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Structural analysis and design of dodecahedron shaped distress relief shelter using Building Information Modeling

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Abstract: **India is prone to substantial amount of disaster by natural calamities, manmade disaster and nuclear hazards. Disaster risk can be further augmented by assailability of changing demographics, indigent socio economic conditions, and unplanned population migrations. Disaster relief shelters play an indispensable role in disaster response and recovery system. Disaster relief shelters provide privacy and security for people. Deployable structures have the competency to transform and adopt multiple predetermined configurations in an anticipated way. The deployment is done through pre designed deploying pattern in a safe and controlled manner. Ease of transportation, erection, overall sustainability by high material efficiency, maximum use of natural resources are the key characteristics that enhance the usage of deployable structures as distress relief structures. Abiding by National Disaster Management Authority of India's 'National Guidelines on temporary shelters for disaster affected families; the dodecahedron shaped disaster relief shelters will serve its purpose. Distress relief shelters not only serves as housing for natural calamity affected population but also for the refugees migrating. Building information modeling (BIM) supports sustaining a competitive ability and surviving in competitive construction environment. BIM supports structural design with knowledge, collaborative, rational based models and operates the knowledge contained in the models to anticipate, task performance, display, and charge throughout the whole project life cycle. This paper will present the analysis and design of deployable structure using BIM for the use of disaster relief shelters. In addition, deploying pattern, load calculation, and software generated structural design is presented.**

Keywords — Building Information Modelling (BIM), Deployable structure, Distress relief shelters, Dodecahedron, Low cost housing, Umbrella mechanism.

I. INTRODUCTION

A. BIM

BIM is a model based intelligent process, which provides good understanding to help us plan, design, construct, infrastructure and maintenance. The BIM allows users to acquire information of the building from starting initial stage to entire project life cycle. BIM helps to connect all the professionals throughout the project life cycle of the building in a common platform. BIM offers a collaborative solution and advance structural knowledge learning without compromising other principles of structural design [6]. BIM is not considered as a software but as the process of creating and using digital models for design, construction and operations of the buildings. BIM allows the users to combine 2D and 3D objects to define building designs, along with external factors like geographical locations and local conditions, into virtual building database. This database provides a single, integrated source of all information associated with the project at ease access to the users of different professions. The model is used for analysis to explore design options and to create visualization that helps users to understand how the building will look before being constructed. Digitalization evolving to become the future of construction industry. BIM is the future of digital design and long-term facility management being a boon in technological advancements in industry. Many different disciplines can take advantage of its benefits

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in the same platform. Thus making the usage of BIM in construction industry is very important. Not only standard buildings can be designed, but also many sophisticated and complex structures can be designed using BIM. BIM software support structural engineers to develop integrative allocation of structural design certification, reduce errors, and increase association between engineering and architecture departments [10]

B. Deployable structure

The deployable structures in the field of construction was first introduced in the 20th century. Deployable structures are structures that can be easily reduced in size for transportation or storage [2]. The potentiality of the structure to be folded into compact section configuration for easy transportation and unfoldment when needed made the deploying construction technology a unique invention of the era. Retaining the workability, operability, serviceability, of the traditional structures, the deployable structures are allowed to undergo large variations in the configuration in a controlled and free manner. The Deployable structure can transform and adopt multiple predetermined configurations and design criteria. The deployment is always carried out in a safe and controlled way. Transportable and collapsible houses were developed in relationship with technical advances of material and manufacturing that occurred in the military, automobile, space craft, and leisure industries [3]. The deployable structures have many potential applications ranging from emergency shelters and other temporary or permanent facilities, providing high security and privacy. The compact volume they occupy during storage, transportation and their fast and easy erection procedure serves as their main advantage. Self-stabilizing deployable structure present stable stress-free state in both folded and unfolded condition exhibits higher advancements in evolving technological era. Today's deployable structures have their members connected in the factory, so that they satisfy a set of preassigned geometrical constraints [1]. Innovative forms and design solutions that can satisfy the high aesthetic demands of modern architectural works can be obtained with the formation of deployable structures. The criteria for the construction and estimate of modern folded structures formed of different materials have led to the improvement in advancement of spatial structures, all in order to achieve contemporary creative engineering solutions.

C. Deployable Distress relief shelters

The popularity of deployable structures has increased since the latter half of the 20th century as they introduce a novel and unique type of engineering [8]. Temporary shelters are preferred to be designed as foldable and movable units [9]. The shape geometry, mechanical properties, material characteristics, deploying pattern with a kinematic behavior and the adaptability to external climatic conditions promotes this deployable structure in distress relief shelter construction. Immediate disaster response takes place after the disaster for 0-25 days rescuing lives, providing emergency shelter, food, and medical aid [3].These types of deployable construction are usually practiced in foreign countries. Though India has many new construction technologies, blooming, deployable structure construction is still a non-familiar construction technology. Due to its complexity in designing and hesitation in adaptation of new construction technology among population, deployable structure remains a non-familiar technology to Indian population. Though deployable structure construction is practiced in other well-known countries, it is a very high cost consuming type of construction. Modifying the shape configuration, material, transportability, assembly, deploying pattern, we can reduce the overall cost of the structure. Dodecahedron shaped distress relief shelter is a new of its kind. Due to its deploying pattern of folding and unfolding conditions, it can be easily stored and transported to distress affected locations. The deployable shelters can be transported in folded conditions, creating accessibility to transport more number of shelters to the affected area. The material of which this dodecahedron deployable shelters are locally available. Thus reducing the transportation of material cost at the place of fabrication. These shelters are usually prefabricated and taken to the sites in need of shelters. From history of past disasters, different states have adopted variety of approaches towards provision of shelters to the disaster-affected population. This history of practice provides us with wide range of experiences, knowledge and possibility to learn the future needs. The complex use of land, lack of open spaces, stocking of existing shelters and damages incurred to it, different lifestyle patterns, infrastructure, different occupation and the urban settings gives a different context of temporary shelters. In this case deployable construction technology will be the solution most looked on. Sanitation is one of the key technology requirement in disaster relief shelters particularly in flood-affected areas where conventional toilets cannot be functioned. In such conditions, temporary Eco-San toilets can be used. These types of technical options should be included in design of disaster relief shelters. In case of dodecahedron deployable structure, it is designed with sanitation and all emergency basic need facilities, thus fulling the serving purpose.

II. DODECAHEDRON SHAPED DEPLOYABLE STRUCTURE

A. Dodecahedron

The word dodecahedron is derived from the Greek word "dōdeka" which means "12" and "hédra" means "seat". The dodecahedron is a polyhedron, which has 12 faces. A regular dodecahedron consists of 12 regular pentagonal

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faces. It is one of the platonic solids. Generally, a dodecahedron is used to refer to a regular dodecahedron with 12 pentagonal sides. A dodecahedron has 20 vertices or corners, and at each vertex, three edges meet. The dodecahedron has 30 edges. There are two different types of angles in a regular dodecahedron. The angle between sides of the pentagon is 180 degrees and the dihedral angle is 116.56 degrees. Dihedral angle in dodecahedron is the angle between two intersecting planes. The dodecahedron is a polyhedron as the polyhedron is a solid shape with all polygonal faces. All the faces of the dodecahedron are pentagons, which is a regular polygon. Folded structures - folds belong to the spatial i.e. three-dimensional structures, where the dimension of the elements is very small compared to the span of the construction [4]. It is importance to determine the deployable structure shape and direction of movement in initial design stage. This is because the shape of deployable structures is a mechanism and it will affect the transmission of load and direction of relying of deployable structures [10].

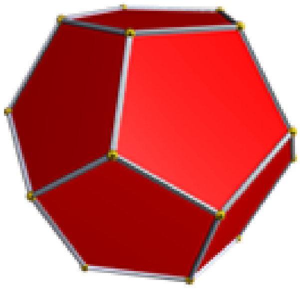

Fig 1: Dodecahedron

B. Material

By reducing the massive use of steel and concrete, we can reduce the total cost of the project by replacing it with the new materials like aluminum, fiber cement concrete & roofing material [7]. Magnesium is the most abundant metal. Magnesium alloys are a popularly used structural materials due to their strength to weight ratio. Magnesium alloy can be commonly used for portable tools, appliances, electronic devices, airplanes, Medical instruments, space vehicles, and land transportation. The density of Mg is averagely two-thirds of that of aluminum and one-fifth of steel. Magnesium alloy has high resistance to corrosion and high strength mechanical properties. Mg is the lightest structural metal, which is 33% lighter than aluminum and 77% lighter than steel. Magnesium alloys can be classified into two groups, one is cast alloys and another is wrought alloys. Cast alloys are made by pouring the molten liquid metal into a mould, within which it solidifies into the required shape after cooling. Wrought alloys, on the other hand, are alloys subjected to mechanical working, such as forging, extrusion, and rolling operations, to reach the desired shape. Aluminum, manganese and zinc are also the main alloying elements that gives high strength to weight ratio. Wrought alloys of magnesium are categorized into heat treatable and non-heat- treatable alloys. Magnesium AZ31B-F, Extruded Solid Shapes is used in this research work.

C. Sanitation

For sanitation purposes, Eco-San toilets are used. Water is not necessarily used in an Eco-San toilet. It is an alternative to leach pit toilets. Eco-San toilets are used in places where water is scarcity is high. A considerable amount of land is excavated for the waste collection pit. The dodecahedron structure is placed directly above the excavated hole, aiming to place the eco-san toilet exactly above the excavated pit. Water is not needed necessarily for eco-san toilets. Instead, ash, sand, loose gravel can be used to cover up the waste. This is a very good practice of sanitation, as the water and natural resources are used at a minimal level. Human waste also acts as natural fertilizer, which helps in plants growth and vegetation

D. Deploying mechanism

In professional design of folded portable structure having understanding related to connection elements and their relation with type of movement desired to make the correct choice is important to avoid malfunction of technical design [12]. The mechanism used here is known as umbrella mechanism. The central stem is connected to the top lever system and bottom lever system. The runner also known as the circular shaft in the central stem is moved in vertical direction so that the stretchers attached to the ribs will deploy. As the runner is moved in vertical direction, the stretchers are automatically extended resulting in deployment of the ribs. The ribs of the upper pentagonal assembly usually has sandwiched pattern in folded condition. The center rib forms the pentagonal frame and the sandwich ribs forms the diagonal frame. The pentagonal plates are divided into triangular plates, which is attached to the top pentagonal plate. These triangular plates are deployed one by one to form the full pentagonal plate within the frames. The lower lever system is deployed in the same way as mentioned previously to form the fully deployed structure

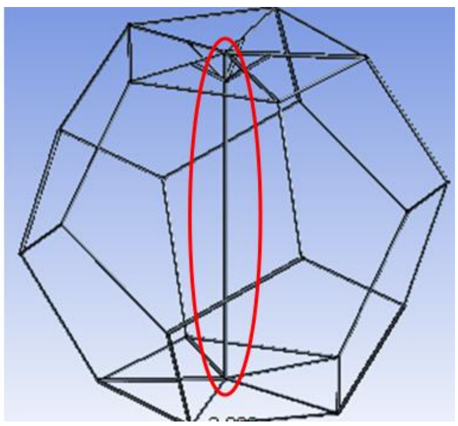

Fig 2: Central Stem

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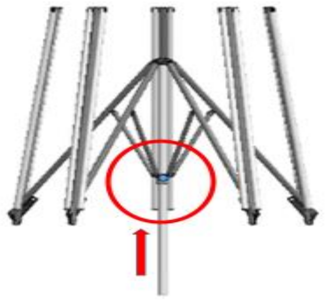

Fig 3: Runner vertical movement

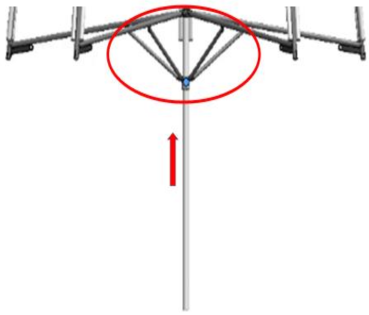

Fig 4: Extended stretchers

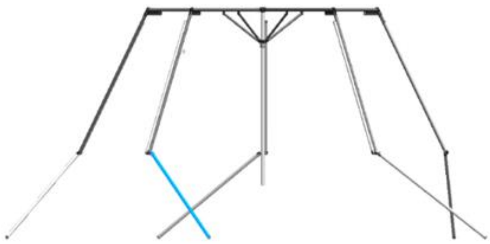

Fig 5: Diagonal Ribs of pentagonal frame

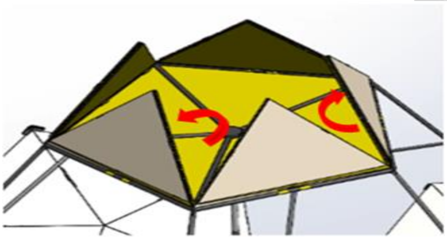

Fig 6: Deployment of plates

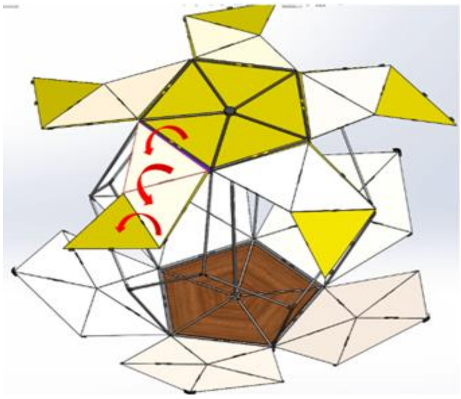

Fig 7: Deployment of plates

Fig 8: Fully deployed plate

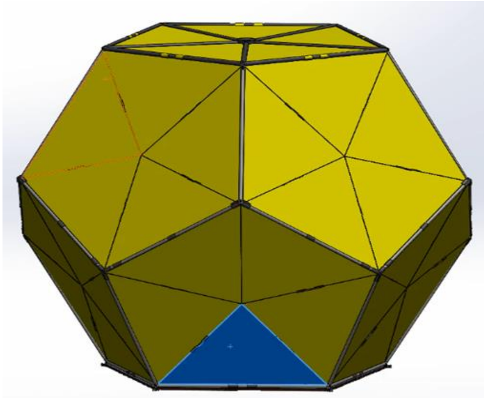

Fig 9: Fully deployed dodecahedron structure

III. 2D BIM AND 3D BIM

BIM helps in interoperability of data from one software to another. In this research work 2D BIM and 3D BIM is used. AutoCAD is the software used to draft 2D floor plan and 3D model of the dodecahedron structure. This CAD file is imported into Solidworks software to create 3D models and visualizations that are more accurate. The CAD file is imported into STAAD.Pro for analysis and design. This facility of interoperability is the main advantage of BIM processing. This facility enables different professionals to work on same project in a common platform. However, there are seven different BIM dimensions, only 2D and 3D BIM is used in this research work.

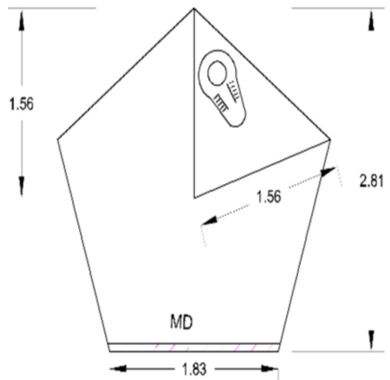

Fig 10: Floor plan from AutoCAD

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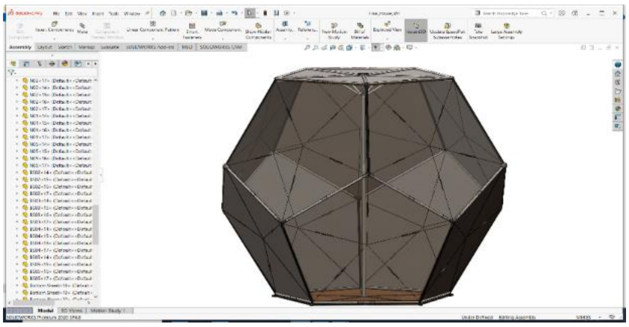

Fig 11: 3D BIM using AutoCAD

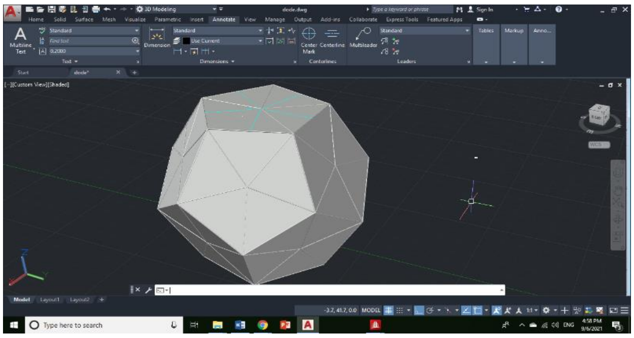

Fig 12: 3D BIM using Solidworks

IV. ANALYSIS AND DESIGN

A. Analysis

The dodecahedron deployable structure is designed for worst-case conditions to serve as distress relief shelters. Analysis and design is carried out in STAAD.Pro software. The imported CAD file is used to form the nodes of the structure, thus creating the geometry of the structure. Nodes and beams are created in geometry. The material properties are created for Magnesium AZ31B-F. The material properties is assigned to the members. Whole structure is assigned with magnesium alloy properties. Whole structure is provided with truss specification. As the structure is a temporary structure, it does not have a foundation. So pinned support is provided at the base. Member properties is assigned to the structure by trial and error method. The central stem is assigned as hallow tube section as per IS 1161: 1998. All other members are assigned as circular section of diameter 0.0254 meter. The plate thickness is assigned as 0.003 meter. Finally, load definition is provided and analysis is done.

B. Load calculation

Self-weight factor of -1 is created in STAAD.Pro and assigned to the whole structure. Live load of -2 kN/m^2 is provided as per IS 875 part 2. Wind load calculation is carried out according to IS 875 part 3, 2015. The basic wind speed (V_b) value is taken as 55 m/s for Darbhanga having highest wind speed in India. Exposed open terrain category is considered. Probability factor (k_1) for temporary sheds is considered as 0.67. Terrain, height and structure size factor (K_2) is 1.05. Topography Factor (k_3) is 1. Importance factor for cyclonic region (K_4) is 1.30 for structures of post cyclone importance for emergency services such as cyclonic shelters.

Wind force for circular object:

$F = C_f \times A_e \times P_d \times G$ [As IS 875 Part 3, Clause 6.4]

Hourly mean wind speed: [as per Clause 10.2]

Hourly mean wind speed at height z for different terrains can be obtained as,

$V_{Z,H} = k_{2,i} \times V_b$

$k_{2,i}$ = Hourly mean wind speed factor for terrain category 1

$0.1423[\mathrm{Ln}(Z/Z_{0,1})](Z_{0,1})0.0706 = 0.78$

$V_{Z,H} = 0.78 \times 55 = 42.9$ m/s

Design hourly mean wind speed at height z

$V_{z,d} = V_{zH} \times K_1 \times K_2 \times K_3 \times K_4$

$V_{z\,d} = 42.9 \times 0.67 \times 1 \times 1.30$

$V_{z\,d} = 37.3659$ m/s

$P_d = 0.6$ V2z,d (N/m2)

P_d = Design hourly mean wind pressure corresponding to $V_{Z,\,d}$

= 0.6 (37.3659)2 = 837.73/1000 = 0.83773 kN/m2

Force coefficient from table 25

Considering the structure as circular, circumradius can be calculated.

Circumradius is given by the formula: Rc= (√3+√15)/4 a

Circumradius = 2.56262 m

b = 2.56 x 2 = 5.126 m

$V_d \times b = 37.3659 \times 5.126 = 191.53$ m^2/s

Height / breadth = 4.100 / 5.126 = 0.799

From table 25, force coefficient $C_f = 0.7$

A_Z = Effective frontal area of structure.

Total surface area = 69.05 / 2 = 34.525 m2

$I_{h,i}$ = Turbulence intensity at height h in terrain category 1 = 0.3507 [As per clause 6.5]

φ = 0.515

Hs = Height factor for resonance response

Hs = 1 + (s/h)^2 = 1+(2.05/4.100)^2 = 1.25

S = size reduction factor

S = 1/ [1+ (3.5 fah /Vh,d)][1+(4faboh/Vh,d)]

boh = Average breadth of structure = 3.30m

As per IS 1893 part 1: 2002, clause 7.6.2

The approximate fundamental natural period of vibration (Ta) in seconds, is estimated as

Ta = 0.09 fa /√d

d = base dimension of building at plinth level in m, along the considered direction of lateral force = 1.8288m

h = height of structure = 4.100 m

Ta = 0.272 seconds

Frequency = Number of cycles per unit time

f = 1/T

f = 1/0.272 = 3.67 Hertz

Substituting the values in Size reduction factor S formula

S= 0.18

N = Effective reduced frequency = fa x L_h / $V_{h,d}$ = 3.67 x 68.01 / 37.3659 = 6.68

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E = Spectrum of turbulence in the approaching wind stream

E = Π N / (1+70.8 N2)5/6 = 0.0254

β = Damping coefficient of the building from table 36

Damping coefficient for bolted steel connection is 0.020

gR = Peak factor for resonant response = $\sqrt{[2Ln(3600\ fa)]}$ =4.35

Substituting the values in Gust Factor G formula,

G = 1+0.3507 $\sqrt{[(32 \times 0.96 \times (1+0.515)^2] + [(1.25 \times 4.352 \times 0.18 \times 0.0254)/0.020]}$

G = 2.35

F = $C_f \times A_e \times P_d \times G$

F = 0.7 x 34.525 x 0.83773 x 2.35

F = 47.57 kN

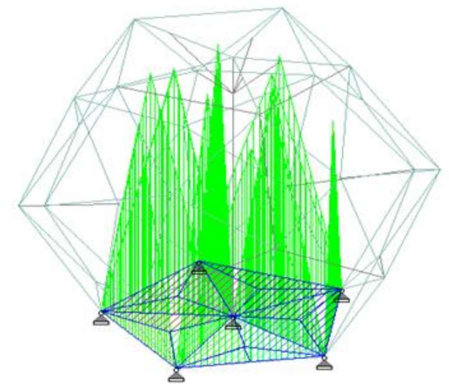

Fig 13: Live Load

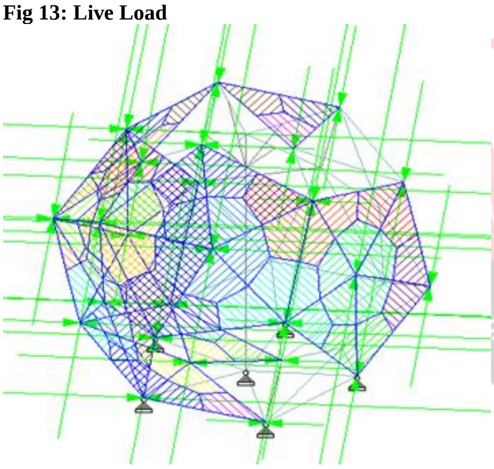

Fig 14: Wind Lad

C. Design

After the analysis is done, designing is carried out. Designing manually all the components considering the complex load combinations will be a time consuming and hectic work, which is also subjected to manual errors. This where BIM plays major role. BIM facilitates auto generation of design using STAAD.Pro, which is the key advantage of BIM processing. Selection of parameter is done in the designing phase. After that design commands are given. Finally once again run analysis is given. Now the model is completely analyzed. The commands given in the designing phase will enable STAAD.Pro software to suggest changes in section that is used. If the suggested section is as same as the provided section, then the design is safe. To check the design property of the member. Double click on the selected member. A dialogue box appears, containing details of the selected member displaying the geometry, property, loading, shear bending, deflection, design property, steel design. The details of initially assigned members can be found from property option and software recommended section can be found in design property option (See Fig 15,16).

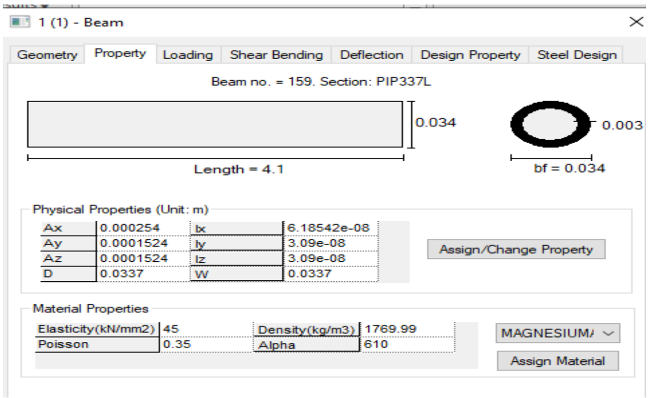

Fig 15: Initially assigned section of central stem

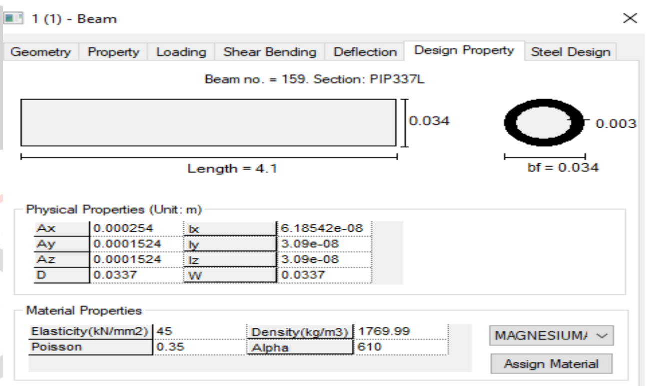

Fig 16: Finally assigned section of central stem

D. Analysis Results

The analysis and design of the structure is done using STAAD.Pro, it is easy to generate the report of complex values. After the analysis is carried out in STAAD.Pro, results can be obtained from post processing option. Nodal displacement summary and support reaction summary is listed below (see table 1,2). As the structure does not have foundation, pinned support is provided. The bending moment at pinned support is zero. Therefore, the bending moment values generated from the report is also zero. Though the analysis and result is done for the whole structure, yet the connection phase is remaining. The connection design is the future scope of the project.

Table 1: Nodal displacement summary

	Node	Load combination	Horizontal	Vertical
Max X	36	6 ULC, 1.5 DEAD + 1.5 LIVE	3.88E+10	-4.81E+09
Min X	39	6 ULC, 1.5 DEAD + 1.5	-9.88E+10	-4.80E+09

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		LIVE		
Max Y	34	6 ULC, 1.5 DEAD + 1.5 LIVE	-2.57E+07	2.63E+10
Min Y	36	6 ULC, 1.5 DEAD + 1.5 LIVE	3.88E+10	-4.81E+09
Max Z	34	6 ULC, 1.5 DEAD + 1.5 LIVE	-2.57E+07	2.63E+10
Min Z	37	6 ULC, 1.5 DEAD + 1.5 LIVE	-1.01E+07	6.86E+09
Max rX	14	6 ULC, 1.5 DEAD + 1.5 LIVE	0.098	-0.008
Min rX	21	6 ULC, 1.5 DEAD + 1.5 LIVE	1.232	-0.786
Max rY	19	6 ULC, 1.5 DEAD + 1.5 LIVE	0.467	-0.302
Min rY	29	6 ULC, 1.5 DEAD + 1.5 LIVE	-16.647	-9.027
Max rZ	23	6 ULC, 1.5 DEAD + 1.5 LIVE	-0.046	0.223
Min rZ	24	6 ULC, 1.5 DEAD + 1.5 LIVE	0.132	-0.338
Max Rst	39	6 ULC, 1.5 DEAD + 1.5 LIVE	-9.88E+10	-4.80E+09

Table 2: Support reaction summary

			Horizontal	Vertical	Horizontal
	Node	L/C	Fx kN	Fy kN	Fz kN
Max Fx	4	6 ULC, 1.5 DEAD + 1.5 LIVE	1.282	2.417	-0.171
Min Fx	3	6 ULC, 1.5 DEAD + 1.5 LIVE	-1.411	3.841	0.855
Max Fy	6	6 ULC, 1.5 DEAD + 1.5 LIVE	-0.012	6.427	0.004
Min Fy	1	1 WL	0	0	0
Max Fz	2	6 ULC, 1.5 DEAD + 1.5 LIVE	0.557	4.158	1.068
Min Fz	5	6 ULC, 1.5 DEAD + 1.5 LIVE	-0.574	5.217	-1.103

V. CONCLUSION

A Dodecahedron shaped deployable structure is designed in this research work. As this structure is designed for worst case loading conditions, these deployable structures can be used as distress relief shelters and refugee camps. Dodecahedron shaped distress relief shelter is designed using BIM Processing. As this deployable structure is light in weight and eco-san toilet is used, this structure is highly sustainable to environment. Usage of Magnesium alloy makes the structure lightweight, thus enabling for easy portability. As Deploying pattern is simple, the structure can be easily deployed manually in the required site. This type of distress relief deploying structure provides great privacy and security to the distress affected people or migrating refugees. The total weight of the structure is arrived to be 531Kg Approximately. Considering the Magnesium alloy per kilogram rate as per industry standard as 800 Rupees. The total material cost is arrived to be 4,24,800 Rupees. As the structure is very low weight, it can be carried easily to the desired places during emergency crisis. As the whole structure is made up of magnesium alloy, the workability of the structure is more as well as corrosion resistance. Magnesium alloy is the strongest and lightweight material ever known to humankind. Which is used in making of aircrafts, military equipment, and car. Using this strongest material provides us with impeccable strength to the structure considering privacy and security. Usually distress relief shelters and refugees camp shelters lack privacy and security. This dodecahedron distress relief shelters provide high privacy, high security, easy portability, simple deployment. Load calculation, analysis and design is done in this research work. Connection detailing and designing will be the future scope of the project Though Dodecahedron distress relief shelters have many pros, yet the cons are also considered. Questionable future of deployable technology in India, requirement of skilled workforce for deploying structure, Setting up a highly functional manufacturing unit for mass production involving exaggerating cost, these are considered as cons of the dodecahedron distress relief shelters. However, since deployable structure is focused to serve mass population privacy and safety is priory concerned more than cost.

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