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BEHAVIOR OF SLENDER STEEL BOX GIRDERS WITH CORRUGATED WEBS SUBJECTED TO TORSIONAL MOMENT

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List of Symbols

A	Cross – sectional area .
A_0	Area enclosed by the centerline of walls along member (flanges and webs).
a	Inclined panel width of a trapezoidal corrugated web.
$B_{\bar{w}}$	Bi-moment acting on the cross – section.
b, b_a, b_h	Length of horizontal fold width of one corrugation profile.
b_{fl}	Flange width.
d	Horizontal projection of the inclined corrugation panel width .
C	Center of local coordination of undeformed cross-section.
$\bar{C}$	Center of local coordination of deformed cross-section.
C_{averge}	The average outstanding distance of flange from web corrugation.
C_1	Min flange outstanding distance from web corrugation.
C_2	Max flange outstanding distance from web corrugation.
C_w	Warping section constant of a girder with flat web.
C^*_w	Warping section constant of a girder with corrugated web.
d_2	Length of corrugation width (b + a).
D_{xy}	Twisting stiffness.
E	Young's modulus of elasticity.
E_{tan}	Tangent modulus ($E / 100$) in post yield range.
f_y	Yield stress.
f_{yf}	Yield stress of flange material.
f_{yw}	Yield stress of web material.
G	Shear modulus.
G	Center of gravity of undeformed cross-section.
$\bar{G}$	Center of gravity of deformed cross-section.
h	Height of the PBGCW.
h_w	Height of the web of PBGCW.
I_{y1}	Second moment of area of corrugation section about y1-axis

I_{y2}	Second moment of area of corrugation section about y2-axis
I_{x-x}	Second moment of area of PBGCW about x-x axis.
I_{y-y}	Second moment of area of PBGCW about y-y axis.
I_w	Normalized warping constant.
ϕ	Angle of rotation of PBGCW in z-direction or Angle of twist
$\grave{\phi}$	Twisting angle per unit length of PBGCW.
ϕ'	End restraint of free warping. (First derivative of the rotational displacement function)
ϕ''	Second derivative of the rotational displacement function (cross-section free constant).
ϕ'''	Third derivative of the rotational displacement function (cross-section constant freely).
h_r	Corrugation depth.
J	Torsional constant.
K_s	Buckling coefficient.
L	Girder span.
L_{fold}	Projection length of one corrugation
M_t	Torsional moment.
M_{cr}	Critical moment.
M_y	Max yield moment of cross-section.
M_{yf}	Transverse yield moment of flange of PBGCW ($= B_i . h_w$).
M_{xy}	Twisting moment per unit length in the diaphragm.
M_f	Flange plastic moment capacity.
M_u	Ultimate moment of cross-section .
P_u	Ultimate partial compressive edge loading.
N_{cr}	Buckling load.
BGCW	Box girder with corrugated web.
BGFW	Box girder with flat web.
R_z	Longitudinal rotation about Z axis.

r	Radius of gyration.
r_τ	Radius of gyration of the cross-section about strong axis.
S	Unfolded length of one corrugation.
S_w	Warping statical moment.
T	Torque force applied on PBGCW.
T_{YZ}	Shear stress in y-z plane.
t	Element thickness.
t_{fl}	Flange thickness.
t_w	Web thickness.
t_s	Wall thickness along member
X,Y,Z	Cartesian coordinates.
URES	Resultant displacement.
θ	Slope angle of inclined corrugated part.
λ_τ	Torsional slenderness ratio of PBGCW.
σ_{zz}	Warping stresses in flanges.
$U_{x,y,z}$	Displacement in the x,y,z directions ,respectively.
$S_{Y_{sec}}$	Biggest section modulus.
$S_{X,Y,Z}$	Normal stress in the x, y, z directions, respectively
W	Work done by external loads.
W_{xy}	Twist per unit length in the diaphragm.
W_{ni}	Normalized unit warping at point *i*
W_{nj}	Normalized unit warping at point *j*
μ	Possion's ratio.
τ_y	Yielding shear stress of steel (according to von-Miess criterion= $\sigma_y / \sqrt{3}$)
λ_τ	Torsional slenderness ratio.
Π	Total potential.

CHAPTER 1

INTRODUCTION

1. Introduction

Modern techniques of fabricating box girders of steel elements have resulted in an increased use of box girders with corrugated webs in steel structures. New generation of optimized steel girders is developed by the advances in structural and fabrication technology. One of the developments in structural steel during the past few years has been the usage of corrugated webs in box beams. Economical design of steel girders normally requires thin webs. The use of corrugated webs is a possible way of achieving adequate out-of-plane stiffness without using stiffeners. Engineers have long realized that corrugates in webs increases their stability against buckling and can results in very economical designs. Common Corrugation profiles used in steel beams are trapezoidal, which is the most frequently used and sinusoidal which is used sometimes in structures that has special requirements to avoid fatigue failure.

Comparing corrugated webs girders with those with stiffened flat webs reveals that trapezoidal corrugations in the web enables the use of thinner webs and corrugated web box-Beams eliminate costly web stiffeners. These beams have 10 to 20% less weight than current traditionally stiffened girders with flat webs.

Slender steel box girders with corrugated webs are fabricated from an arbitrary numbers of flat plates joined by welding along their edges, so that the cross- section consists of a set of connected thin rectangles. When a plate box girder with flat webs does not have an adequate lateral support, its strength is governed by its resistance to torsional buckling modes; one of them is lateral torsional buckling.

Plate box girders with corrugated webs have been recently used in Europe, Japan and other countries. Extensive studies have been conducted on this type of girders under different types of acting loads except under pure torsional moment. Most of steel design codes introduce very approximate formulas for limited cases to calculate the torsion or lateral torsional buckling of box girders with flat or corrugated webs, such as LRFD 1999, EC3 while other codes do not address the subject at all, such as the Egyptian code 2001.

This thesis focuses on plate slender steel box girders with corrugated webs under pure torsional moment, since its behavior under torsional moments has not been studied properly.

A parametric study is conducted primarily using non-linear finite element (F.E) analysis to figure out the most effective geometrical parameters under this case of loading. Additionally, geometrical models are presented for the same problem and material and geometric nonlinearities are incorporated within the F.E. model. Applications are carried out on various cross-sections of Box girders to calculate the critical torsional and warping stresses.

A mathematical model is presented to theoretically depict the ultimate torsional strength as well as the overall torsional stiffness of these girders and is verified with the finite element results.

An additional study is concerned with the different parameters that affect the torsional resistance of cross section of BGCW in order to get a empirical equation from the output of the finite element study including diverse affecting parameters.

The finite element model with optimum cross section configurations for BGCW are compared with the corresponding conventional box girders with flat webs under pure torsional moments to figure out which have higher torsional moment capacity and resistance to warping stresses .Answering how much gain in torsional strength we can get by using BGCW .

2. Contents

This thesis consists of seven chapters and is arranged as follows:

2.1Chapter 1: Introduction

This chapter contains a general introduction to the research and a description of the thesis, as well as a brief content of each chapter.

2.2 Chapter 2: Background and Literature Review

This chapter contains a general introduction to the research, and discusses the concept and historical background of the different methods of analysis of steel I-beams with corrugated webs, steel box girders with corrugated webs and their behavior especially in torsion as well as torsional buckling modes. Focusing on the analysis and behavior of curved box girder bridges showing the differences between stresses taking into account warping and those calculated by ignoring warping to evaluate the effect of warping stresses in curved girders.

Cross-section classification for BGCW (width –thickness ratios of the elements used) describes how sections are classified as plastic, compact, semi-compact, non-compact or slender-element sections and gives the limiting proportions of the elements by which these classifications are made.

2.3 Chapter 3: Mathematical Model

This chapter contains a general variation formulation to perform analysis of bifurcation of non prismatic beams with open thin walled sections, having at least one plane of symmetry. It presents the non-linear flexural / torsional analysis of open thin- walled sections, which geometrically satisfies the basic conditions of non-linear properties of cross section.

By using the total potential energy theory, a general formulation is derived for BGCW. Then by using the simplified orthogonality conditions for symmetric cross-sections and the total potentional energy of the plate girder is derived. The first and second variations of the total potentional energy are formulated, and the section properties are taken into consideration.

The purpose of the mathematical model is to seek for an approach to calculate the maximum torsional stresses which the section of a box girder with corrugated web can carry. The mathematical model is introduced to calculate, using simple steps, the ultimate torsional strength and the overall torsional stiffness of such girders.

2.4 Chapter 4: Analysis and Parametric Study of Box Girder with Corrugated Web under Pure Torsion Moment.

This chapter includes non- linear finite element modeling for box girders with corrugated webs under torsional loading. This model considers both material and geometrical non-linearities. Based on the present parametric study, the best ratios were chosen for the tested geometrical parameters in the study. The flange width to thickness ratio (b_{fl} / t_{fl}), the web height to thickness ratio (h_w / t_w), the corrugation depth to flange width ratio ($h_r / 0.5b_{fl}$), and horizontal fold width to web thickness ratio (b / t_w) . An overall comparison is made between the torsional stiffness of the box girder with corrugated web (T / ϕ) obtained from mathematical equation with that obtained from the finite element method.

2.5 Chapter 5: Empirical Equation of Steel Box Girder with corrugated Web subjected to torsional Moment (Multi-Linear Regression Analysis).

This chapter focuses on the effect of the corrugation of the web on the behavior of the box girder cross section and its influence on the girder resistance to pure torsional moment. Based on the results obtained from the finite element method for four groups of models, the most effective parameters of the box girder with corrugated web under pure torsional moment are investigated. The different parameters that affect on the behavior of this type of girders and its torsional resistance are scrutinized.

A multi-linear regression analysis using mathematical software is performed on the results obtained from the finite element analysis. This analysis is used to develop simple expression - empirical equation -for the effect of various parameters influencing on that affect on the behavior of box girder with corrugated webs (**BGCW**) under pure torsional moment. The moment is applied at the mid- span of the beam and the moment capacity is normalized as the ratio of torsional moment - to- yield moment and torsional moment - to- ultimate moment.

The parametric equation is found agreeable with the result obtained from the finite element analysis in pervious chapter (4), discussing the influence and margins of the different effective parameters of four groups of girders. The influence of flange slenderness ratio, web slenderness ratio, flanges outstand ratios, and corrugation floppiness are assessed.

The torsional resistance of cross section slenderness of **BGCW** λ_τ - to flange outstanding ratio $h_r / 0.5b_{fl}$, flange width to thickness ratio b_{fl} / t_{fl}, web slenderness ratio h_w / t_w, horizontal fold width to web thickness ratio b / t_w are discussed.

2.6 Chapter 6: Comparison between Box Girders with Corrugated Webs and Conventional Box Girders with Flat webs under Torsional moment.

The chapters contains building a finite element model for box girder with flat web and compare it with a corresponding models of plate box girder with corrugated web.

The main purpose of this chapter is to highlight the answering the most important question in the whole issue, do plate girders with corrugated webs have higher resistance to torsional moment than the conventional plate girders.

The results obtained are used to compare the behavior of plate box girders with flat webs (**BGFW**) under torsional moment only with plate box girders with corrugated webs under the same loading condition and to explore the change of the ultimate capacity of the girders with the change of the different parameters studied.

2.7 Chapter 7: Summary, Conclusions and Future Developments

This chapter includes a brief summary of the present research, answering the most significant issue , do plate box girders with corrugated webs have higher resistance to torsional moment than the conventional box girders with flat webs?, and how much gain in torsional strength can be obtained. Based on the this study, it can be concluded that plate girders with corrugated webs have higher torsional and warping moment capacity than conventional girders with flat webs and are recommended for use specially in curved bridge girders.

Optimum values for flange width to thickness ratio, web height to thickness ratio, corrugation depth to flange width ratio, horizontal fold width to web thickness ratio were found. The conclusions drawn from this thesis are indicated and recommendations for further researches are suggested.

2.8 Appendices

Appendices A, B and C contain the cross section classification, the complete mathematical calculation of the overall torsional stiffness for all box girders with different geometrical properties and define the finite element program output results .

CHAPTER 2
BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

Economical design of steel girders normally requires thin webs. The use of corrugated webs is a possible way of achieving adequate out-of-plane stiffness without using stiffeners. Engineers have long realized that corrugation in webs increase their stability against buckling and can result in very economical designs. The web corrugation profile can be viewed as uniformly distributed stiffening in the transverse direction of the beam.

When girders with corrugated webs figure (2-1) are compared with those with stiffened flat webs, it was found that trapezoidal corrugation in the web enables the use of thinner webs. Hence, using corrugated web I-Beams or box girder can eliminate costly web stiffeners.

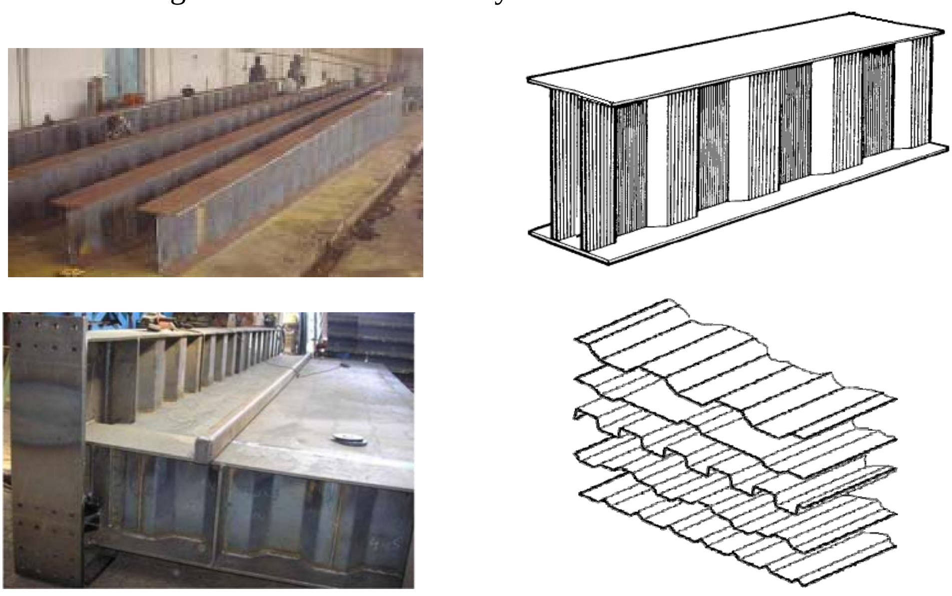

Figure 2-1: Girder with Corrugated webs
-a: Girders or box girders with corrugated web steel
-b: Corrugated sheets profile or / manufacturing.
(http://lightweightbeam.com/productie.html)

Although the advantage of the corrugation is not easy to describe in general term, Masami Hamada (1984) found those beams to have 9 to 13% less weight than current traditionally stiffened girders with flat webs. As well and higher load carrying capacity, corrugated web in box section of girders provide a high strength-to-weight ratio. Furthermore, erection cost is reduced, since the corrugation in the web provides a higher resistance against bending about the weak axis, none of the auxiliary lifting equipment normally needed is required.

2.2 Historical Background

2.2.1 Girder with Corrugated Webs

Plate box girders are used mostly in bridges and industrial buildings. In its simplest form, a plate box girder is built using two flange plates welded to a web plate to form an “II” section. For large spans/loads, figure (2-2) shows the use of deep plate girders results in slender webs, thus, making the web buckling problems more relevant in design. This is why the webs in plate girders are often reinforced with stiffeners to allow for the use of thin webs.

The stiffeners in most cases are designed to divide the web into panels supported along the stiffener lines. Welding of stiffeners, however, has two disadvantages; the first is the high fabrication cost, and the second is the reduced fatigue life. The designer’s task is to find a combination of plate thickness and stiffener spacing that optimizes the girder’s weight and at the same time reduce the fabrication cost.

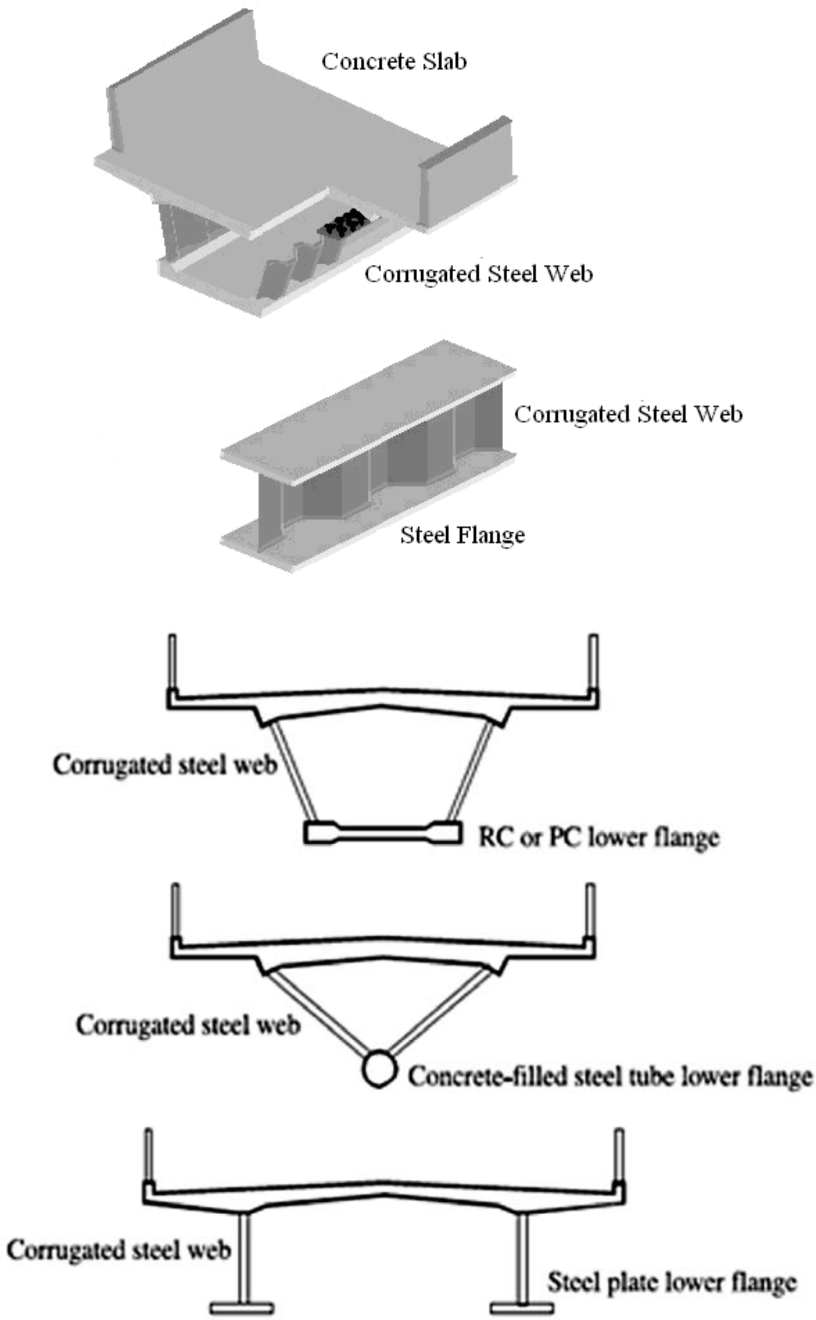

Figure 2-2: Schematic representation of bridge girders with corrugated steel webs, **Sayed -Ahmed E.Y** (2001)