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Optimization of woven jute/glass fibre-reinforced polyester hybrid composite solar parabolic trough collector

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Abstract. In the present work, structural analysis of 5.77m × 4m woven jute (J)/glass (G) fibre-reinforced polyester hybrid composite solar parabolic trough is carried out based on trough parameters to obtain the minimum RMS local slope deviation, termed as SDx value under gravity loading. The optimization is done by varying parameters viz. direction and size of reinforced conduits, stacking number and sequence of hybrid trough laminate at fibre orientation of $\Delta\theta=45°$ and $\Delta\theta=60°$ amongst the layers at 0° collector angle. The analysis revealed that the configuration in which the conduits are placed in both X and Y directions is preferred over other configurations to scale down the effect of wind loads. Furthermore it has been observed that laminate of the order $[0°_G/45°_G/-45°_J/90°_J]_s$ undergoes minimum surface deformation amongst all the other configurations at conduit reinforcement in both X and Y directions for a conduit thickness of 0.75 mm and radius of 10 mm and obtains the overall SDx value of 1.3492 mrad. The results shows that proposed trough model is very promising and evolves a cost effective system.

1. Introduction

The effective and cost-effective use of solar energy is of paramount importance when it comes to using alternate sources of energy. Over the past few years, the researchers have tried to analyse potential solar devices by making use of new materials and studying them from structural, thermal and optical outlook. Hence, the composite materials are gaining momentum to make solar collector systems and one such use is in solar parabolic trough based technology, in which trough reflectors concentrates the direct solar radiations onto an absorber tube located in the focal line of parabola [1]. The amount of radiations reflected from the trough reflector that are actually falling on the absorber tube depends upon collector's strength to maintain its ideal shape under gravity and wind loads. Thus, the need of using superior materials arises to achieve higher optical efficiency at low manufacturing costs. Natural fibre polymer composite materials are one such class of materials that are cost effective, have low density and offers sufficiently high specific strength. The attempts have been made in the recent years to fabricate the composite trough but still they are not used predominantly due to high costs involved in making its mould. The use of polyester resin and woven fibre glass cloth for parabolic trough after doing reinforcement with PVC conduits in both its transverse and axial direction by Kalogirou et al. [1], the use of polyester resin and chopped stranded fibre glass cloth after placing the PVC conduits in only longitudinal direction by Valan Arasu and Sornakumar [2], the use of epoxy woven fibre glass composite trough by doing reinforcement with polystyrene strips by Gianlucca

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Coccia et al. [3] are few of the examples. But all these configurations saw the use of synthetic fibres in an experimental work.

For obtaining the cost effective and high stiffness/weight ratio structure, there has to be a use of alternate materials, their repair and its optimization [4]. Therefore, in the present work, the use of Woven/Jute Glass Fibre Reinforced Polyester Hybrid Composite (WFRPH) material in Parabolic Trough Collector (PTC) is exercised on the basis of stiffness/weight and cost/performance of the trough. After selecting the material, its optimization is done by varying the parameters like direction and size of conduits, stacking number and sequence of hybrid Trough Laminate (TL) at different fibre orientations and then is analysed structurally at 0 °collector angle under gravity load.

2. Methodology

2.1. Geometrical modelling and numerical procedure

A WFRPH PTC consists of two columns of composite mirrors having total of 8 mirrors and each having dimensions of 1439.5 × 1998 × 4 mm that are attached to the support structure as shown in figure 1. The composite mirrors or the trough is made of stacks of laminae with direction specific fibres to form the TL which is reinforced with PVC conduits in both X and Y directions to increase its stiffness/weight ratio. Each mirror is separated from its adjacent mirror by a gap of 4 mm. The support structure consists of 8 arms that are tied to the trough at specific points and the mirror arms are connected to the pylons through torque tube as shown in figure 2.

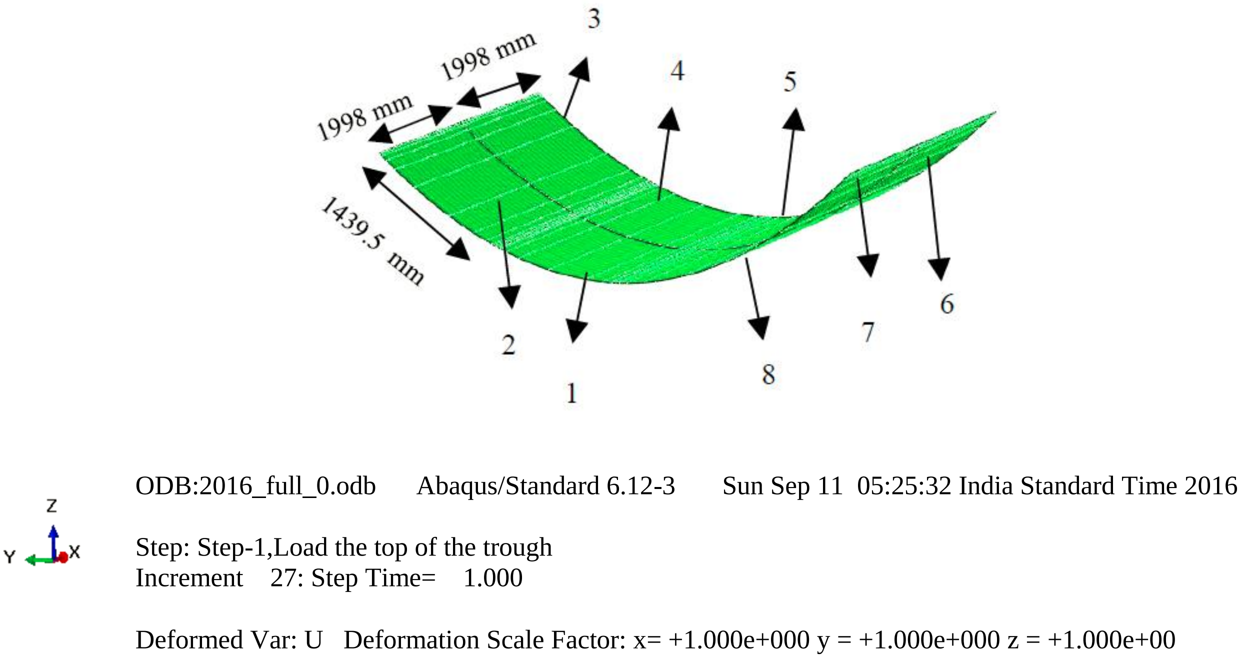

Figure 1. WFRPH Parabolic trough reinforced with PVC conduits with mirrors numbered from 1-8.

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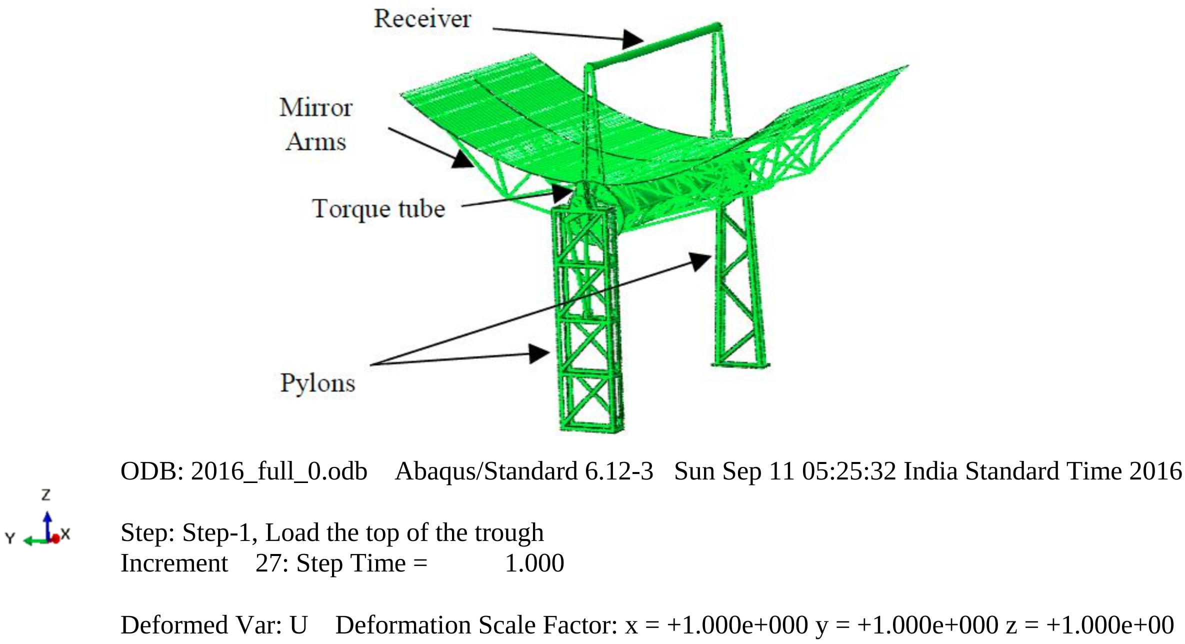


Figure 2. A WFRPH solar PTC.

Following mesh element types are used to ensure convergence and mesh element size and total number of elements are found to be 20 mm and 3,05,592 respectively after mesh convergence study.

a) Trough: S8R (eight noded quadrilateral shell element with reduced integration)
b) Arm, Receiver tube, Torque Tube & Pylons: C3D10, C3D15, C3D20R (Quadratic tetrahedral element, quadratic wedge & quadratic hexahedral element respectively)
c) Conduits used for reinforcement: B31 (linear line element)

The basic formulation of equilibrium equations is done using Newton’s full solution technique for the finite element model [5].

$$F^N (u^M_{(i)} + c^M_{(i+1)}) = 0 \tag{1}$$

where F^N is the force component of the Nth variable, $u^M_{(i)}$ is the value of M^{th} variable after an iteration i and $c^M_{(i+1)}$ is the deviation of this solution from exact solution.
Using Taylor series expansion about $u^M_{(i)}$,

$$K^{NL}_{(i)}\, c^L_{(i+1)} = - F^N_{(i)} \tag{2}$$

In the above equation except the first two terms, rest are neglected if $c^M_{(i+1)}$ is very small,

where $K^{NL}_{(i)} = \frac{\partial F^N}{\partial u^L} (u^M_{(i)})$ is the system’s tangent stiffness or Jacobian matrix and $F^N_{(i)} = F^N (u^M_{(i)})$.

The next approximation can be calculated by

$$\Delta u^M_{(i+1)} = \Delta u^M_{(i)} + c^M_{(i+1)} \tag{3}$$

Iterations are repeated in each increment until convergence is achieved.

2.2. Boundary conditions

Surface to surface interaction and multi-point tie constraint is provided between conduits and TL and between TL and support structure. The PTC is analysed at 0 ° and 90 ° collector angle under gravity load by providing the ENCASTRE Boundary Conditions (BCs) at appropriate places. The post processing of the results is done in MATLAB by following the elemental approach [6].

3. Results and Discussion

The basis of optimization is calculation of SDx value (in milliradians) which is also the statistical parameter characterizing the shape accuracy of the whole mirror surface and is calculated by the following formula which was mentioned by Lüpfert et al. [7].

$$SD_x = \sqrt{(\sum_{i,\,j=1}^{n}(sd_{x_{ij}}^2 \times \frac{a_{ij}}{A_{tot}}))} \quad (4)$$

where sd^2_{xij} are local slope deviation values, a_{ij}'s are the according element surface areas projected onto the aperture plane and A_{tot} is the aperture area. The mechanical properties used in relations of equation for law of mixtures have been mentioned in table 1 to get in-plane and transverse elastic constants for all the configurations [8],[9]. All the mechanical properties are calculated by using 50/50 V/V% of fibre/resin**.**

Table 1. Mechanical properties of fibres and resins used for modelling [8], [9].

	Elastic modulus (E) (in GPa)	Shear modulus (G) (in GPa)	Poisson's ratio (ν)	Density (ρ) (in Kg/m³)
Woven glass	72	29	0.25	2600
Woven Jute	25	7.24	0.38	1450
Unsaturated Polyester Resin	3.4	1.2	0.4	1110

3.1. Optimization of size and direction of reinforced conduits

The direction of reinforced conduits is one of the significant factors in calculation of trough surface deformations. From table 2, it is quite evident by the SDx values of all the three configurations that stiffness/weight ratio of the structure when the reinforcement is done in only X direction is higher than any other configuration under gravity loading. But this SDx value is very close to reinforced structure in both X and Y directions, so it is encouraged that latter configuration is used to counterbalance the wind loads from both yaw angle and pitch angle perspective because of its bi-directional strength. It can also be seen that reinforcement in only Y direction is least effective from structural point of view due to largest SDx value amongst the three configurations.

Table 2. Variation of SD_X values of all mirrors (in mrad) at fibre orientation of Δθ=45° of WFRPH trough model at 0 °collector angle.

Reinforcement direction	Collector Angle		Mirror 1	Mirror 2	Mirror 3	Mirror 4	Mirror 5	Mirror 6	Mirror 7	Mirror 8	**Average**
X	0°	SDx	1.4064	1.1987	1.1917	1.4080	1.4006	1.1980	1.1961	1.4042	**1.3005**
	90°	SDx	0.5955	1.1032	1.0936	0.5880	0.5905	1.0026	1.0009	0.5895	**0.8205**
Y	0°	SDx	6.2265	3.2210	3.2216	6.2341	6.2230	3.2147	3.2081	6.2292	**4.7223**
	90°	SDx	1.5712	2.2172	2.2138	1.5740	1.5398	2.0495	2.0468	1.5458	**1.8448**
X,Y	0°	SDx	1.4957	1.2088	1.2031	1.4975	1.4946	1.2009	1.1978	1.4956	**1.3492**
	90°	SDx	0.6362	1.1063	1.0985	0.6279	0.6269	1.0131	1.0019	0.6244	**0.8419**

All the above three configurations are analysed by fixing the thickness of conduits as 0.75 mm and radius as 10 mm. The size of conduits is completely dependent upon the mesh size which is further dependent upon the convergence rate and the BCs. Also the laminate pattern is taken as $[0^\circ_G/45^\circ_G/-45^\circ_J/90^\circ_J]_s$ (0° is parallel to X direction) in all the three configurations since it is also the optimised configuration as discussed in the next section.

3.2. Optimization of TL

Finally the stacking sequence, its number and the orientation of fibres is optimised to achieve the best TL configuration and hence the least SDx value. Since in-plane mechanical properties of TL depends upon these factors, thus, to maintain homogeneity of its in-plane properties, TL is made symmetric and quasi-isotropic (orientation wise). As shown in the figure 3 and figure 4, the fibre orientation of Δθ=45° and Δθ=60° amongst the laminae (or layers) is studied separately by varying their stacking sequence and fixing the conduits in X and Y directions both. The number of layers are decided by taking the minimum thickness of laminae as per its practical viability and a total of 66 cases are studied in accordance to the symmetry of TL at Δθ=45° and Δθ=60°. For fibre orientation of Δθ=45°, the number of layers are taken as 8 where each layer is 0.5 mm thick and for fibre orientation of Δθ=60°, the number of layers are taken as 6 where each of the outer two layers from either sides are 0.5 mm thick. In general, at Δθ=45°, general notation of all the configurations can be $[h^\circ_P/i^\circ_P/j^\circ_Q/k^\circ_Q]_s$ where h/i/j/k exhibits the values 0/45/-45/90 respectively and P denotes G (or woven glass fibre and polyester lamina) whereas Q denotes J (or woven jute fibre and polyester lamina) and the sequence of both h/i/j/k and PQ can vary (variation of h/i/j/k is shown in table 3). Also interchanging only i, j in the same configuration (i.e. by keeping h, k and P, Q fixed) does not alter the results, so they are considered as one configuration which makes the total number of cases as 48 for Δθ=45°. Similarly at Δθ=60°, general notation of all the configurations can be $[a^\circ_P/b^\circ_P/c^\circ_Q]_s$ where a/b/c exhibits the values 0/60/-60 respectively and PQ has the usual notations and total number of cases studied are 18 at Δθ=60°.

From figure 3 it is clear that $[0^\circ_G/45^\circ_G/-45^\circ_J/90^\circ_J]_s$ obtains the SDx value of 1.3492 mrad at Δθ=45° at 0° collector angle under gravity loading which is also lowest as compared to its rest of the configurations and the SDx value of 1.3503 mrad at $[0^\circ_G/60^\circ_J/-60^\circ_J]_s$ configuration at Δθ=60° which is slightly higher than the above configuration. These SDx values are dependent upon interlaminate stresses and bending stresses produced as per theory of bending and classical laminate theory other than previously mentioned parameters like BCs, direction of reinforcement and collector's stiffness/weight ratio.

At Δθ=45°, from figure 4 it can be seen that at configurations K and L of TL in all the Glass and Jute sequences i.e. GGJJ, GJGJ, JGJG and JJGG, the surface deformation is maximum due to poor fiber sequence. According to Pagano and Pipes, interlaminar normal stresses (arises due to mismatch in moduli and Poisson's ratios between the layers) plays an important role in deciding the strength of the TL due to which SDx values are quite high in these configurations [10]. By similar reasoning, it can be said that configurations A and B have significantly lower SDx values due to their lesser tendency to delaminate. Similarly at Δθ=60°, the configuration A of TL in all the glass and jute sequences has shown the minimum SDx value amongst the rest of configurations but this minimum value is still higher than configuration A and B of Δθ=45° fibre orientation which makes it to be the optimum configuration.

Table 3. Different TL fibre orientations of WFRPH trough model.

Δθ=45°					
A 0/45/-45/90	B 0/45/-45/90	C 0/45/90/-45	D 90/45/0/-45	E 0/90/-45/45	F 90/0/-45/45
G 45/90/-45/0	H 45/0/-45/90	I 45/0/90/-45	J 45/90/0/-45	K 45/-45/90/0	L 45/-45/0/90

Δθ=60°		
A 0/60/-60	B 60/0/-60	C 60/-60/0

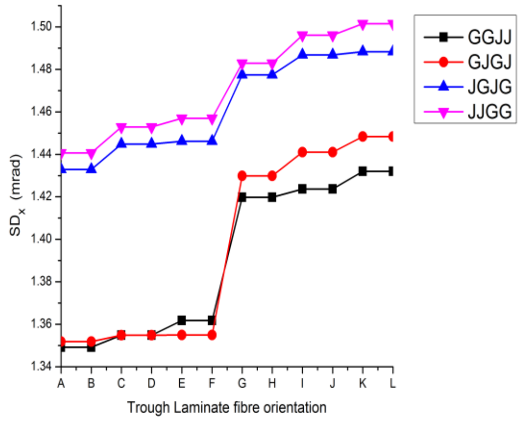


Figure 3. SDx values for different TL configurations when Δθ=45°.

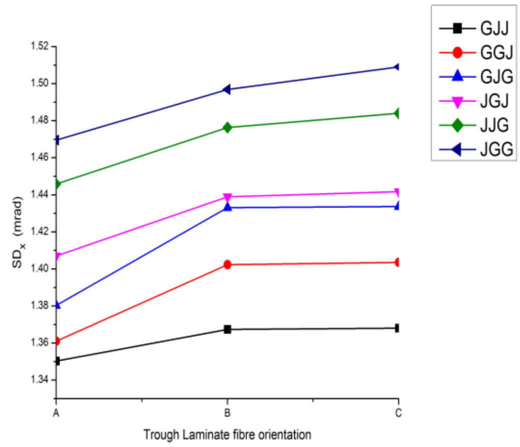
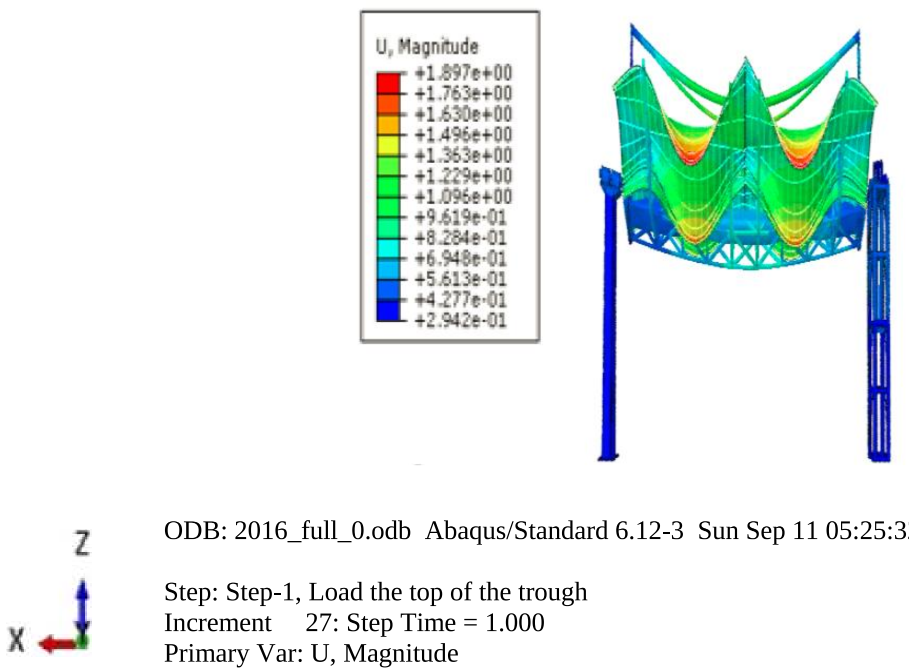


Figure 4. SDx values for different TL configurations when Δθ=60°.

In all the above configurations, WFRPH composite trough undergoes righted U and inverted U shaped deformations depending upon the BCs of the PTC, curvature effect of trough, collector orientation and its stiffness/weight ratio as shown in the figure 5 (a), (b).

(a)



ODB: 2016_full_0.odb Abaqus/Standard 6.12-3 Sun Sep 11 05:25:32 India Standard Time 2016

Step: Step-1, Load the top of the trough
Increment 27: Step Time = 1.000
Primary Var: U, Magnitude
Deformed Var: U Deformation Scale Factor: x = +l.000e+000 y = +1.000e+000 z = +1.000e+03

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(b)

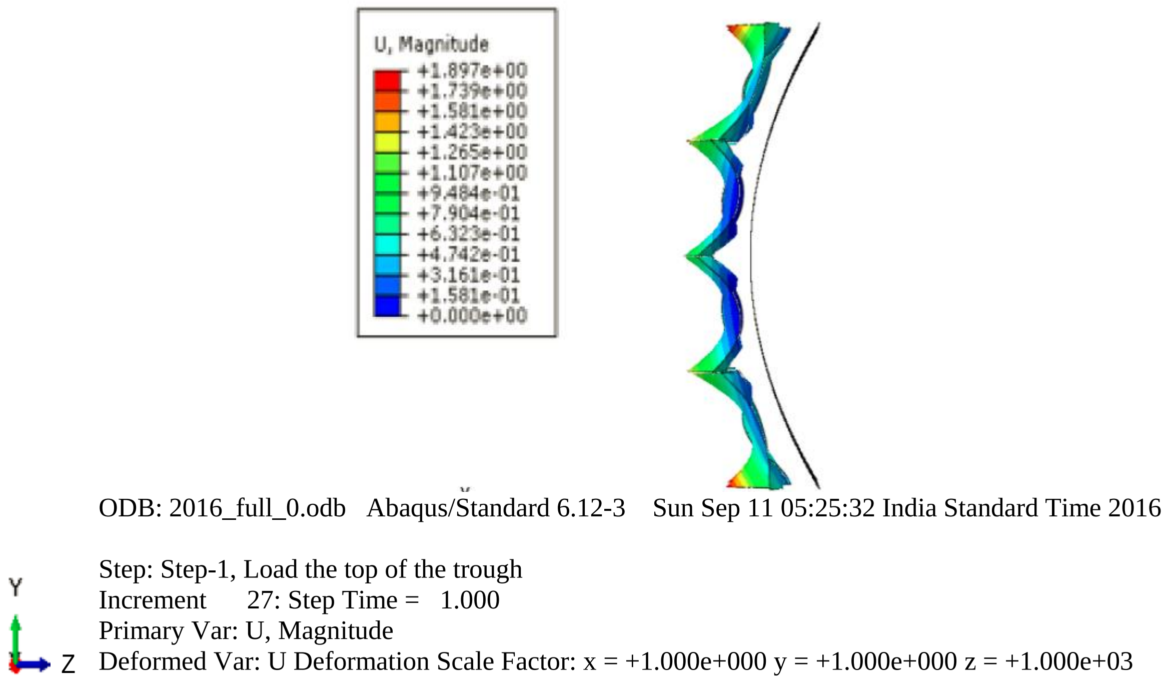

Figure 5. Deformation of WFRPH composite trough collector in 0 ° collector angle. (a) from its undeformed shape (superimposed) as shown in black in XZ plane (b) Trough deformation from its undeformed shape (superimposed) as shown in black in YZ plane. Color scale of deformation surface in mm, deformation scaling factor: 1000.

4. Conclusions

The deformation of cost effective solar PTC is studied using WFRPH composite to improve its optical efficiency. To ensure high stiffness/weight ratio and thus lower SDx values, its optimization is done by varying different trough parameters viz. direction and size of reinforced conduits, stacking number and sequence of hybrid TL at fibre orientation of Δθ=45° and Δθ=60° amongst the laminae at 0° collector angle. The analysis shows that reinforcement in the X direction is the most effective amongst the rest of the configurations under gravity load but it is recommended that reinforcement is done in both the directions to scale down the effect of wind loads. Furthermore it can also be seen that laminate pattern of $[0°_G/45°_G/-45°_J/90°_J]_s$ undergoes minimum surface deformation when reinforced in X and Y directions both due to the presence of reduced interlaminar stresses in this configuration. Though SDx values are strongly dependent upon the parameters like collector's stiffness/weight ratio, curvature of trough, and the BCs but the results proves that arguably WFRPH PTC is the promising substitute of conventional trough collector and hence can be easily used for compensating the costs required to fabricate the mould in batch production of parabolic trough reflectors.

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