Engineering Structures 111 (2016) 505–524

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Comparison of optimal designs of steel portal frames including topological asymmetry considering rolled, fabricated and tapered sections

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ARTICLE INFO

Article history:
Received 13 August 2015
Revised 12 December 2015
Accepted 17 December 2015
Available online 13 January 2016

Keywords:
Hot-rolled steel
Fabricated beams
Portal frames
Genetic algorithms
Serviceability limits
Buckling limits

ABSTRACT

A structural design optimisation has been carried out to allow for asymmetry and fully tapered portal frames. The additional weight of an asymmetric structural shape was found to be on average 5–13% with additional photovoltaic (PV) loading having a negligible effect on the optimum design. It was also shown that fabricated and tapered frames achieved an average percentage weight reduction of 9% and 11%, respectively, as compared to comparable hot-rolled steel frames. When the deflection limits recommended by the Steel Construction Institute were used, frames were shown to be deflection controlled with industrial limits yielding up to 40% saving.

1. Introduction

For steel portal frames, a recent paper [1] has shown that asymmetric shapes with photovoltaic (PV) panels on the southward side were advantageous for a low energy driven design. Asymmetry and PV panels allowed for reduced embodied energy solutions (less insulation) to achieve zero carbon standing by increased PV renewable space. The increased degree of asymmetry was shown to be very useful for zero carbon building code compliance where a calculated degree of asymmetry (from an energy simulation optimisation) could be used to meet zero carbon requirements.

In another recent paper [2], a framework for a structural design optimisation for symmetrical portal frames that used S275 steel was presented that considered frames from rolled sections and frames from fabricated sections. This present paper now investigates the effect of asymmetry [1] on the structural design optimisation with photovoltaic panels on the southward side of weight 0.4 kN/m^2. Two frame configurations are considered; symmetric frames and asymmetric frames with an apex ratio of 0.8. Within the design optimisation, a decoupled approach from the energy optimisation is taken with the main goal to establish the effect of asymmetry on the optimisation. No attempt is made to link the structural design optimisation to energy optimisation as it was shown that the steel weight would have an insignificant effect on the energy design.

The frame constructions in this paper differ from those by McKinstray et al. [2] due to the asymmetry and the additional tapered frame GA configurations case. Tapered frames [3,4] are the more efficient type of portal frame as these allow the cross-section to vary as required [5] rather than being limited to a single critical ultimate limit state (ULS) load position that would control a frame made from rolled or fabricated I sections. This present paper investigates the structural effect of this asymmetry on the structural members. An optimisation framework is described to design portal frames for minimum primary member weights in accordance with the Eurocodes. Unlike [2], S355 steel is used as it has become common practice to use this grade in portal frames due to its availability and similar price to S275. Although it does not provide any benefits in terms of reducing deflections, the additional yield strength can be useful in reducing buckling. For each of the construction methods, a single optimisation configuration case is used (see Fig. 1 and below);

C1 – Rolled I beam sections (selected from the Tata Steel bluebook [6]). This configuration has 6 decision variables.

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http://dx.doi.org/10.1016/j.engstruct.2015.12.028
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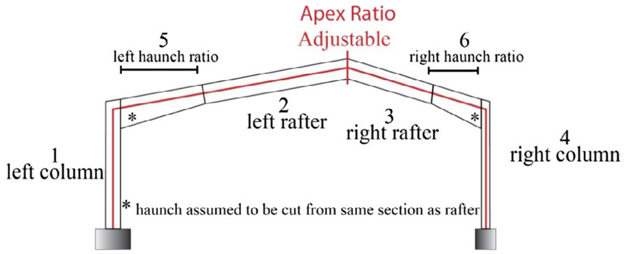
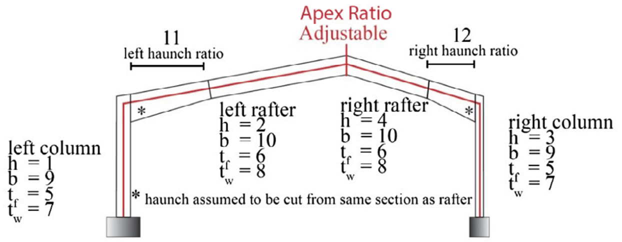
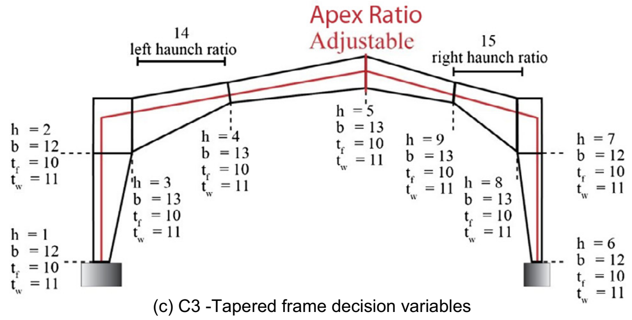


(a) C1 - Rolled section decision variables



(b) C2 - Fabricated frame decision variables



(c) C3 -Tapered frame decision variables

Fig. 1. Frame configurations and design variables.

C2 – Fabricated I sections (I beams fabricated from 3 plates). This configuration has 12 decision variables.

C3 – Fully fabricated tapered frames (I beams fabricated from 3 plates but with varying section depth). This configuration has 15 decision variables.

As mentioned earlier, the addition of PV is accounted for through increased permanent loading on the southward side, represented by an additional 0.4 kN/m^2. In addition, the effects of wind loading are added to the list of considered load combinations. Asymmetry also increases the severity of a load occurring only on one side of the frame. To address this, load combinations are considered with loads present on one side as well as both sides of the roof. These result in 120 load combinations, including 28 serviceability limit state (SLS) combinations (14 load combinations for differential deflection limit, 14 for absolute deflection limit) and 92 ULS combinations. The deflection limits recommended by the Steel Construction Institute (SCI) [7] are adopted; a comparison is also made to the less conservative limits from the industry [8] in Section 2. The effects of the additional wind load combinations beyond the gravity load combination used by McKinstray et al. [2] are investigated in Section 2 also, for frame moments.

A wide range of topologies as well as different ranges of variable and permanent actions are considered. The controlling load combinations were identified at positions through the frame as well as the increase in moment at the column tops. It was found that wind loading can increase maximum design moments in the column tops by a factor from 1 to 3, depending on the span and column height.

A reference frame configuration is optimised, with a span of 35 m and column heights of 6 and 12 m (see Section 4). It is optimised for symmetric and asymmetric configurations with apex ratios of 0.5 and 0.8 respectively [1]. The influence of the combination of wind loading, PV loading and asymmetry on the primary steel mass for the reference frame is established. It is shown that the SCI serviceability limits greatly control the design and that with deflection limits the additional PV loading has a negligible effect on the optimum primary member weight.

A topographical parametric study is then described (Section 5) covering different spans (14.5–50 m) and column heights (4–11.4 m) for different site locations (wind speeds) and displacement limits (SCI and Industrial limits). Here, the effects of wind loading, asymmetry and deflection limits are investigated. It was found that wind load has a significant effect on the optimisation compared to just the gravity load combination. Tapered sections were found to allow for additional weight savings (2–10% extra) compared to fabricated sections. The effect of asymmetry is shown to be small with average weight increase of 4–13%, with the smallest increase found in tapered frames followed by rolled sections and then fabricated sections.

2. Limits state design

Modern practice has shown that plastic design produces the most efficient designs in the majority of cases [9,10]. Elastic design is still used, particularly when serviceability limit state deflections will control frame design [8,11,12]. Phan et al. [8] and McKinstray et al. [2] both demonstrated that if the deflection limits recommended by the SCI are adopted, serviceability limit states control design. In addition, deep fabricated sections tend to be incapable of fully utilising the material in the cross-section beyond the elastic modulus. Additionally tapered sections are also generally not considered suitable for plastic design. Therefore, elastic design is used here. A frame analysis program, written by the authors in MATLAB, was used for the purpose of the elastic frame analysis. The internal forces, namely, axial forces, shear forces, and bending moments can be calculated at any point within the frame. The MATLAB program was capable of capturing the behaviour of tapered members.

2.1. Frame loading types

A number of load combinations [13] must be verified in the design of steel portal frames. This is obtained through the rules for actions found in BS EN 1991 [14] and the rules for combinations of actions in BS EN 1990 [15]. The combination of actions is the combination of permanent, variable snow and wind actions on the structure multiplied by load factors determined from the design code.

Permanent actions are the self-weight of the structure including primary steelwork, purlins and secondary steel (0.1 kN/m^2), cladding materials (0.2 kN/m^2), building services (0.25 kN/m^2) and photovoltaic panels and services (0.4 kN/m^2). Permanent loads are determined from the manufacturer's specification and are identical to [2], apart from the additional PV loading that is included on a single roof side. In addition, variable actions including access, wind and snow are considered. Snow loading is calculated based on BS EN 1991-1-3 [16] and its National Annex [17], assuming that a non-accidental case (drift) of 0.4 kN/m^2 is typical. Loads on roofs that are not accessible, except for normal maintenance and repair, are classed under category H in BS EN 1991-1-1 [14]. For that