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Theoretical Study on Forming of Twisted T-section Longitudinals (1st Report) †

- Investigation from the Aspect of Inherent Strain -

Madhu S NAIR * and **Hidekazu MURAKAWA** **

Abstract

Twisted 'T' section longitudinals, like curved plates, are formed in shipyards using a combination of mechanical methods and line heating. The required three-dimensional shape is attained by plastic strain during the process. Thus any analysis of the above forming process can essentially be divided into two parts. The first part is to determine the type and location of inherent strain required to achieve the desired shape. The second part is to determine proper heating conditions to attain the above inherent strain. This report deals with the first part, wherein a study has been undertaken on the inherent strain field required to achieve the desired shape of a twisted 'T' section longitudinal using elastic FEM analysis. Information based on the above can be used to determine the forming procedure.

KEY WORDS: (Line Heating) (Inherent Strain) (In-Plane Strain) (Bending Strain) (Twisting) (Buckling)

1. Introduction

The Line heating method has been widely used to form curved plates and sections of ship hulls in shipyards. The forming process consists of heating and cooling, in a predetermined pattern of lines by using a heat source, which most commonly is a gas torch. In many cases, mechanical processes to give the plate/section a certain intermediate shape may precede the above heating process. Highly skilled workmen, who make final decisions regarding the location and magnitude of pressing/heating based on experience and intuition, presently carry out this work. However due to various factors, the shipbuilding industry is finding it difficult to attract new personnel willing to take up such forming jobs. This has made it necessary to look at alternative options for forming. One option that has received considerable attention is the development of numerical tools for analysis of the process, which could then be suited to subsequent automation.

The plate forming process has received considerable attention over the past few years.[1,3] A great amount of research work has been undertaken in this regard, with a view to developing intelligent systems capable of forming complex double curvature shapes by line heating. A few such systems have been developed and are being evaluated at various yards in Japan. As a natural extension of the above, the forming process of stiffeners has also received attention. Most of the large merchant vessels being built today, are longitudinally framed with built-up 'T' sections. These 'T' section longitudinals have complex 3-dimensional curvatures, especially towards the fore and aft ends of the ship. This report concentrates on the 'T' section longitudinal forming process.

Presently in the shipyards, the 'T' section is formed by a combination of press bending and line heating. The required 3-dimensional shape is attained by plastic strain occurring during the processes. Thus an analysis of the forming processes can essentially be divided into two parts[1-2]. The first part is to determine the type and location of inherent strain that would result in deformations required to achieve the desired shape. Based on this, a decision can be made as to the type of method to be used and heating location. The second part is to determine the relation between heating conditions and the resultant inherent strain. In this report the first part as mentioned above is investigated using FEM analysis.

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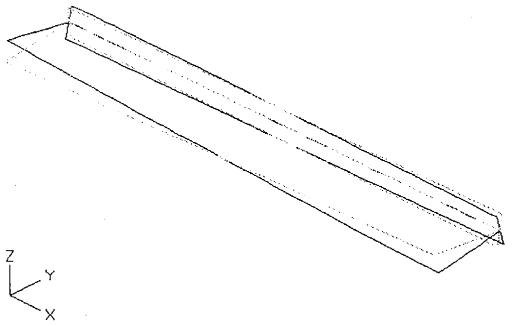

Fig.1 Model for twisting.

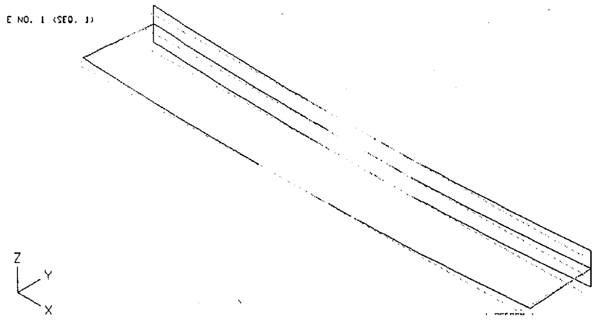

Fig.2 Model for bending.

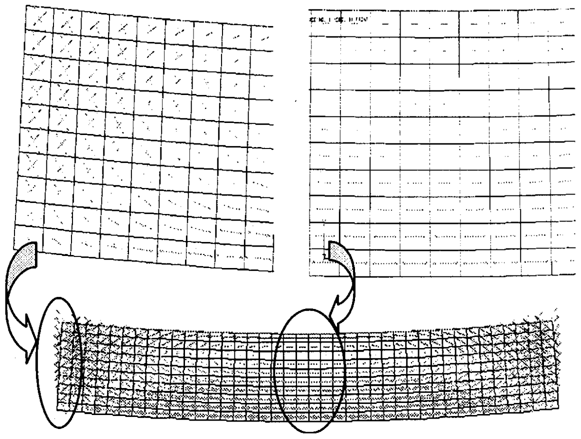

Fig.3 Principal in-plane strains due to bending.

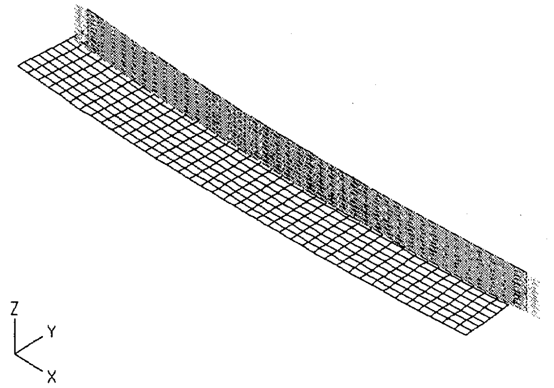

Fig.4 Principal bending strain due to in-plane bending.

2. Twisted Shape

The shape of the model and co-ordinate system used for the study is shown in **Fig.1** and **Fig.2**. The dimensions of the model used for the analysis were 2000 x 300 x 150 x 10/20 mm. The web and the flange are subdivided into 40 x 10 mesh divisions. Four noded shell elements are used for the analysis. The constraints applied are just the minimum required to prevent rigid body motions in the x-y plane except for the forced deformation. It is assumed that the final twisted form of the 'T' section longitudinal can be considered as a combination of bending deformation and twisting deformation.

The bending deformation is assumed as

$$v = ax^2 \qquad (1)$$

and the twisting deformation as

$$w = bxy \quad \text{on the web} \qquad (2)$$

$$v = bxz \quad \text{on the flange} \qquad (3)$$

where u, v, w are the displacements in x, y, z directions. The constants a, b define the magnitude of bending and the magnitude of twisting, respectively.

3. Basic Approach to Problem

3.1 Reverse analysis

A reverse analysis is initially carried out, wherein the 'T' section is deformed from the final shape to a flat un-deformed shape. Large deformation elastic FEM analysis is used for this. The bending and twisting processes are considered separately. The strain is decomposed into in-plane strain ε^m and bending strain ε^b, where,

$$\varepsilon^m = \frac{1}{t}\int_{-\frac{t}{2}}^{\frac{t}{2}} \varepsilon \, dz \quad \text{and} \quad \varepsilon^b = \varepsilon - \varepsilon^m \qquad (4)$$

and t is the thickness of the plate.

3.2 Evaluation of strain

The computed strains are plotted separately in the form of a vector plot. Then the type of strain, its distribution and relative magnitude are evaluated to decide on the process to be adopted.

3.3 Forward analysis

In case it is decided to adopt line heating, a forward elastic FEM analysis is carried out, applying certain predominant strains as inherent strain, ignoring other strain components. The attained shape is compared with the desired 'target shape' and the accuracy is evaluated.

4. Inherent Strain Due to In-plane Bending

The distribution of principal in-plane and bending strains due to in-plane bending is shown in **Fig.3** and **Fig.4**, respectively. The strain across the mid section of the longitudinal is almost uni-axial and linearly distributed. However, shear strain becomes dominant towards the ends of the longitudinal. This is due to the fact that the ends of the longitudinal are free in the in-plane direction. The in-plane strain is predominant in this case, with the maximum magnitude strain being in the middle region of the web. The bending strain in the flange is uniform.

Fig.5 shows the relation between the strains and the magnitude of bending. The magnitude of in-plane strain in the web is of a relatively high order, being 3.08% when bending magnitude is 80mm. As compared to this, the bending strain in the flange is of much lower magnitude.

At present the bending process is being carried out in shipyards using hydraulic frame benders. A curved inverse line is plotted on the web, which becomes a straight line when the longitudinal attains the planned shape. This is a simple and efficient method to generate the high in-plane strain required. Compared to this, line heating would be an inefficient method since it would result in a much longer production time. Hence as regards the in-plane bending process, the current practice of bending using the frame bender, can be considered as an appropriate method for an automated process also.

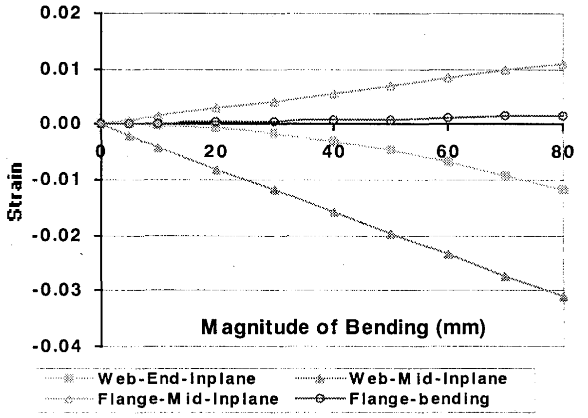

Fig.5 Variation of strain due to bending.

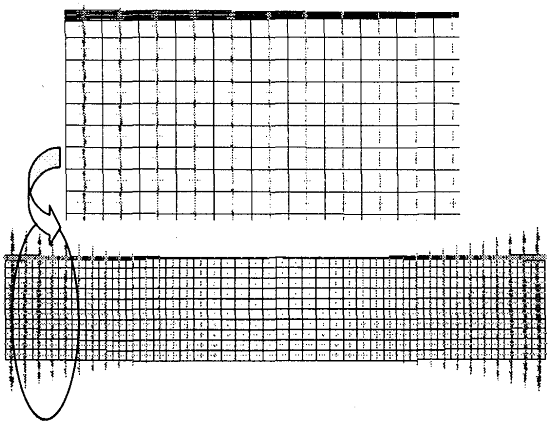

Fig.6 In-plane strain due to twisting process.

5. Inherent Strain Due to Twisting

The distribution of principal in-plane and bending strains due to twisting are shown in **Fig.6** and **Fig.7**, respectively. The relation between the strains and the magnitude of twist is shown in **Fig.8**.

It is observed that the in-plane strain becomes large towards the ends. However as shown in Fig.8, it is of a negligibly small magnitude when the magnitude of twist is small. As regards the bending strain, it can be seen that it is uniform throughout the length. Also the two bending strain components are equal to each other and at an angle of 45^0 relative to the edge, which corresponds to the shear type bending strain. This can be readily seen from the second derivatives of the deflections, such that on the web,

$$\left(\partial^2 w \big/ \partial x^2\right) = \left(\partial^2 w \big/ \partial y^2\right) = 0 \tag{5}$$

$$\left(\partial^2 w \big/ \partial x \partial y\right) = b \tag{6}$$

on the flange,

$$\left(\partial^2 v \big/ \partial x^2\right) = \left(\partial^2 v \big/ \partial z^2\right) = 0 \tag{7}$$

$$\left(\partial^2 v \big/ \partial x \partial z\right) = b \tag{8}$$

The twist range of interest is also marked in the Fig.8, which in the case of normal merchant ships is about 1deg/meter. While the in-plane strain on the web and the flange are of a very small order at 1deg/meter twist, the bending strain on flange is two times the bending

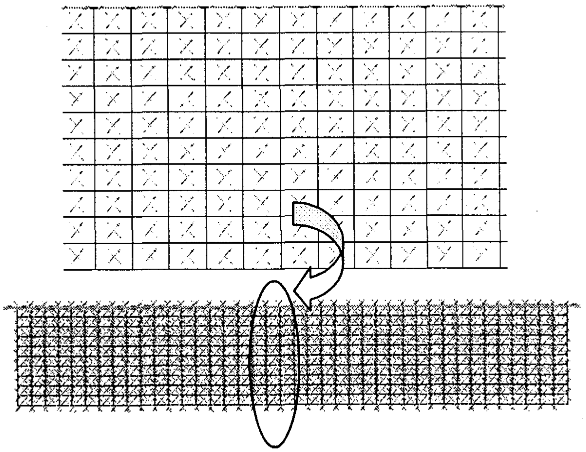

Fig.7 Bending strain due to twisting.

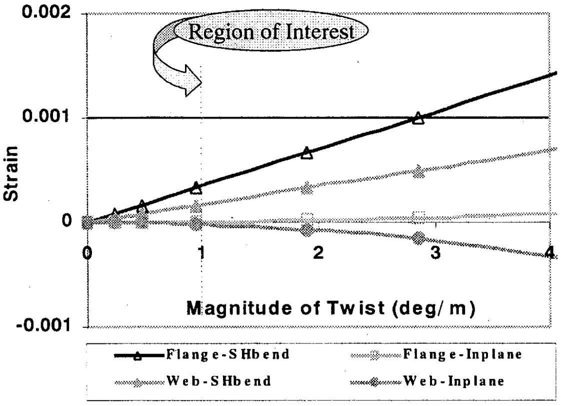

Fig.8 Variation of strain due to twisting.

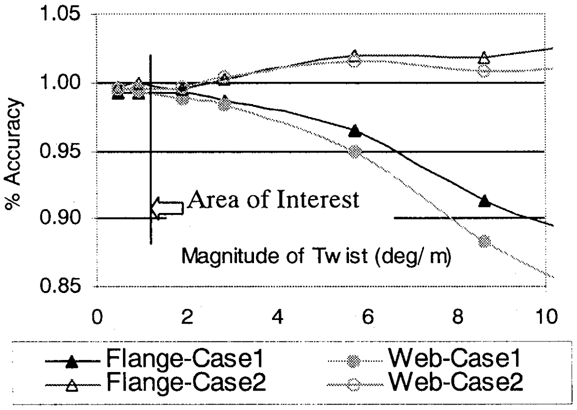

Fig.9 Accuracy of attained shape.

strain in the web. Considering the fact that the flange thickness is two times the web thickness in this analysis, it can be observed that bending inherent strain is proportional to the thickness. Also the bending strain varies linearly with the magnitude of twist. If the in-plane strain during this stage can be neglected, as appears possible during low magnitudes of twist, the twisting process becomes one of generating the required bending inherent strain.

The above pattern of bending strain can be produced by line heating distributed throughout the length. The direction of heating lines on the face and the back side to the edge. This is in line with current practice. However as any line heating will also produce allied shrinkage in the web, which is unwanted in this case, equivalent 'shrinkage compensation' will have to be carried out on the flange. This is also in line with current practice.

6. Forward Analysis

On the basis of the above observations, a forward analysis was carried out to simulate the effect of strain components on the twisting process. The attained shape was compared with the 'target shape' and the results are shown in **Fig.9**. As a first step, only shear bending strain on the web and flange was applied as inherent strain and all other strain components were neglected (Case 1). It can be seen that at magnitudes of twist of about 1deg/meter, the attained shape has about 99% accuracy as compared to the 'target shape'.

As a second step, in addition to the above, the in-plane strain at the mid region of the web was applied as a constant inherent strain on the web (Case 2). In this case, the shape attained is very close to the 'target shape', even at higher magnitudes of twist. Thus it can be concluded that at low magnitudes of twist, applying the inherent shear bending strain alone can attain practically acceptable levels of accuracy. However at higher magnitudes of twist, uniform in-plane inherent strain is to be applied on the web, in addition to the shear bending strain. It can also be inferred that even though the in-plane strain distribution as shown in Fig.6 appears to be complex towards the end, it can be neglected, as it does not affect the accuracy to a major extent.

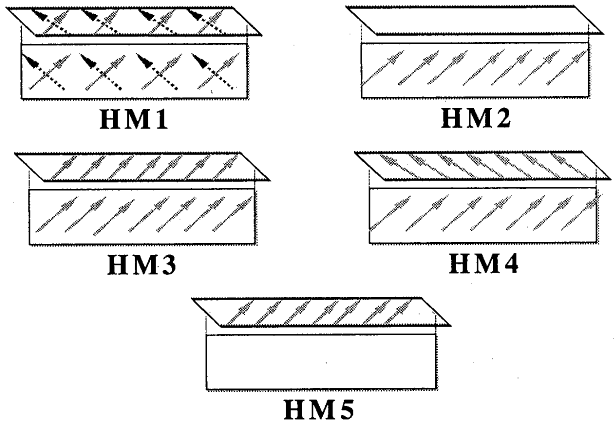

Fig.10 Heating methods.

7. Line Heating Methods

Broadly based on current practices being adopted in various shipyards, five probable methods of line heating, designated HM1 to HM5 as shown in **Fig. 10**, are evaluated in this study. As a first step, it is assumed that the heating is carried out using a 'bending type' heat source[4)], which will produce predominantly bending deformation. Hence in this report it is assumed that such heating will produce only bending strains.

HM1 envisages line heating on the face at an angle of 45^0 to the edge followed by line heating on the backside in an orthogonal fashion. HM2 to HM5 envisages heating only on one side. The heating is carried out either on the web, or flange, or both, in directions as shown in Fig.10. The relative magnitude of inherent strain applied on the web and the flange for the five heating cases considered are as given in **Table.1**, where (F) and (B) indicates heating on the face or on the backside respectively.

Fig.11 and **Fig.12** compares the deformations produced by the different heating methods, on the web and on the flange respectively. HM1 is considered as the benchmark heating method, since as already evident from Fig.9, this method produces about 99% accuracy at low magnitudes of twist. HM3 is an efficient method to produce the twisting deformation. However the lateral shift in the HM3 curve in Fig.11 indicates that, even though the twisting is achieved the distribution of the twist is not as desired. HM5 is also an efficient heating method to produce twist, but heating on the flange alone cannot attain the required magnitude. HM2 and HM4 are inefficient methods and do not deserve further serious consideration.

Table 1- Relative magnitude of inherent strain applied.

	Web	Flange
HM1	1(F) + 1(B)	2(F) + 2(B)
HM2	2(F)	0
HM3	2(F)	4(F)
HM4	2(F)	-4(F)
HM5	0	4(F)

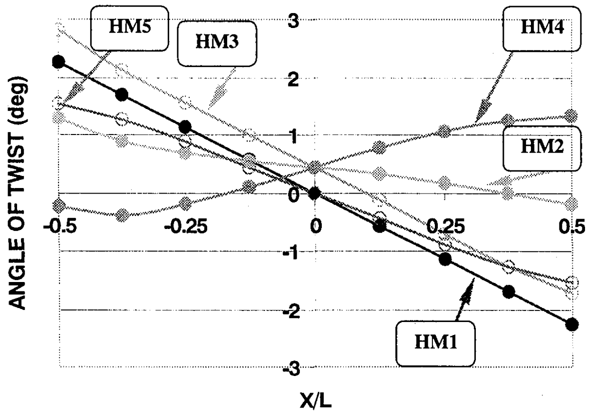

Fig.11 Comparison of heating methods with respect to the deformation on the web.

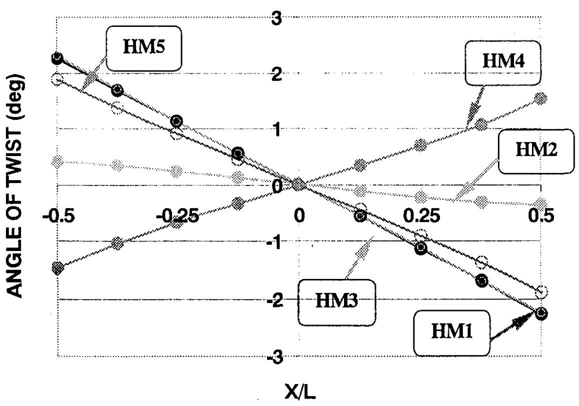

Fig.12 Comparison of heating methods with respect to the deformation of the flange.

From the above it is observed that even though HM1 is the best heating method to produce twisted shapes, it involves heating on both sides, which means additional handling and turning over of the longitudinal. From a practical viewpoint, to avoid handling and turning over, HM3 and HM5, being efficient twisting methods need to be investigated further.

8. Alternative Methods for Forming

8.1 Hot forming

Hot forming is a method similar to the forging process and theoretically can be used to form twisted shapes. Normally such a method is used only for generating very large strains. Since the strains involved in the forming of longitudinals are of a much lower order, this method of forming may not be an ideal one.

8.2 Buckling

The concept in this method is that the longitudinal can be buckled to form a twisted shape, when compressive inherent strain is applied on the flange of a longitudinal with a small value of initial shear (twisting type) inherent strain. This option investigates whether the small initial twist acts as a 'trigger' leading to subsequent twisting.

9. Buckling as a Forming Method

A small initial shear bending strain is applied on the web and flange of the longitudinal. Two cases are considered. The initial shear bending strain corresponds to a twist of 0.2 degree/ meter in Case 1, and to a twist of 0.4 degree/ meter in Case 2. Under these conditions, progressively increasing compressive in-plane inherent strain is applied on the flange and the deformations observed.

The deformed shape of the longitudinal is shown in **Fig.13**, wherein it can be seen that even though buckling occurs, it is accompanied by a change in the mode. Moreover, the deformation is not of twisting type as desired. **Fig.14** shows the variation of angle of twist with increasing shrinkage strain. It is observed that the onset of buckling occurs at a strain of about 0.37%, which is much higher than the normal yield strain of mild steel. Further buckling occurs rather sharply and control of the process would be practically difficult. Based on the

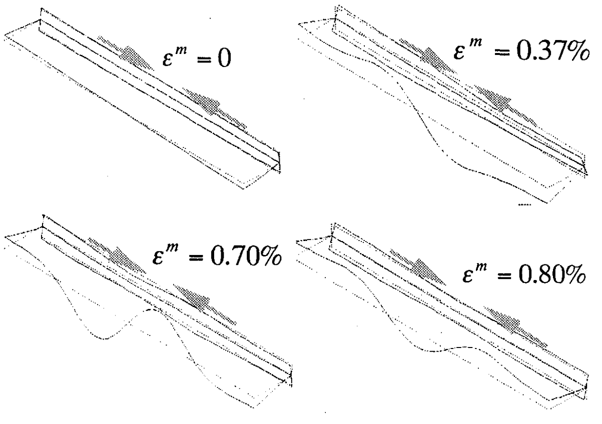

Fig.13 Change in buckling mode with increase in compressive strain on the flange.

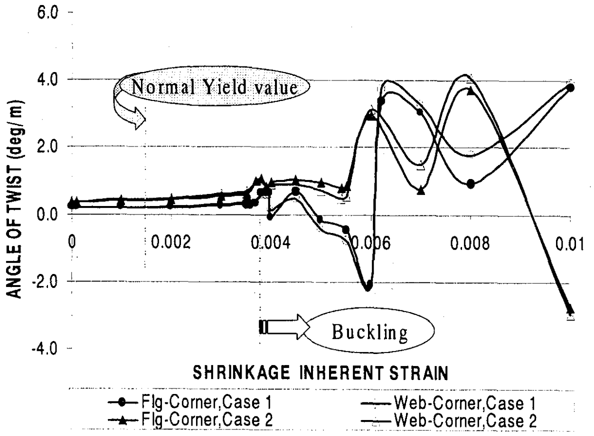

Fig.14 Variation of angle of twist during buckling.

above observations, buckling does not appear to be a suitable method for forming twisted shapes.

10. Conclusions

The twisted 'T' section longitudinal forming process has been investigated from the point of view of understanding the inherent strain. An elastic reverse deformation analysis is carried out to define the inherent strain field. Based on this, the process to be adopted is proposed. A forward elastic deformation analysis is then carried out and the attained shape is compared with the target shape. As an alternative method, the possibility of buckling the longitudinal into the desired shape by applying compressive inherent strain on the flange is also investigated. On the basis of current practices being adopted in various shipyards, five probable heating methods are evaluated for their efficiency. Based on this study, the following conclusions are drawn.

(i) The inherent strain due to in-plane bending deformation is mainly in-plane and is of an order 10^{-2}. Such a high strain is best attained by mechanical bending on a frame bender.

(ii) The inherent strain due to the twisting deformation is mainly of shear type bending, which is constant and uniform along the length. The bending strain components are orthogonal, equal to each other and at an angle 45^0 relative to the edge.

(iii) The twisting deformation and the resultant shear type bending strain can be attained by line heating on the face followed by line heating on the backside, in an orthogonal direction.

(iv) The bending inherent strain is proportional to the plate thickness and varies linearly with the angle of twist.

(v) The forward deformation analysis shows that at low degrees of twist the inherent shear type bending strain alone produces practically acceptable levels of accuracy. However to attain such accuracy levels at higher angles of twist, uniform in-plane inherent strain is also to be applied on the web, in addition to the shear type bending strain.

(vi) Forming, by trying to buckle a longitudinal with an initial shear type inherent strain, and applying further shrinkage strain on the flange, does not appear to be a practically viable method for twisting.

(vii) Out of the five different heating methods evaluated for their efficiency to produce twisted shapes, HM1 is observed to be the most efficient one. However based on practical considerations, HM3 and HM5 are methods that merit serious consideration.

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