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Reinforced steel I-beams: A comparison between 2D and 3D simulation

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This study reports the accuracies of Finite Element (FE) simulations, based on two and three dimensional (2D and 3D) modelling of strengthened steel I-beams in static linear and non-linear analyses. To investigate the effects of simulation modelling methods on the accuracy of the results, 28 computer and laboratory specimens were used. To strengthen the beams, Carbon Fibre Reinforced Polymer (CFRP) and steel plates were applied, and to simulate the specimens, ANSYS software was utilized. All specimens were modelled by using shell elements or solid elements in the 2D and 3D modelling cases, respectively. The results show that non-linear and 3D simulation methods predicted the experimental results appropriately.

1. Introduction

Structures may need to be strengthened due to a design fault, construction error, or change in function. Various methods have been used for strengthening structures. For steel structures, applying CFRP is the most common strengthening method.

Recently, studies on the strengthening of steel beams with Fibre Reinforced Polymer (FRP) have attracted greater interest. Applying CFRP sheets for strengthening steel I-beams was researched by Liu et al. [14]. An analytical model to predict the linear and non-linear behaviour of steel beams rehabilitated using FRP strips was suggested by Youssef [24]. Flexural strengthening of steel I-beams with CFRP sheets was also explored by Nozaka et al. [15] and Zhao and Zhang [25]. Applying CFRP sheets for shear and flexural strengthening of steel I-beams was explored by Pantaik et al. [17]. Investigation of the delamination failure of metallic beams reinforced by externally bonded FRP was addressed by Colombi [5]. Strengthening steel–concrete composite bridges with CFRP was examined by Dawood et al. [6], Rizkalla et al. [18], Al-Saidy et al. [2], and Schnrech et al. [19–21]. The study of the fabrication and mechanical properties of internally pre-stressed steel I-beams produced by combining steel T profile and pre-stressing steel plate (PSP) was conducted by Ozcatalbas and Ozer [16]. Deng and Lee [7,8] demonstrated the results of a study on the static behaviour of metallic beams bonded with CFRP plates. The fatigue behaviour of steel structures retrofitted by using FRP materials was investigated by Bocciarelli et al. [3].

One of the most appropriate methods to study the effects of strengthening existing structures is simulation by using computer software. In most of the structural analysis software, the Finite Element Method (FEM) is used. The strengthened steel structures may be simulated in either 2D or 3D [5,9,10,12,13,22].

In the 2D simulation, all parts of the specimens are modelled by using the plane elements. In this case, the structure is simulated in the plane, and the dimension of the structure in the out-plane is defined as thickness. In the 3D simulation, all parts of the beams are simulated by using the solid elements that have dimensions in all directions. The problems

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observed in the 3D case are higher run-time because of the higher amount of elements and equations. This problem is more significant when the non-linear analysis method is used. Designers may prefer to simulate the strengthened structures in the 2D case because of the lower run-time.

Colombi [5] evaluated the analytical method to investigate the fracture mechanics of CFRP flexural strengthened steel beams by using ANSYS software and the 2D simulation method to simulate the specimens. To date, the accuracy of this simulation method, especially for steel beams that have noticeable deformation in the out-plane direction (namely, lateral–torsional–buckling), has not been adequately investigated.

Deng et al. [9] validated an analytical solution to calculate the stress in the CFRP flexural strengthened steel beams by using ABAQUS software. A linear 3D FE Model was established, in which only one half of the beam was considered because of symmetry. All nodes at the mid-span were restrained to produce the required symmetry. Although, the steel beams had symmetrical loading and boundary conditions, the effect of lateral–torsional–buckling on the asymmetrical behaviour of the beams, especially in the plastic region, was not studied.

Linghoff et al. [13] made FE-models based on the 3D-brick elements and 2D-shell elements (combination of the elements). The CFRP laminates were modelled as a linear material. In addition, the orthotropic behaviour of the CFRP laminates was defined.

Haghani et al. [10] used FE modelling for CFRP flexural strengthened steel beams to investigate the effect of using normal and reverse tapering, with and without adhesive fillets, on the interfacial stress distribution in the adhesive joints at different locations, including the mid-thickness of the adhesive layer as well as the interfaces. Only half of the beam was modelled because of symmetry. As mentioned, steel beams may have asymmetrical behaviour due to the effect of lateral buckling that was not recognized in the half-modelling case. The modelling was conducted by using FE code ABAQUS. They found that in the 3D case the distribution of stress and strain in the CFRP's and adhesive along the width was achievable that in the 2D modelling, it was not possible.

Linghoff and Al-Emrani [12] used ABAQUS software to model CFRP flexural strengthened steel beams in the 3D case. The elements were merged together by sharing common nodes at the interfaces. Therefore, full interaction was assumed between the different elements to investigate the failure modes. To reduce the effort of computational time, the symmetry of the beam in two different planes was used and, therefore, only a quarter of the beam was computed. This kind of modelling did not lead them to investigate asymmetrical behaviour in both longitudinal and transverse directions.

Seleem et al. [22] modelled CFRP flexural strengthened steel and steel-composite beams in the 3D simulation and non-linear analysis case by using ABAQUS software. They modelled the specimens in full size.

As mentioned, 2D and 3D modelling are used to simulate flexural strengthened steel structures, however, to date, a comparison between the results of 2D and 3D simulation have not been reported. The questions that arise are: (a) do the results of analyses of strengthened steel structures with CFRP or steel plates in 2D and 3D have agreement with each other? and (b) which method has the highest accuracy compared to the experimental test? These two questions constitute the objectives of this study. In addition, this study helps to select an optimized approach for 2D or 3D FE simulation of strengthened steel I-beams. The selection can be done based on the run-time and the accuracy of the results. To compare the results of 2D and 3D modelling, the critical parameters are chosen as follows:

- Strain on the tensile flange at the mid-span.
- Tensile strain on CFRP/steel plate at the mid-span.
- Vertical deflection of the girder at the mid-span.
- Lateral–torsional–buckling at the mid-span.
- Peeling stress on CFRP/steel at the end of the plate.
- Shear strain on adhesive at the end of the CFRP/steel plate.

2. Materials and methods

2.1. Materials

2.1.1. Steel beam

In this research, steel I-sections from grade A36 (ASTM) are strengthened by using CFRP strips and steel plates. Table 1 shows the dimensions and material properties of the I-beams. Fig. 1 indicates the dimension of the specimens, and Fig. 2 shows the dimensions of the steel I-section.

Table 1
Dimensions and material properties of steel I-beams.

Steel I-section dimensions (mm)					E-Modulus (N/mm^2)	Stress (N/mm^2)		Strain	
Width	Height	Flange's Thick.	Web Thick.	Length	Mean value	Yielding (F_y)	Ultimate (F_u)	Yielding (ε_y) %	Ultimate (ε_u) %
100	150	10	6.6	2350	200,000	250	370	0.12	13.5