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EFFECT OF ORTHOTROPY ON DISTORTIONAL BEHAVIOUR OF LAMINATED COMPOSITE TRAPEZOIDAL BOX GIRDER

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Abstract: *Box girders, often used as basic components in modern bridge structures. High torsional stiffness of box sections lead to better stability and eccentric load distribution characteristics. The combination of FRP and box-girder is ideal in light-weight long span bridges. Analysis for longitudinal bending and pure torsion can be made by means of elementary theories while distortional effects in the box girders cannot be predicted by these theories. The distortional action of the box girder consists of (a) transverse deformation and (b) longitudinal deformation (warping). Laminated composites, which are of orthotropic nature and earlier limited to aerospace applications, are gradually being applied in structural applications. The orthotropic nature of FRP has to be taken into consideration in all these analysis. The effect of orthotropy due to fiber orientations is studied by changing the orthotropy ratio of different elements of the FRP single- cell trapezoidal box beam subjected to the distortional loading. All these studies are carried out by using the FEM package ANSYS.*

Keywords: *FRP Box Girder, Distortional Behaviour, Distortional Stress, Warping Stress, Orthotropy.*

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INTRODUCTION

Road transportation system is the basic infrastructural facility needed for any country to achieve self sufficiency by having a smooth flow in demand and supply chain. To maintain all-weather transportation system, bridges have a special importance. Modern roads can be said to be a measure of country’s development. With an ever-increasing demand for expansion of highway networks, to cater for increased traffic, new challenges have come up to researchers and designers to provide best innovative bridge structures. It has led to numerous improvements leading to the development of various types and kinds of bridges.

The cross- section of box girder may distort under torsion effects with distortion as the main source of warping stress. The additional flexural stress due to distortion of the cross section may be of the same order of magnitude as flexural stress. It is therefore essential to take into account the distortion behaviour of box members when it is thought likely to occur in addition to a consideration of flexural and torsion effects that may appear.

In recent years, advanced composite materials in the form of fibre-reinforced plastics (FRPs) have found extensive application in large structures, specifically in bridges. Since the advantages of composite materials were well established by aerospace industry, it has been proposed that composites may address some of the problems associated with deficient infrastructure. Composites are primarily attractive because of their high strength- to-weight, and stiffness-to-weight ratios, and better durability characteristics.

Fibre reinforced polymer (FRP) composites were first introduced in civil infrastructure applications in the early 1950s as alternative measures for reinforcing concrete. However, FRP composites were not perceived as materials likely to make an impact on infrastructure applications such as bridges. There was no significant progress in this area until mid-1990s when civil engineers started to look for materials which are lightweight and resistant to environmental degradation. At the beginning of new millennium, deterioration of concrete/steel structures has become an important issue in the civil engineering community.

Growing maintenance and durability problems in transportation infrastructure have led researchers to explore laminated composite FRP box-girders in bridges. The external loads in such bridges cause essentially membrane forces in the elements of the box-girder. The in-plane properties of FRP can be tailored to adapt and resist efficiently such a state of stress. High torsional stiffness of box sections lead to better stability and eccentric load distribution characteristics. The combination of FRP and box-girder is ideal in light-weight long span bridges. The potential for application of FRP box section has been particularly high in deployable bridges used in defence, temporary bridges, emergency replacement bridges and short span light loaded vehicular bridges etc.

2. Literature Review:

Khalifa et al. (1996) used FEM software for the analysis of FRP cable-stayed pedestrian bridge. Chamis and Murthy (1989) presented a step by step procedure for the preliminary design of fibre composite box-beam, based on approximate closed form equations. They did not considered factors such as shear-lag, distortion. Rehfield et al. (1990) and Wu and Sun (1992) have developed a theory for the study of non-classical behaviour of thin walled composite beams. Upadyay and Kalyanaraman (2003) considered the various factors that affect the laminated FRP box-girder behaviour and developed a simplified, approximate and computationally efficient procedure for the analysis of single cell FRP box-girder bridges . F. Shadmehri et. al (2007) studied flexural torsional behaviour of single cell laminated composite box beam using extended Hamilton’s Principle. Upadyay and Kalyanaraman (2010) derived a procedure for a generalised optimum design of laminated composite FRP box-girder bridges, using genetic algorithms (GA). The formulation of the optimum design problem in the form of objective function and constraints presented. Husham Almansour (2010) had carried out efficient performance based design of laminated FRP box girders for short span bridges.The lamina formed from E-Glass fibre and Vinylester Matrix. Kundan Mishra et al (2012) had derived flap deflection, lag deflection & twist of a rectangular composite box beam (Carbon Epoxy) using FEM software ANSYS. Dabrowski (1968) established a more rigorous theory when he developed the governing equation for box girder distortion and provided solutions for several simple cases so that the distortional behaviour of box girders could be understood. Wright and Robinson (1968) developed an analysis based on an analogy with the theory of beams on elastic foundation for box girders of deformable cross section. Chapman et al. (1971) conducted a finite element analysis on steel and concrete box-girder bridges to investigate the effect of intermediate diaphragms on the warping and distortional stresses. D.S.Prakash Rao (1985) investigated the effect of cross section as well as the warping restraint, span and the type of loading on the behaviour of a box girder under eccentric load. Chidolue, Chinenye A. et al (2012) was derived the differential equation for distortional analysis of thin-walled doubly symmetric (rectangular) box girder structure using Vlasov’s theory. Numerical study was carried out using the derived equation.N.N. Osadebe and C.A. Chidolue (2012) had shown response of double cell mono symmetric box girder structure to torsional-distortional deformations. The torsional and distortional deformations of the double cell cross sectional profile were compared with those of the mono symmetric cross sectional profile.

There are very limited studies in the field of laminated FRP box girder.Only very few researchers have done work in the field of distortional behaviour of thin walled box girders.There is not detailed study available on distortional behaviour of laminated composite FRP box girder. The present state of art has motivated the interest to contribute towards a better understanding of distortional behaviour due to orthotropy nature of laminated composite FRP Trapezoidal box girder.

3. Distortion of Box Girder:

The distortional behaviour of a box girder is dependent on the manner in which the external torque is applied to the girder (Tom and Todd, 2002). A torsional load, either comprised of a vertical couple or a horizontal couple, can be modeled as a uniform torsional component superimposed on a distortional component, as demonstrated in Figs.1 and 2. The rectangular thin-walled box has a respective depth and width of h and b. Each couple can be modeled by the uniform torsional components given in Fig. 1(b) or 2(b) superimposed on the distortional components given in Fig. 1(c) or 2(c). Although the boxes in Figs. 1(a) and 2(a) are subjected to the same magnitude of torsion (m_T), the resulting distortional stresses are opposite in direction since the distortional loads shown in Figs. 1(c) and 2(c) are opposite. The pure torsional components shown in Figs. 1(b) and 2(b) generate a uniform Saint-Venant shear flow along the circumference of the box girder cross section, and warping stresses due to this torsional component are usually negligible. However, significant distortional warping stresses may be induced due to the distortional loads shown in Figs. 1(c) and 2(c) if the box is not properly braced.

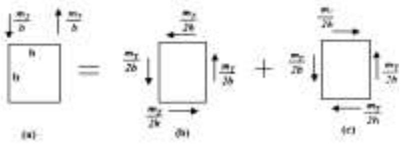


Fig.1. Torsion and Distortion of Rectangular Box Girder Due to Vertical Forces

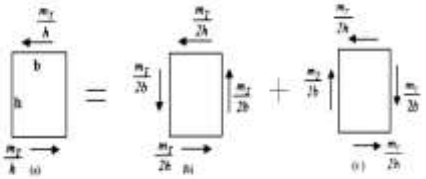
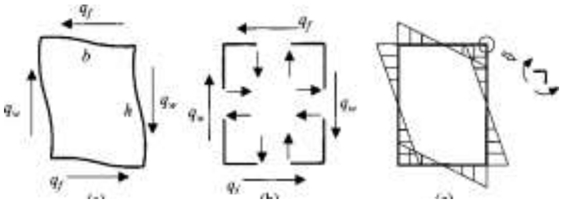


Fig.2. Torsion and Distortion of Rectangular Box Girder Due to Horizontal Forces



(a) (b) (c)

Fig.3 Out-of-plane Distortional Stresses in Box Girders

3.1 Out-of -Plane Distortional Stresses:

The transverse effects of distortional components as shown in Figs. 1(c) and 2(c) are generally resisted by both in-plane and out-of-plane shears in the girder plates. These two shear components result in different distortional stresses. Fig. 3(a) shows the typical distorted shape of the box girder that result in out-of-plane bending of the plate components. Fig. 3(b) shows the shears that develop in the through-thickness direction as a result of the distortion. The distortional loads on the flanges and webs are partially resisted by these through-thickness shears that develop in the plates. Out-of-plane bending stresses are induced with the corresponding moments shown Fig. 3(c).

3.2 In-Plane Distortional Warping Stresses:

Distortional loads are also partially resisted by the in-plane shears that develop on the cross sections of the individual plates, as demonstrated in Fig. 4(a). The large arrows represent the in-plane shears that resist the distortional loads that are represented by the small arrows on the

girder plates. The individual plates will experience in-plane bending from these shears, and longitudinal bending stresses may be induced on the cross section. The longitudinal bending stresses are known as the distortional warping stresses, and a typical distribution of the warping stresses in a trapezoidal box girder is illustrated in Fig. 4(b)

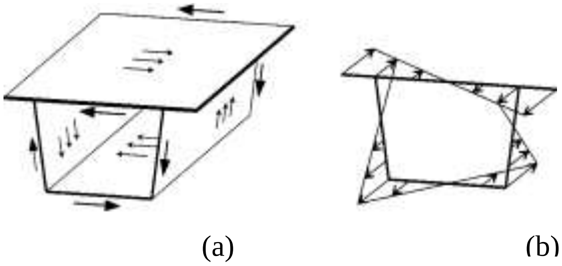


Fig.4 In-plane Distortional Warping Stresses in Box Girders

4. Validation Study:

The FEM model for the distortional analysis of isotropic steel box girder is validated by comparing the results obtained from the BEF analogy for rectangular box girder. For this purpose the following section is considered.

Top flange width = 3048 mm
Bottom width of flange = 3048 mm
Depth of girder = 2438.4 mm
Top and bottom flange thickness = 9.525 mm
Web thickness = 9.525 mm
Length of girder = 30480 mm

The material properties of the above section are as follows

Young's modulus, E = 206844 N/mm^2
Poisson's ratio, ν =0.3

A steel plate diaphragm of 9.525 mm is provided at each end of box girder.

Boundary conditions:

1. At Z=0; Ux, Uy, Uz displacements are restricted and rotations are allowed. 2.At Z=L; Ux and Uy are restricted and Uz and all three rotations are allowed.

The model is modeled in ANSYS software and the element taken for the validation is SHELL Elastic 4 node 63. A load of 22241N concentrated torsional load acting midway between diaphragms is applied

Table 1 Comparison of BEF analogy results with ANSYS results

Type of stress	BEF Analogy	ANSYS (11.0)	% Error
Distortional stress	3.30	3.471	4.9 %
Warping stress	7.325	7.502	2.33%

From the above table it is clear that there is good agreement between the results obtained from FEM model with the BEF analogy.

5. Convergence Study:

For convergence study , trapezoidal laminated composite box girder with 0° fiber orientations is considered.

Top flange = 500 mm
Bottom flange = 300 mm
Depth of girder = 300 mm
Thickness of flanges = 3mm
Thickness of web = 1.5 mm
Length of girder = 3000 mm

Material properties of Graphite Epoxy are used. Torsional load of 500 N is applied at the centre between supports.

Boundry condition:

1. At Z=0; Ux, Uy, Uz displacements are restricted and rotations are allowed. 2. At Z=L; Ux and Uy are restricted and Uz and all three rotations are allowed.

The following mesh sizes were studied: 50 mm, 100 mm, 150 mm , 200 mm

Table 2 Converegence of results with meshing size

Mesh size	Distortional stress	Warping stress
50	15.6	14.73
100	19.006	18.005

150	23.745	22.427
200	28.65	26.33

It is observed that an optimum level was reached in case of meshing size of 100 mm and the same has been used in all the numerical studies.

6. Problem under Study:

For this study , trapezoidal laminated composite box girder section is considered.

Width of top flange = 500 mm
Width of bottom flange = 300 mm
Depth of girder = 300 mm
Thickness of flanges = 3 mm
Thickness of web = 1.5 mm
Length of girder = 3000 mm

Material properties of Graphite Epoxy are used. Torsional load of 500 N is applied at the center between supports.

6.1 Boundry condition:

1. At Z=0; Ux, Uy, Uz displacements are restricted and rotations are allowed. 2. At Z=L; Ux and Uy are restricted and Uz and all three rotations are allowed.

6.2 Material Properties:

The properties of the graphite epoxy material used are as under:

Table 3 Material properties of graphite epoxy

Constants	Values
Longitudinal Elastic modulus, E_{11} (N/mm^2)	145000
Transverse Elastic modulus, E_{22} (N/mm^2)	16500
Shear modulus, G_{12} (N/mm^2)	4480
Poisson's ratio, $\nu 12$	0.314
Poisson's ratio, $\nu 21$	0.037

6.3 Loading:

In present studies a concentrated torsional load acting midway between supports is applied . Here a simply supported box beam with its loading is shown in Fig 1.4.2

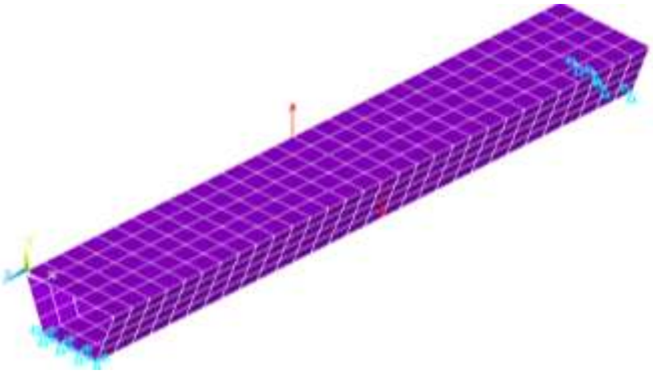


Fig.5 Finite Elememt Model

7. Results and Discussion:

In FRP box girder every element is treated as an orthotropic element because of the different fiber orientations. In the present study the variations of the distortional and warping stresses by changing the fiber orientations of the top flange, bottom flange and web thickness is studied. The cross-sectional details are as mentioned in section 6 and properties are taken from the Table 3 . The thickness of each layer for all cases taken here is same. In order to find the orthotropy ratio D_{11}/D_{22}, the D matrix is needed for each laminate. The Table 4 and Table 5 show the details of the orthotropy ratio and fiber orientations of the flanges and webs respectively.For flanges seven types of orthotropy ratios are taken and for webs five orthotropy ratios are taken.

Table 4 Flange construction for box girder for different orthotropy ratios

Lay up sequence of flange	Ortotropy ratio (D11/D22)	Fibre orientations, θ (above mid plane)
1	8.79	(0,0,0,0,0)s
2	1.55	(± 45,0 90, 0)s
3	1.36	(90, 45, -45, 0, 90)s
4	1	(45,-45,45,-45,45)s
5	0.74	(0, ± 45,90,0)s
6	0.51	(0,90,0,90,0)s
7	0.114	(90,90,90,90,90)s

Table 5 Webs construction for box girder for different orthotropy ratios

Lay up sequence of web	Orthotropy ratio (D11/D22)	Fibre orientations, θ (above mid plane)
1	8.78	(0,0,0,0,0)
2	2.19	(0, 90 ,90, 90,0)
3	1	(45,-45,45,-45,45)
4	0.46	(90,0,90,0,90)
5	0.114	(90,90,90,90,90)

7.1. Effect of Top Flange Orthotropy:

A) Case I:

For observing the effect of top flange orthotropy on the distortional stresses of the FRP box girder, fiber orientations of webs and bottom flange are kept at 0 degree orientations and orthotropy ratios of top flange are varied.

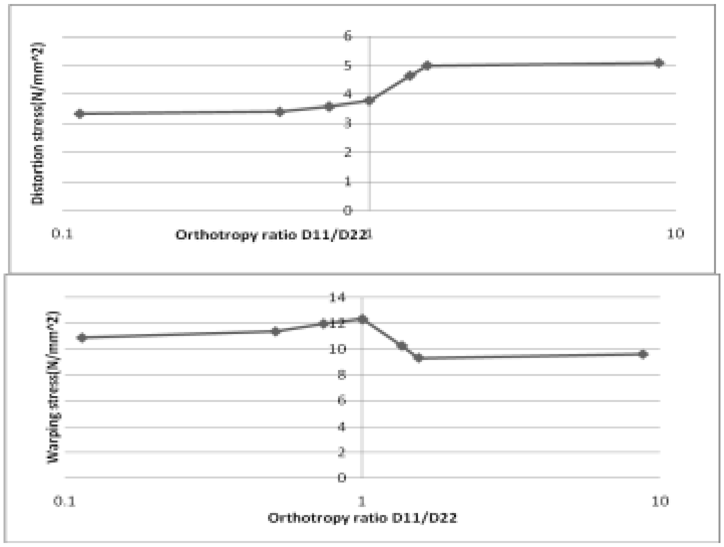


Fig.6 Variation of Distortion stress and Warping stress with D11/D22 of top flange.

For orthotropy ratios below 1,distortional srtess remains almost constant and from orthotropratio 1 to 1.55 , distortional stress increases and further it becomes almost constant.For orthotropy ratio below 1 , there is slight increase in warping stress and then warping stress reduces up to orthotropy ratio 1.55 and then it almost become conastant.

B) Case II: Fiber orientations of webs and bottom flange are kept at 90 degree orientations and orthotropy ratios of top flange are varied.

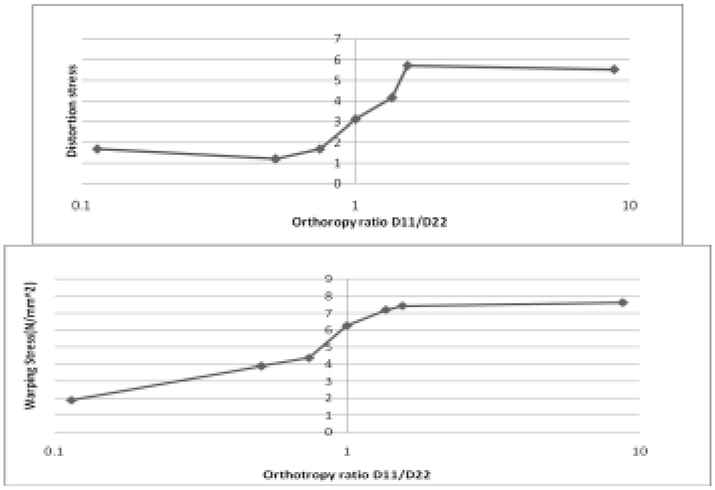


Fig.7 Variation of Distortion stress and warping stress with D11/D22 of top flange.

For orthotropy ratio 0.114 to 0.51, there is slight reduction in distortion stress and then up to orthotropy ratio 1.55 , warping stress increase as orthotropy ratio increases and then afterwards warping stress become constant. Warping stress increases with increase in orthotropy ratio up to orthotropy ratio 1.55 and then warping stress becomes almost constant for further orthotropy ratios.

From case I and case II , it is observed that major changes are taking place in vicinity of ,

$D_{11}/D_{22} = 1$.

<u>7.2. Effect of Web Orthotropy:</u>

A) Case I : Fiber orientations of top flange and bottom flange are kept at 0 degree orientation and orthotropy ratios of web are varied.

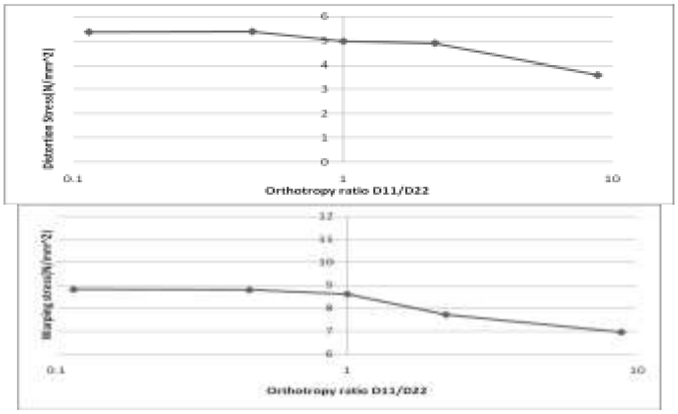


Fig.8 Variation of Distortion and Warping stress with D11/D22 of web

For orthotropy ratio below 1, distortortion stress is almost constant while for orthothotropy greater than 1, distortion stress is on lower side for higher orthotropy ratios.For orthotropy ratio beyond 1, warping stresses decreases with increase in orthotropy ratio and becomes almost constant for orthotropy ratio below 1.

B) Case II : Fiber orientations of top flange and bottom flange are kept at 90 degree orientation and orthotropy ratio of web are varied.

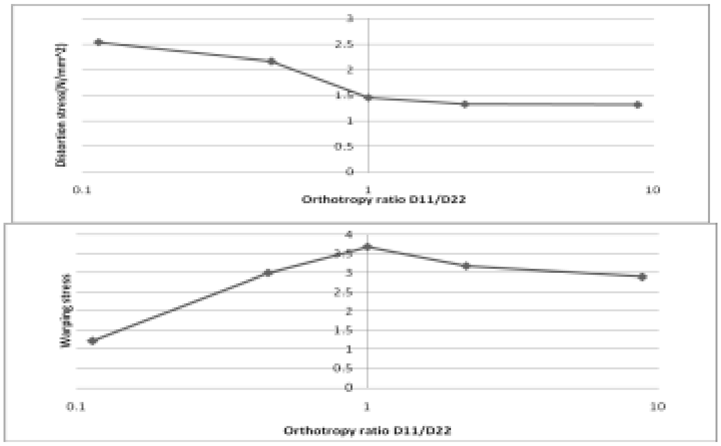


Fig.9 Variation of Distortion stress and Warping stress with D11/D22 of web

For orthotropy ratio below 1, there is reduction in distortion stress and after orthotropy ratio 1, distortion stress becomes constant. Warping stress is sensitive and increases for orthotropy ratio below 1 and for orthotropy ratio greater than 1, warping stress become almost constant.

7.3. Effect of Bottom Flange Orthotropy:

A) Case I: Fiber orientations of webs and top flange are kept at 0 degree orientations and orthotropy ratio of bottom flange are varied.

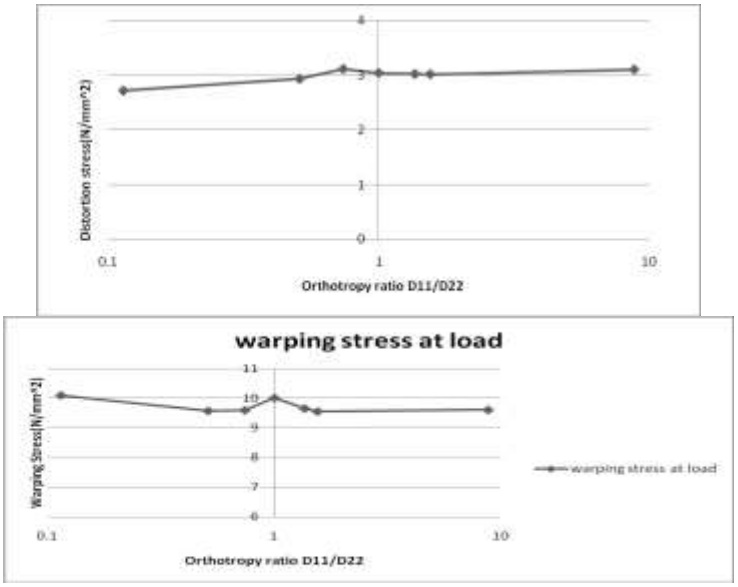


Fig.10 Variation of Distortion stress and Warping stress with D11/D22 of bottom flange

Here is not too much change in warping and distortional stress with orthotropy ratio of bottom flange.

B) Case II: Fiber orientations of webs and topflange are kept at 90 degree orientations and orthotropy ratio of bottom flange are varied.

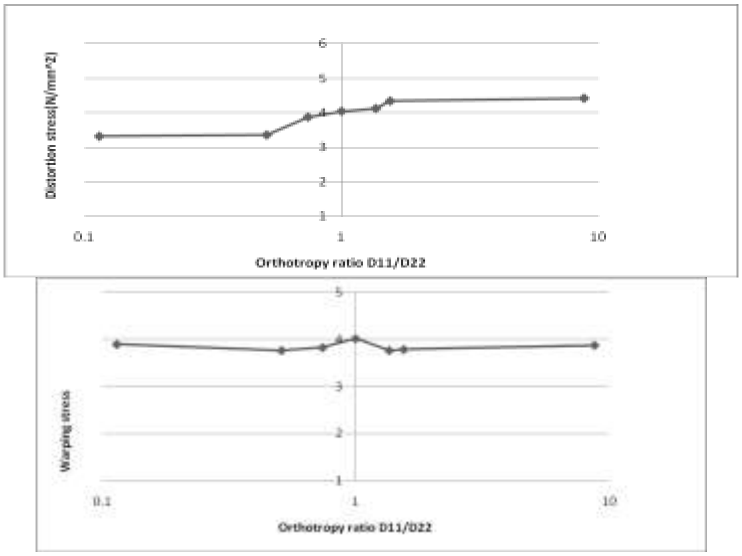


Fig. 11 Variation of Distortion stress and Warping stress with D11/D22 of bottom flange

From case I and case II, it is observed that the distortion and warping stresses are insensitive to bottom flange orthotropy.

8. CONCLUSIONS:

1) Top flange orthotropy:

i) Major variation in stresses occurs in vicinity of orthotropy ratio (D11/D22) equal to 1.

ii) For lower and higher orthotropy ratios, stresses almost remain constant.

2) Web orthotropy:

i) When fibers in top flange and bottom flange are kept at 0 degree orientation and orthotropy ratios of web are varied, distortortion stresses and warping stresses are almost constant for orthotropy ratio below 1 while for higher orthothotropy ratio, distortion stresses and warping stresses are on lower side.

ii) When fibers in top flange and bottom flange are kept at 90 degree orientation and orthotropy ratios of web are varied, for higher orthotropy ratios (greater than1) distortion and warping stresses are almost constant but these stresses are on lower side than stresses for orthotropy ratio below 1.

3) Bottom flange orthotropy:

Distortion and warping stresses are not so sensitive to bottom flange orthotropy.

4) Hence it is observed that distortional stress and warping stress can be controlled by changing orthotropy ratios of top flange and web.

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