AN ECONOMIC PROPOSAL IN THE DESIGN OF THE ONE STOREY – LEVEL STEEL STRUCTURE. THE USE OF CASTELLATED AND SINUSOIDAL STEEL SECTIONS

GEORGE XANTHAKIS, LAMBRINI PANAGOPOULOU
Department of Steel Structure
ASPAITE (School of Pedagological and Technical Education)
Marousi, Athens
GREECE
E-mail: xanthakisg@ba.aegean.gr

Abstract: Economy, ease and speed of construction are the main factors for using steel as a building material. In this paper castellated sections and sinusoidal steel sections are presented as the main frames of industrial buildings. The key to the use of this section is the significant weight reduces in comparison to the structure with hot rolled profiles I-sections. In the first part of this study, the special characteristics of these sections, their structural behavior, the advantages of using them and a literature review are presented. In the second part an analysis of an one-level storey steel structure (using the statical analysis program, Instant) is performed. The numerical results indicate that the use of these sections is an economical and advantageous choice.

Key-Words: Industrial buildings, castellated sections, sinusoidal steel sections.

1. Introduction

Castellated I-beams (fig.1) are being extensively used in structural applications such as building floor systems, wide roof or hall covering systems, pedestrian bridges and other structures. Such beam types are made from standard profile I-sections cut in the web and welded lengthwise to form a new cross section with increased height and moment carrying capacity. Depending on the web-cutting pattern, the castellated beam produced may have hexagonal or circular web openings. The newly formed cross section is higher than the original one, but its moment carrying capacity is not proportionally increased due to problems that arise from the weakened web such as instability problems or problems due to stress concentration around the web openings leading to material failure.

During the last years especially for the main frames of single-storey steel buildings the use of corrugated web beams, mainly with sinusoidal corrugation (fig.2), has been increased very much. Due to the thin web of 1,5 mm to 3 mm corrugated web beams afford a significant weight reduction compared with hot rolled profiles or I-sections. In addition, there are also applications in heavy industrial buildings. Thanks to good distribution of mass within the cross-section, those girders can be characterized by high bending capacity with relatively low self-weight. Buckling failure of the web is prevented by the corrugation.

A lot of studies about the structural behavior of these sections and a number of different possible failure modes are presented in the past. Castellated sections are ruled by Eurocode EN1993-1, Annex N, while beams with sinusoidal webs by Eurocode EN1993-1-5, Annex D and also taking into consideration guidelines as the German Da – St- Ri015.

2. Problem Formulation (literature review)

2.1 Castellated Beams

The main initiative for producing and use Castellated I-beams is to suppress the cost of material by applying more efficient cross sectional shapes made from standard profiles in combination with aesthetic and architectural design considerations. The web openings can also be utilized for cross passing utility systems in building floors. The production cost for short span castellated beams is higher than the material economy. Thus, the majority of cases in which such beam types are employed are long span applications (with uniform distributed load), where the main consideration in the design is the moment carrying capacity of the member. Serviceability checks including flexural deflections under transverse loading are of high importance in the design.

The presence of web openings in steel beams introduces three different modes of failure at the perforated sections:

- shear failure due to reduced shear capacity,
- flexural failure due to reduced moment capacity,
- the 'Vierendeel' mechanism, due to the formation of four plastic hinges in the tee-sections above and below the web openings under the Vierendeel action, (transferring of lateral shear force across a web opening)

In general, both the shear and the moment capacities of the perforated sections may be readily assessed. However, the moment capacities of the tee-sections (above and below the web openings) under local moments are relatively difficult to be evaluated in the presence of co-existing axial and shear forces due to global bending action. Moreover, it is necessary to use plastic design to incorporate the formation of four plastic hinges in the tee-sections for an improved prediction of the load carrying capacity of the beams

Extensive experimental and numerical investigations were found in the literature highlighting the distortional buckling behavior of doubly symmetric steel I-sections mainly by Bradford [1, 2], Vrcelj and Bradford [3] and Zirakian [4]. However, very few tests were found in the literature on the distortional buckling behaviour of castellated beams. These tests were carried out by Zirakian and Showkati [5] and provided useful information in the form of failure loads, failure modes, load-lateral deflection curves and load-strain curves that could be used in developing finite element models. Finite element modelling could provide better understanding for interaction of lateral torsional and distortional buckling behaviour of castellated beams.

An overall review of the design recommendations shows that in general, there are two design methods in assessing the structural behavior of steel beams with web openings:

- Tee-section design. In this method, the perforated section is considered to be built up of two tee-sections which are separated by a distance according to the height of the web opening, and all the global actions are re-presented as local forces and moments. The structural adequacy of the steel beams depends on the section capacities of the tee-sections under co-existing axial and shear forces, and local moments.
- Perforated section design. In this method, the perforated section is the critical section to be considered in design, and the structural adequacy of the steel beams depends on the section capacities of the perforated sections under co-existing shear force and bending moment due to global actions. Simple shear moment interaction curves are often used, and thus the design procedure in this method is generally simple but the results are often very conservative.

Current design rules specified in the American Institute for Steel Construction AISC [6], Australian Standards [7], British Standards 5950 [8] and Eurocode 3 (BS EN 1993-1-1) [9].

Fig. 1: Castellated beams

Fig. 2:Single storey building. Corrugated web beams

2.2 Corrugated Web Beams (With Sinusodial Corrugation)

Corrugated webs are used to increase the shear stability of the webs of beams and girders and to eliminate the need for transverse stiffeners. A trapezoidally corrugated steel plate is composed

ISBN: 978-1-61804-071-8

of a series of plane and inclined sub-panels. The primary characteristics of the corrugated steel plates are negligible bending capacity and adequate out- of –plane stiffness.
The machines of latest generation are able to produce theses beams by a fully automated process. The web material comes from a coil. It is unrolled and cut to length automatically by the machine. A so called "corrugator" forms the sheet to a corrugated web. The flanges has been already prepared and stored in special flange baskets. After the running-in of the web and flanges into the welding station all members are moved to the correct position, are pushed together and are welded by the welding robots.
The bearing behavior of a beam with corrugated web is comparable with a lattice girder. Normal force and bending moment are carried by the flanges only. Due to the corrugation the web is not able to carry any normal stresses in the longitudinal direction of the beam. Therefore the web is loaded by shear force only. Lateral-torsional buckling of beam is verified by global out-of-plane buckling of the compression flange. The verification is a conservative assumption because the torsional stiffness is neglected. Produced sinusoidal corrugated webs have a small corrugation height compared with the width of flanges. Therefore the influence of transverse bending moments is negligible. The web loaded by shear force can fail due to yielding, local buckling and global buckling. It was found by Pasternak [10], testing, and FEM analysis, that no local buckling occurs for all actually produced beams with sinusoidal corrugated webs.
Beams with corrugated webs are ruled by the Eurocode EN 1993-1-5, Annex D (EC-3 2006). There used to be older standards as well, e.g. the German DASt-Ri 015 from 1990 [11]. But these standards deal about beams with trapezoidal corrugated webs only (EC-3 2006). Only by consideration of additional papers and expert opinions Pasternak [12, 13], it became possible to use this document for the calculation of sinusoidal corrugated webs. The EN 1993-1-5 [14] gives rules for both trapezoidal corrugation and sinusoidal corrugation. In the last years many tests and finite element simulations have been carried out.

3. Problem Solution- Frames analysis

3.1 Design Approach of Portal Frames

The skeleton of a typical single-storey building consists of three major elements: cladding for both roof and side-walls, secondary steel to support the cladding and form framing for doors and windows, and the main frame of the structure, including all necessary bracing. The cladding is supported on secondary members, which transmit the loads to main structural steel frames. An economic solution for these members (purlins and side rails) is provided by the use of cold-formed light sections. The loads are transferred from the sheeting onto the purlins and rails, which in turn are supported by a main structure-frame
Two steel portal frames have been developed as a viable alternative to traditional hot-rolled I-sections. The rafter and column members are formed from castellated sections, or corrugated web beams with sinusoidal corrugation, which are bolted at the eaves and apex joints, and connected to the foundation through plates. The span of the frames investigated is 20 m, with a constant eaves height of 6 m and a pitch of 10^o. The portal frames are delivered to site in sections cut to length and with connection holes at the factory as part of the manufacturing process. The spacing of the frames, determined by the overall economy of the building, is 5 m, while the total length of all structure is 50m. A cold-formed lipped Z-section could be used for the purlins. The purlins are assumed to be continuous over two spans of 5 m each and spaced at a maximum of 1.50 m centres. X-bracings in the plane of the roof were used to stabilize the frames. They were chosen over cross-bracings so that there is less obstruction in the bracing area. Another characteristic, which made this bracing system an obvious choice, is its ability to share any force equally between the members. All bracings were connected at the middle of the web of the purlins with a plate. X-bracings between the portal frames are used to give the appropriate rigid stiffness in this direction. The columns considered fixed on their base. The frames were designed to carry:

- <u>Dead load</u> (weight of purlin and roof cladding and members self-weight)
  The dead loads applied of the cladding and the self weight of the purlins is 0.15kN/m^2
- <u>Imposed loads</u>

i. Wind loading (normal to the inner or outer surface, or on the sloping roof of the structure, according to EC-1, acting either as a positive or a negative pressure), V_{ref}=27m/sec, Ground category I, $q_p(zc)$=1.23KN/m^2.

ii. Snow loading (according to EC-1), S_k=0.80KN/m^2, Altitude=550m , Area: Athens
iii. Temperature loading (according to EC-1)

- Seismic loads (are applied according to Greek Antiseismic Regulation)
  Ground Acceleration: A=0.16g (I)
  Seismic Behavior: q=1.00
  Foundation factor: θ=1.00
  Structure importance: γ_I=1.00
  Soil category: B

3.2 Software assumptions

INSTANT software is used for the analysis of the structure. Linear beam element with six degrees of freedom per node is used. Masses of the structure are calculated automatically from the vertical loads. (considering them distributed along the elements). Spectral dynamic analysis method (mode superposition) is used to compute the structure response due to seismic loads according the method of Greek Antiseismic Regulation 2003. Structure response due to seismic loads is calculated by complete quadratic combination of modes (CQC). Superposition in space is based on Newmark formulas, which means that the response S of the structure is the maximum of the following combinations:

S = 1.0Sx + 0.3Sy + 0.3Sz,
S = 0.3Sx + 1.0Sy + 0.3Sz,
S = 0.3Sx + 0.3Sy + 1.0Sz,

where Sx, Sy, Sz are the responses in the direction x, y, and z respectively.

The internal forces of a beam element in a point is {Fx, Fy, Fz, Mx, My, Mz}. The program calculates in every node of the structure the values of the 6 components of this vector. It is obvious, from the definition of the method, that the resulting magnitudes in every node do not coexist (they do not act at the same time). Defining a seismic combination (static loads with their factors and earthquake), all combinations of seismic loads are generated. In the case when are defined accidental eccentricities, the above combinations are repeated 4 times, one for each eccentricity direction (+X, -X, +Z, -Z). Load combinations are defined according to Eurocode 3.

Regulations: Eak 2003 (fek 781, June 18, 2003), Eurocode 3 – Part 1.1 (ENV 1993-1-1:1992), Eurocode 3 – Part 1.3 (ENV 1993-1-3:1996), Eurocode 3 – Part 1.1 (EN 1993-1-1:2005).

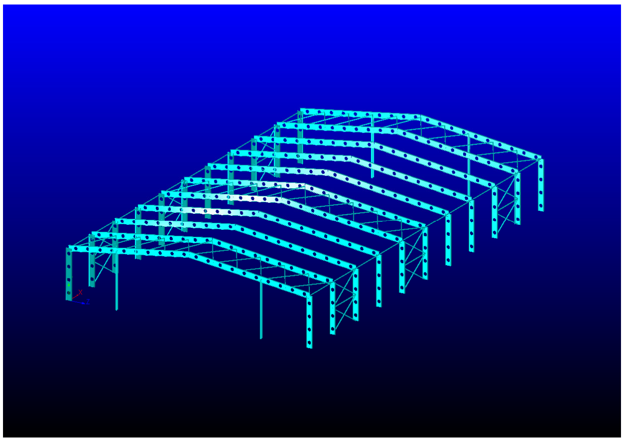

Fig. 3: 3-D model castellated beams

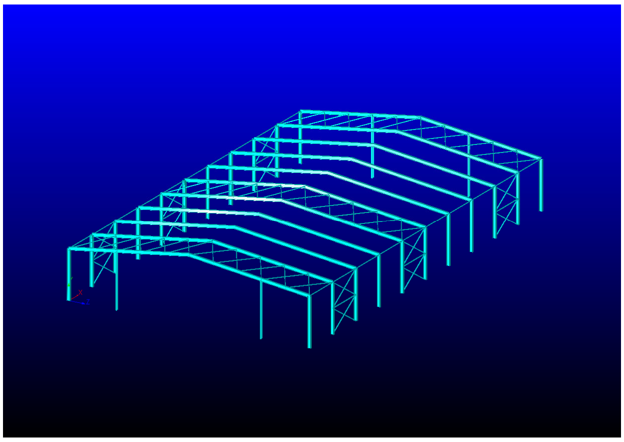

Fig. 4: 3-D model corrugated beams

3.3 Results of Analysis

In this part, are presented the results of the paper investigation.Two steel portal frames (fig. 3,4) are analyzed as a viable alternative to traditional hot-rolled I-sections. The rafter and column members are formed from castellated sections, or corrugated web beams with sinusoidal corrugation, which are bolted at the eaves and apex joints, and connected to the foundation through plates.

The adequate beam sections are presented in table one for the three portal frames. Table two shows the displacements of these frames, while in table three weight estimation for each frame is presented.

	Hot rolled I-sections	Castellated beams	Sinudoidal beams
Columns	IPE450	IPE400/600	SS357x300x12L
Girders	IPE450	IPE400/600	SS357x300x12L
Face columns	IPE220	IPE220	SS345x150x6L
Eaves girder	SHS80x8	SHS80x8	SHS80x8
Purlins	KMC-Z210-20	KMC-Z210-20	KMC-Z210-20
Side Rails	KMC-C140-20	KMC-C140-20	KMC-C140-20
X-Bracing roof	SHS55x4	SHS55x4	SHS55x4
X-Bracing vert.	SHS90x4	SHS90x4	SHS90x4

Table 1: Member sections

	Hot rolled I-sections	Castellated beams	Sinudoidal beams	displ. Limit
max horiz. disp.	2.10cm	2.00cm	1.75cm	H/150=4cm
max vert. disp.	3.30cm	3.32cm	2.90cm	L/200=5cm
max vert. disp.(imposed)	2.40cm	2.29cm	2.11cm	L/250=4cm

Table 2: Joint displacements

	Hot rolled I-sections	Castellated beams	Sinudoidal beams
Columns	10,250	7,100	7461
Girders	17,305	11,995	12605
Face columns	1,165	1165	745
Eaves girder	1,625	1,625	1,625
Purlins	3,955	3,955	3955
Side Rails	1,702	1,702	1702
X-Bracing roof	3,039	3,039	3039
X-Bracing vert.	1,668	1,668	1668
Totall Weight(Kgr)	40,709	32,249	32,800

Table 3: Weight Estimation

4. Conclusions

The subject of this paper is to present the castellated sections and the corrugated web steel sections as the main frames of industrial buildings. The key to the use of this section is the significant weight reduces in comparison to the structure with hot rolled profiles I-sections.

Castellated I-beams are made from standard profile I-sections cut in the web and welded lengthwise to form a new cross section with increased height and moment carrying capacity. The cases in which such beam types are employed are long span applications, where the main consideration in the design is the moment carrying capacity of the member.

Also, the use of corrugated web beams, mainly with sinusoidal corrugation, has been increased very much. Thanks to good distribution of mass within the cross-section, those girders can be characterized by high bending capacity with relatively low self weight. Buckling failure of the web is prevented by the corrugation. Due to improvements of the fabrication, are able to produce these beams by a fully automated process.

For the standard frame openings of industrial buildings the use of sinusoidal web beams and castellated beams resulted in the reduction of the weight of the structure of around 20-25 % (in comparison to the weight of the structure by using standard hot rolled I sections) depending on the loadings of the structure. In addition, the weight reduction increases when these beams are used for larger opening's, more than 30 m, instead of using a truss frame type.

The development of steel analysis and design programs, which included in their databases these sections, the fact that, regulations as ENV1993-3 gives design rules and the automatically fabrication, makes these section an ‘easy’ and economical solution for one storey steel structures

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