observe how the cross-section geometry influences the behaviour of CFRFG's.

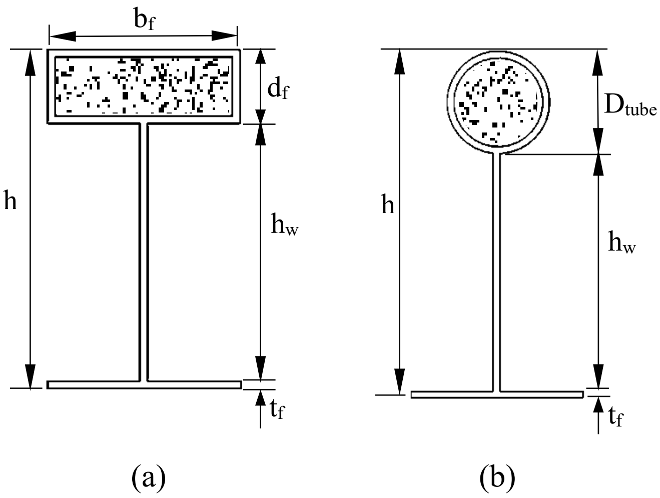


Figure 1: Concrete filled tubular flange girders including (a) a rectangular flange and (b) a circular flange

2. FINITE ELEMENT MODEL SIMULATION AND VALIDATION

2.1 Finite element model description

The specimen details incorporated into the finite element (FE) model are based on the two rectangular tubular flange girders which were examined in the test programme of Muteb et al. [7]. Accordingly, the principal dimensions of the specimens are presented in Table 1 including the width, depth and thickness of the tubular flange (B_{Tf}, D_f and t_t, respectively), the height and thickness of the web (h_w and t_w, respectively), the width and thickness of the bottom flange (B_{Bf} and t_f, respectively) and the stiffener thickness ($t_{stiffener}$). With reference to Fig. 2, both test specimens have the same tube flange width (B_{Tf}) and thickness (t_t) but different rectangular tube depths (D_f). The beams are 0.17 m in overall height and 2.02 m in length, as shown in Fig. 2, and are subjected to two concentrated loads (P/2, each) in the vertical direction. The distance between the loading points is 0.64 m. There are six stiffeners along the beam length and each is 2.85 mm in thickness. These are located at the supports and loading points to prevent local instability of the web at these locations. Simply supported boundary conditions are employed in the FE model, replicating the experimental arrangement and these are simulated by restraining suitable displacement and rotational degrees of freedom at the beam ends.

Furthermore, bearing plates with dimensions 90×80×10 mm are applied under each loading point in order to prevent any local buckling in the steel section due to the concentrated load.

Initial geometric imperfections are usually introduced in steel sections during production, fabrication and handling and can have a significant influence on the behaviour, and therefore they are included in the FE model. The shapes of the imperfections are determined from a linear elastic eigenvalue buckling analysis, in which an initial geometrical imperfection has an amplitude of L/1000, where L is the member length, in accordance with the permitted out-of-straightness tolerance in EN 1090-2 [8]. Fig. 3(a) illustrates the first buckling mode of the tested girders. Both the FE model and the experiment failed by excessive deformations, as shown in Fig. 3(b). It is suggested that the maximum acceptable limit of allowable deflection is L/120, where L is the member length [7,9]. The material properties incorporated in the model are presented in Table 2 including the yield strength (f_y), ultimate strength (f_u), Young's modulus (E) and Poisson's ratio for steel. Also included in the table are the compressive strength (f_c) and Poisson's ratio of the concrete [7].

Table 1: Dimensions of the CFRFG cross-section

Dimension	CFRFG1	CFRFG2
B_{Tf}	80	80
D_f	20	40
t_t	2.85	2.85
h_w	147.15	127.15
t_w	2.85	2.85
B_{Bf}	80	80
t_f	2.85	2.85
$t_{stiffener}$	2.85	2.85

*all dimensions in mm

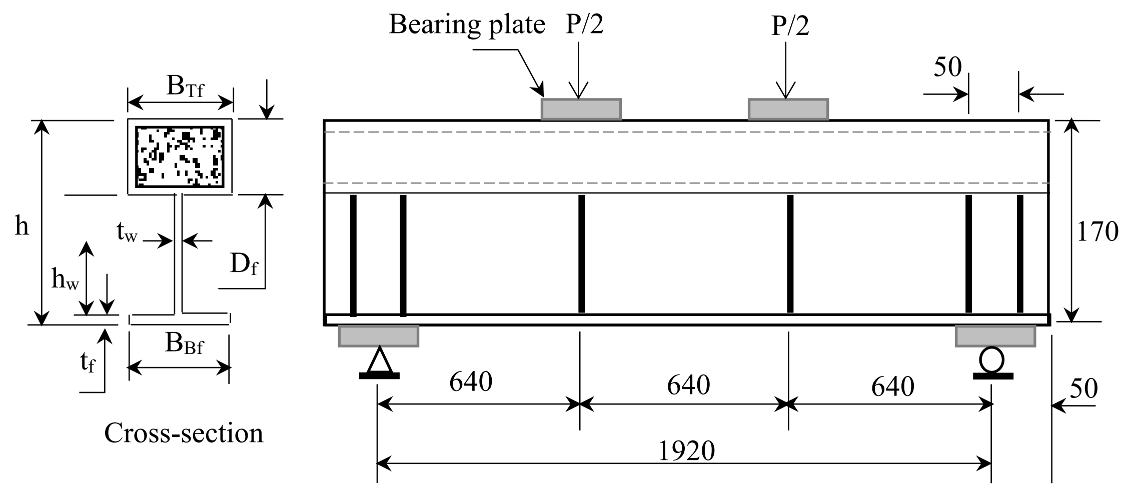


Figure 2: Schematic of the simply supported beam and cross-section for a composite beam with a concrete filled rectangular compression flange (all units in mm)

Table 2: Details of the material properties [7]

Material	Property	Symbol	Value
Steel	Yield stress (N/mm^2)	f_y	236.8
	Ultimate stress (N/mm^2)	f_u	377.2
	Young's modulus (N/mm^2)	E_s	200000
	Poisson's ratio		0.3
Concrete	Compressive cylinder strength of concrete (N/mm^2)	f_c	42.5
	Poisson's ratio		0.20

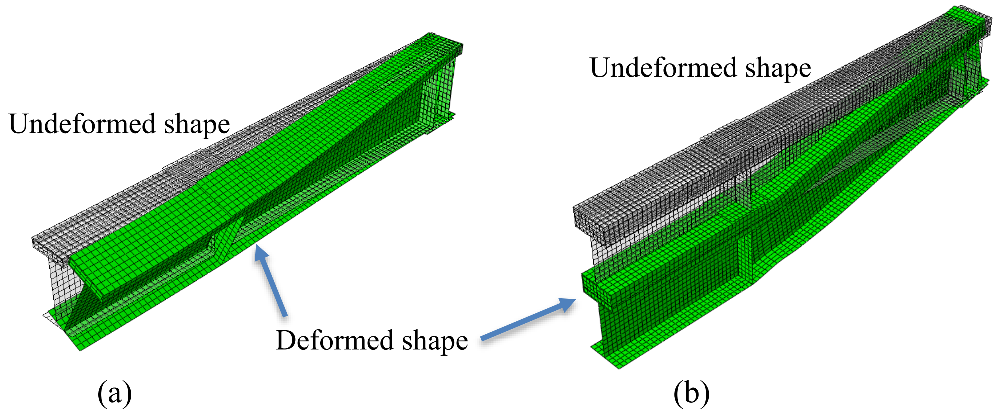


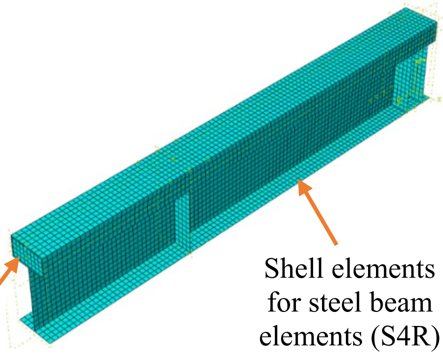
Figure 3: Buckled/deformed and undeformed shapes at mid-span for CFRFGs

2.2 Material modelling

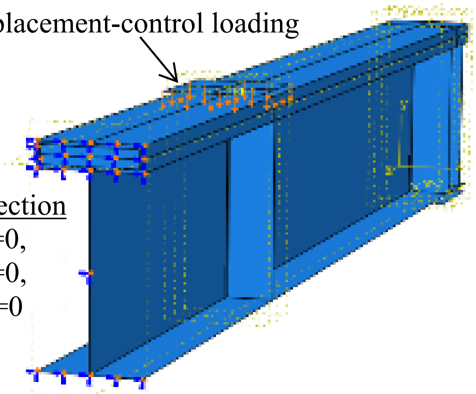
For this study, a nonlinear three-dimensional finite element (FE) analysis is conducted using the ABAQUS software. The concrete is modelled using the solid element known in the ABAQUS library as C3D8R [10], which is an 8-node brick element with reduced integration. On the other hand, the steel beam and stiffeners are simulated using four-node, shell elements with reduced integration (S4R). The S4R shell element has six active degrees of freedom per node, including three displacements and three rotations. The reduced integration enables more efficient computation without compromising the accuracy of the results. A tie contact is defined between the surfaces of the steel section and the edges of the stiffeners. Following a mesh sensitivity study, an element size of 10×10 mm as shown in Fig. 4(a) is employed throughout the model which provides the optimum combination of accuracy and computational efficiency.

2.3 Support and loading conditions

The geometry and loading conditions of the beam are symmetrical about the mid-span and therefore only half the girder length is modelled. Accordingly, one end section of the beam model has simply supported boundary conditions whilst the other end has symmetrical boundary conditions, as shown in Fig. 4(b), in which u_x, u_y, u_z, θ_x, θ_y, and θ_z are the displacements and the rotations about the global x, y and z axes, respectively. The y-z plane is considered to be in-plane whilst the x-z and x-y planes are out-of-plane, in the current study. At the end of the beam (i.e. at the support), the vertical (u_y) and lateral displacements (u_x) of all nodes along the y-axis (i.e., when $x = 0$), and the twist rotations about z and y-axes (θ_z and θ_y) are restrained against movement and therefore assigned values equal to zero. At the middle of the beam, the longitudinal displacements (u_z) and rotations about the x and y-axes (θ_x and θ_y) are also restrained against all movement. The loading is applied to the top surface of the beam in displacement control through two concentrated loads along the full length or one loading point when half the span is considered.



(a)



(b)

Figure 4: FE model for the CFRFG, including (a) finite element mesh (b) support and loading conditions

2.4 Validation of the load-displacement response

The load-displacement response of CFRFGs from both the FE model and the experimental programme by Muteb et al. [7] is presented in Fig 5. Overall, the simulated load-deformation curves are shown to provide a good reflection of the experimental behaviour and the model also provides an excellent prediction of the ultimate load capacity of the CFRFG. The slight variation between the FE and experimental responses presented in the figure are most likely due to one or a combination of several factors such as the influence of residual stresses which are not included in the FE simulation or the material modelling assumptions.

3. PARAMETRIC STUDY

Using the FE model, a parametric study has been conducted and is described herein to investigate the effects of the geometric parameters on the ultimate behaviour of CFRFGs and the influence of the most salient parameters on their performance.

A number of parameters are varied in the parametric study including the depth of the rectangular tube (D_f), the height of the web (h_w) and the width of the bottom flange (B_{Bf}). The details of the specimens included in the parametric study are presented in Table 3. The tube width and thickness are kept constant at 80 and 2.85 mm, respectively.

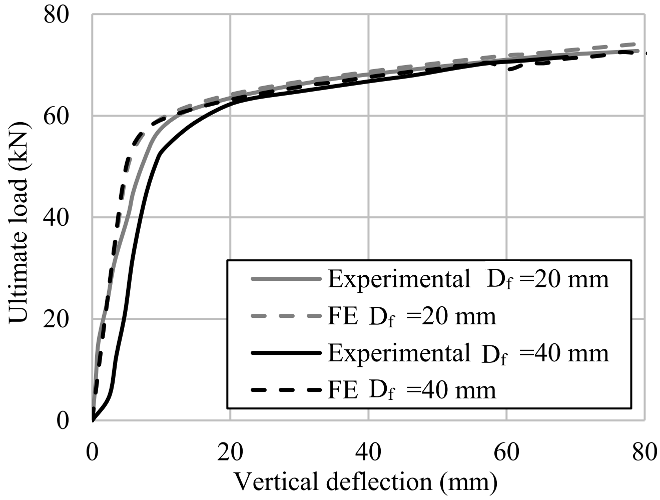


Figure 5: Ultimate load versus deflection relationship from the FE analysis and experimental results

Table 3: Details and FE strengths of CFRFGs

Specimen	Geometric details						$M_{u,FE}$ (kNm)
	D_f (mm)	B_{Tf} (mm)	B_{Bf} (mm)	h_w (mm)	t (mm)	B_{Tf}/D_f	
GR1	20	80	80	147.15	2.85	4	18.75
GR2	20	80	80	250	2.85	4	37.66
GR3	20	80	120	147.15	2.85	4	22.85
GR4	20	80	120	250	2.85	4	43.20
GR5	40	80	80	127.15	2.85	2	19.98
GR6	40	80	80	250	2.85	2	43.10
GR7	40	80	120	127.15	2.85	2	23.97
GR8	40	80	120	250	2.85	2	49.49

3.1 Effect of the tubular flange width-to-depth ratio (B_{Tf}/D_f)

Two different width-to-depth ratios (B_{Tf}/D_f) are studied in this investigation for the concrete filled tubular flange; the results are presented in Table 3 whilst the ultimate moment versus deflection responses are given in Fig. 6. Analysis of the results indicates that reducing the aspect ratio of the flange (B_{Tf}/D_f) for the beams included in this study results in an increase of the flexural capacity of the CFRFGs. As shown in Fig. 6, the ultimate moment of GR2 in which B_{Tf}/D_f is equal to 4, is 37.66 kNm while for GR6 (with B_{Tf}/D_f = 2), the ultimate moment is 43.10 kNm. This suggests that the contribution to the flexural capacity made by the tubular flange increases for a relatively lower B_{Tf}/D_f ratio; i.e. by increasing the depth (D_f).

3.2 Effect of bottom flange width (B_{Bf})

In order to investigate the effect of plate width (B_{Bf}) in the tension region of the cross-section on the behaviour, two different widths of the bottom flange are studied. The moment-deflection curves presented in Fig. 7 verify that, as expected, increasing the tensile flange width raises the ultimate moment capacity of the section. From a cost perspective (both materials and fabrication), it is important to consider whether the increased volume of steel required in GR7 (B_{Bf}=120 mm) compared to GR5 (B_{Bf}=80 mm), for example, is translated into improved moment capacity. These two beams have an ultimate moment capacity of around 23.97 kNm and 19.98 kNm, respectively, and a gross cross-sectional area (steel only) of 1356 and 1242 mm^2, respectively. Therefore, a 9% increase in steel volume can result in a 20% improvement in bending moment capacity, for the same stiffener arrangement.

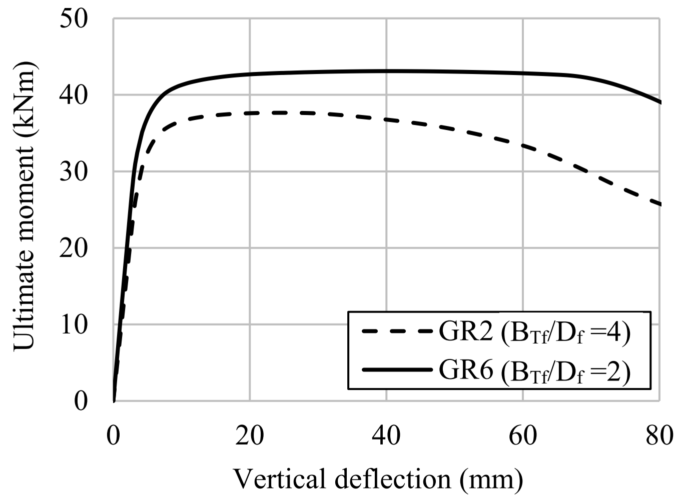


Figure 6: Ultimate moment versus deflection responses with different B_{Tf}/D_f

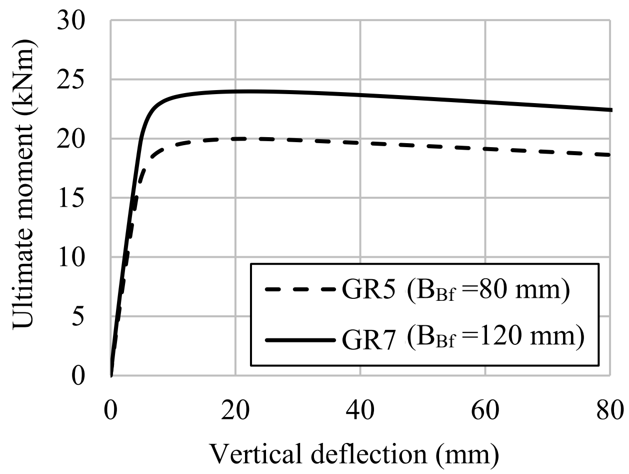


Figure 7: Ultimate moment versus deflection responses with different bottom flange width

3.3 Effect of the web height (h_w)

As observed in Table 3, an increase in the web height (h_w) leads to an increase in the moment capacity of the CFRFG, as expected. For example, the ultimate moment of GR1 (h_w=147.15) is 18.75 kNm whereas the value of $M_{u,FE}$ for GR2 (h_w=250) is 37.66 kNm, as shown in Fig. 8. Also, it is observed that the initial stiffness of the curves is greater with an increase in h_w. The web height is a key parameter to consider in the design of plate girders. Clearly, decreasing the h_w reduces the volume of steel in the section as well as the fabrication costs as less welding is required and the associated risk of weld distortion is lowered. However, it also reduces the bending moment capacity. Therefore, this discussion highlights the importance of a careful consideration of all factors (capacity requirements, flange depth, web depth, welding needs, etc.) when designing a CFRFG.

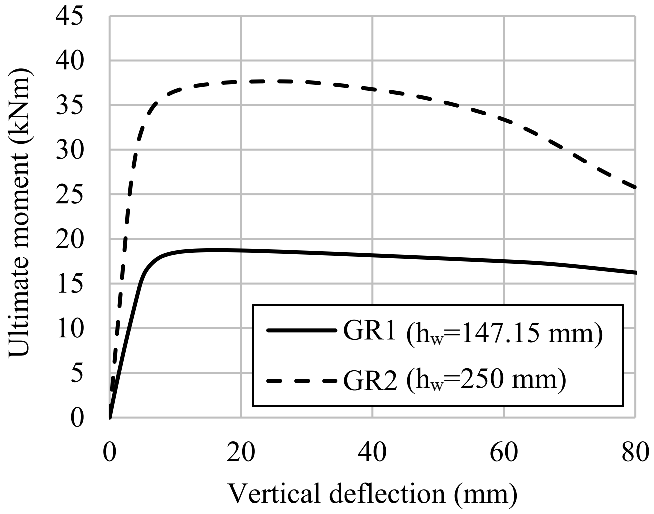


Figure 8: Ultimate moment versus deflection responses with different web height

4. CONCLUSIONS

This paper presents a non-linear analysis and initial study into the behaviour of concrete filled rectangular flange girders (CFRFGs) under flexure. The ABAQUS software [10] is employed to study the response and also the relative influence of the most salient parameters. The accuracy of the FE model is initially assessed using the experimental results of Muteb et al. [7], who conducted the only two tests on these types of members that are available in the public domain. It is shown that the proposed FE model is able to provide a very good prediction of the general behaviour and the ultimate capacity. The following conclusions can be made from this work:

1. In terms of the geometrical details, it is shown that reducing the aspect ratio of the flange (B_{Tf}/D_f) increases the flexural capacity of the CFRFGs.
2. The bending moment capacity of CFRFGs is increased by increasing the web height (h_w).
3. It is clearly demonstrated that increasing the bottom flange width (B_{Bf}) results in an increase in the flexural strength of the girders.

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