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Reinforcing strategies for double-coped beams against local web buckling

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ABSTRACT

This paper presents a comprehensive numerical study on the strength and behaviour of double-coped beams (DCBs), with the focus on reinforcing strategies against local web buckling. Four reinforcement types, namely, longitudinal web stiffener (Type A), combined longitudinal and vertical web stiffeners (Type B), vertical and double longitudinal web stiffeners (Type C), and full-depth doubler plate (Type D), are considered. Through examining a suite of validated numerical models with a spectrum of cope details, it is found that the considered reinforcement types are in general effective, especially for the models with long or deep copes. Depending on the cope details and stiffener type, a series of failure modes, including local web buckling, web shear yielding, web shear buckling, tensile fracture of the bottom cope corner, and web crippling, are identified, and the effectiveness of the different reinforcement types on preventing or postponing these failure modes is discussed in detail. A preliminary design rule for checking the capacity of the reinforced coped section is also proposed in the paper, and additional analysis is performed to further evaluate the influences of varying reinforcement dimensions and boundary conditions on the ultimate capacity of the DCBs. Based on the numerical analysis, a set of prescriptive recommendations on reinforcement details is finally proposed, offering a simple yet safe guidance for new design or upgrade of DCB members.

1. Introduction

In typical steel structures such as building frames, the flanges of secondary beams are often notched/coped in order to provide sufficient clearance for the connection zone and to facilitate the fabrication of flooring, decking, and ceiling systems. A beam is known as a single-coped beam (SCB) if part of the top flange is removed. When both flanges need to be partially removed at the beam ends according to certain construction or structural requirements, the beam is called a double-coped beam (DCB), as shown in Fig. 1(a). For both cases, the strength of the coped end is inevitably compromised, and as a result, these members may experience complex failure modes, including local web buckling [1–3], block shear [4–8], fatigue fracture [9–11], and lateral-torsional buckling [12,13]. Local web buckling, a phenomenon caused by local instability of the compressive coped edge, is one of the most common local failure modes for both SCBs and DCBs [14]. The failure mechanism was investigated by a number of researchers, leading to the stipulation of design equations in the AISC Steel Construction Manual [15] and SCI design guidelines [16]. With continuously emerging test and numerical data, some further amendments to the existing design rules were also suggested [3,17,18].

Recognising the detrimental effects caused by the copes, a series of reinforcing strategies with various stiffener types were proposed for SCBs. Cheng et al. [1] numerically examined the effectiveness of three types of stiffeners, namely, longitudinal web stiffener, combined longitudinal and vertical web stiffeners, and doubler plate, on the local web buckling capacity of SCBs. The details of these stiffeners are reproduced in Fig. 1(b). It was claimed that the longitudinal stiffener and doubler plate reinforcement types were suitable for standard hot-rolled steel sections. In the case of slender webs, i.e. thin web members with $D/t_w > 60$ (D = Full beam depth, t_w = web thickness), combined longitudinal and vertical stiffeners might need to be employed. Yam et al. [19–21] later confirmed the benefits of these stiffeners via an experimental study, and it was found that the combined longitudinal and vertical stiffeners could effectively prevent web crippling near the end-of-cope section (position of the section is defined in Fig. 1(a)), and thus were recommended for the case of deep copes.

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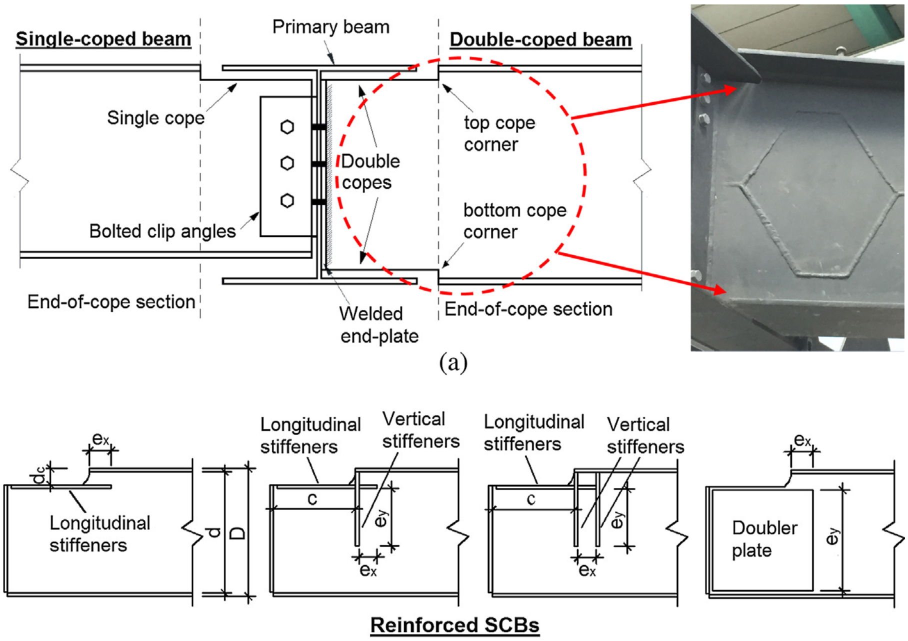

(a)

(b)

Fig. 1. Coped beam connections: a) practical coping details of steel beams, b) typical reinforcement for SCBs.

The subsequent parametric study revealed that SCBs reinforced by longitudinal or combined longitudinal and vertical stiffeners were able to develop either the plastic moment capacity of the full beam section or the shear yield capacity of the coped section, but it should be noted that this conclusion was made based on models with a fixed beam span (i.e. 2 m) under a single concentrated load. In addition, using two vertical stiffeners was suggested for very slender beam sections such as built-up girders. Some of the afore-mentioned reinforcement types have been included in the AISC Steel Construction Manual [15].

While the existing studies clearly demonstrated the beneficial effects of the various reinforcing strategies for coped beams, these results were obtained based on the research data related to SCBs. So far, relevant information on reinforced DCBs is very rare. Some investigations warned that due to the absence of the restraint from both flanges, DCBs can exhibit much weaker local web buckling performance compared with the case of SCBs [22,23]. In addition, as the reinforced DCBs may have different behaviour from reinforced SCBs, the applicability of the existing reinforcing strategies to DCBs is still unclear. These facts highlight the necessity of understanding the strength and behaviour of reinforced DCBs, such that effective reinforcing strategies can be proposed to support new design or retrofitting of such members. To this end, an experimental study [24] was recently performed by the authors and co-workers of this paper. The results indicated that some of the existing reinforcing strategies (for SCBs) may also be effective for DCBs against local web buckling, but meanwhile, new failure modes were observed which need extra attention.

This study is an extension of the previous experimental programme [24] to acquire more in-depth understanding of the performance of reinforced DCBs. In this paper, the general information on the tests and the key results are briefly introduced, and the corresponding detailed Finite Element (FE) analysis on the test specimens is performed. The influence of initial imperfection magnitude is also discussed. After achieving satisfactory agreement between the test results and the FE predictions, a further parametric study is performed exploring the influence of various parameters, including coping dimension, reinforcement types and dimensions, and boundary conditions, on the strength and behaviour of DCBs. Based on the results from the parametric study, a set of design recommendations is finally proposed.

2. Modelling approach and validation

2.1. Tests conducted by Lam and colleagues [24]

Eight full-scale DCB specimens were tested in the research programme by the authors and his co-worker [24]. The specimens were made from S355 UB406 × 140 × 39 steel beams. Two coping dimensions, i.e. $c = 450$ mm ($d_c = 25$ mm) and $c = 550$ mm ($d_c = 50$ mm), were considered as illustrated in Fig. 2 and Table 1. For each coping dimension, one specimen was unreinforced (UR) and the remaining three were strengthened with varied reinforcement types, namely, longitudinal web stiffener (LWS), full-depth doubler plate (FDP), and partial-depth doubler plate (PDP). The longitudinal web stiffeners were fillet welded along the top edge of the coped web on both sides of the web, and the doubler plate was welded on one side of the coped web. The extension of the stiffener or doubler plate (e_x, Fig. 2) was 50 mm and 100 mm for C450 and C550 series specimens, respectively. For the case of PDP, the plate depth was half of the coped web depth. Flush end-plate connections were adopted at the coped end for all the specimens. A simply-supported condition was arranged for the test beam, where the coped end was supported by the reaction frame via the end-plate connection. The far end of the beam was placed on a roller support. The loading condition of the test beam is schematically shown in Fig. 2. Lateral-torsional buckling of the test beam was prevented by out-of-plane restraints provided to the flanges of the beam close to the loading point and the end supports.

According to the test results, local web buckling governed the final failure mode for the two unreinforced specimens. Adding a pair of longitudinal web stiffeners eliminated local web buckling, but tensile cracking at the bottom cope corner was finally developed. Employing a doubler plate could delay the occurrence of local web buckling, and a full-depth doubler plate seemed to be more effective than a partial-depth one. In addition, the cope