Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Strength design optimization of sandwich composite structures under heavy dynamic loads

To cite this article: A Osman *et al* 2023 *J. Phys.: Conf. Ser.* **2616** 012053

Strength design optimization of sandwich composite structures under heavy dynamic loads

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Abstract. Recent researches have witnessed an increased interest in the Rapid Runway Repair (RRR) methods to rehabilitate damages that may be caused by different incidents, such as: natural disasters of earthquakes, floods or man-made vandalism in civil wars. RRR is a strategic process for airport operations for civil and peace-making missions. The current RRR techniques like precast concrete slabs, metal mats, and fiberglass mats have different pros and cons. The current study numerically investigates CFRP sandwich composite structure for RRR usage, where its strength is maximized by design optimization to reach the possible carrying aircraft wheel capacity and safety factors. The proposed composite structure is advantageous of no corrosion, low erection time, high capacity-to-weight ratio, same finish of runway surface and repaired area, and can be applied over spots of unlevelled or inadequate bearing capacity of 60 cm diameter. The strength of the basic design of composite sandwich structure is first assessed to its maximum allowed carrying aircraft wheel capacity by FE modelling. Secondly, The Genetic Algorithm (GA) optimization technique is applied for maximizing the strength of the composite structure webs satisfying the minimum safety factor of five failure criteria of Tsai-Wu, Tsai-hill, Hoffman, Hashin and maximum stress. Finally, the achieved results promoted the usage of the composite structure to operate at the taxiways, runways, and theoretically, landing and take-off areas.

1. Introduction

Transport infrastructures are the essential lifelines that support and provide the population's basic requirements, such as: food, electricity, telecommunications, waterworks, health and safety networks, and sewage systems [1]. As a result, the transportation network is essential [2], and its malfunction jeopardizes individual lives. In times of emergency of natural disasters, air transport fields are considered the most strategic transportation infrastructure and require high attention. Such that, other transportation infrastructures maybe disconnected as a result of catastrophic events as earthquake, flood, or hurricanes. Given this, air transport fields are the unique rapid connection between territories [1,3,4]. To maintain a successful rescue operation, fully functional transportation system is essential [5–7]. As a result, repair and maintenance work should be done quickly and effectively to guarantee the operations run smoothly [8].

The North Atlantic Treaty Organization (NATO) released the Standardization Agreement (STANAG) 2929 on this subject in 2016 [2]. The Air Force has long investigated rapid runway repair (RRR) because of its strategic relevance. When a speedy repair is required, it offers information and components that are beneficial to the civil sector as well. A conventional pavement damage is regarded as a crater with a real diameter of 12 m and a maximum depth of 3 m. The phrase "real diameter" refers to both the actual warp-induced crater and the nearby damaged pavement. Two types of repairs might be used in such circumstances, which are: site repairs and repairs using prefabricated components. Application of modular prefabricated components on roller-compacted granular materials is referred to as "repairs using prefabricated elements." Compared to those used on-site, this approach offers increased strength and prevents Foreign Object Debris (FOD).

Currently, there are three types of modular repairs are commonly used, which are: Precast or prestressed concrete slabs, metal mats, and fiberglass mats. The precast concrete slabs are installed 15cm thick and 1.5m wide on a levelled base that is 15cm below the final pavement level, Slabs feature two slots for lifting, a double internal reinforcement, and a steel confinement profile around their perimeter [9], whereas pre-stressed concrete slabs are fabricated of a standard size of 2m wide and 6m length and produced with thicknesses of 14cm, 18cm, 20cm, and 24cm. Prestressing of the concrete slab is used to reduce the cracks and steel reinforcement. Figure 1, shows a photo of the pre-stressed concrete airfield slabs, named as (PAG). Both systems offer durability and bearing capacity but face a number of operating challenges: The seams should be finished with hot mastics, resins, or hot bitumen once the old pavement has been trimmed precisely to the right number of slabs [10]. The metal aluminium mats (AM-2) are a prefabricated metal components that is hand assembled for covering a crater hole filled and prepared with crushed stone. The aluminum mats are of 4 cm thick and they are utilized due to its their great strength and relatively low weight. The outside mat elements are linked to each other to prevent removal and the risk of FOD, and joints are precise and uncomplicated, figure 3 shows the process of AM-2 assembly over a crater hole. Fiberglass mats are type of fabrics impregnated with thermoset or thermoplastic resins, the damaged pavement are firstly leveled with well distributed particle size of aggregates, rolled and leveled with trimmed down portion of pavement, to reduce the risk of FOD, a fiberglass mat made of two or more layers is placed on top, [11]. Finally, bolts and plugs are used to secure the mat to the pavement. The longest step of this quick and easy process is connecting to the ground [12].

Figure 1. Pre-stressed concrete labs [4]

Figure 2. Aluminium mats (AM-2) [5]

Figure 3. Fiberglass mats [5]

The excellent strength-to-weight of composite materials makes their usage in a variety of structural applications very advantageous, and promote composites as great alternative to metallic materials. Utilizing composites allow the designer to control the material orthotropic characteristics, such that it could be changed to suit a particular structural need. The laminate stacking sequence (ply orientation) is the main design variable that has to be used to manage and accomplish this objective. In the current study, a sandwich composite structure developed by A. Osman for decking light weight deployable bridges is investigated for runway repair [13]. Airfield industry considers safety as a first priority. Therefore, the sandwich composite mat bearing capacity is examined and maximized to suit the worst loading case of various aircrafts wheel loads. Design optimization is used to find the optimal design among a vast range of design points. The GA built-in the finite element package ANSYS is implemented to increase the margin of failure in relation to the applied loadings, the stacking order of the laminate fibres is taken into consideration as the design variable. Five failure criteria are used to conduct the failure analysis, namely: Tsai-Wu, Tsai-Hill, Hoffman, Hashin, and maximum stress. The sandwich composite mat is examined twice, once while performing the material properties of wet carbon/epoxy characterized A. Osman [13], the second using MTM28-1/T700 prepreg material properties for the vertical webs only, the mechanical characteristics are identified by the manufacturer.

2. Sandwich composite mat structure

The sandwich composite mat core structure consists of honeycomb polyisocyanurate foam beams of 64 kg/m3, and depth of 76mm, and wrapped with 6 unidirectional carbon fabrics of 0.41 kg/m2. The fibre architect is a balanced symmetric laminate of [01, ±451]S structure. The polyisocyanurate foam beams are separated by vertical webs of carbon unidirectional fabric having [02, ±451]S fibre orientation. The zero direction is aligned normal to the facing skins in order to utilize the webs' maximum compression capacity. The upper and lower facing skins are composed of 22, and 6 carbon UD layers. The maximum dry fibre areal weight of the core is 3.26 kg/m2. The total core areal weight is 14.11 kg/m2. Figure 4 shows an illustration of the core configuration. The main supporting component for the sandwich core compression capacity is the vertical webs. The carbon/epoxy laminate webs' buckling capacity is maintained by the elastic lateral support of the foam as well as the mid bracing by honeycomb beams.

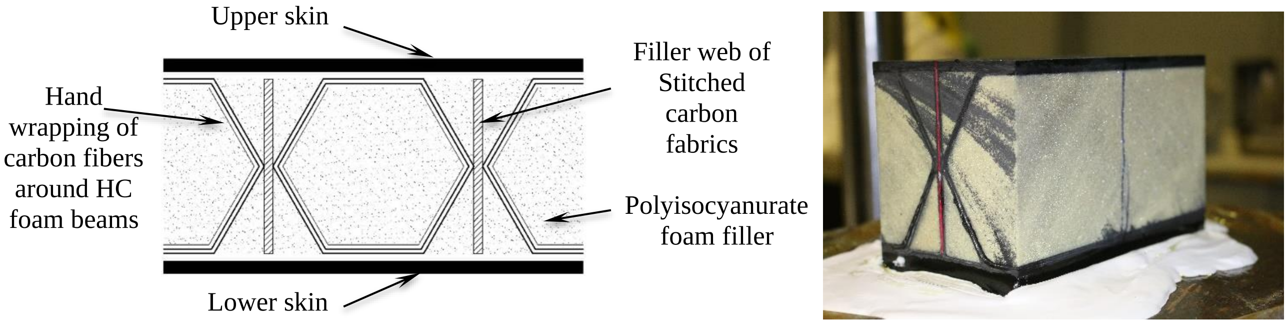

Figure 4. An illustration of the mat sandwich core design configuration [13]

3. Aircraft wheel design loads

The sandwich composite structure is designed to sustain the aircraft wheal loads: F4, C130, C141, C5, and C17 tabulated in Table 1. Each aircraft wheel load and its associated footprint dimension are used to calculate the maximum induced tire pressure over the area supported by the vertical web of the sandwich core structure. Such that, the maximum tire pressure is consequently used to optimize the design of the vertical carbon laminate webs of the core. The tire pressure envelops of all aircraft types resulted in a value of 1.89 MPa.

Table 1. Aircraft wheel design loads [14–19]

Aircraft type	Max takeoff weight (kN)	load of main gear	No. of main gear wheels	Wheel load (kN)	Contact area (cm^2)	Width of wheel (cm)	Tire pressure (MPa)
F4	263	90.00%	2	118.39	645.16	25.40	1.89
C130	794	95.84%	4	190.19	2032.25	45.08	0.841
C141	1565	94.40%	8	184.66	1294.19	35.97	1.355
C5	3810	94.32%	24	149.74	1756.77	41.91	0.791
C17	2654	92.00%	12	203.44	2025.80	45.01	1.01

4. Integrity of proposed system

In the current study, two connecting joint configurations are proposed to provide a fully integrated mat system. Figure 5.a represents a shear joint that depends on aligning an aluminium rod through an aluminium ring encased in GFRP core to assemble two mats from sides, whereas another configuration is proposed of a clamp connecter composed of an aluminium male connector encased in GFRP core in one side of a mat that is connected to another mat has a female aluminium connector as shown in figure 5.b. The final mat assembly can be represented as illustrated in figure 5.c.

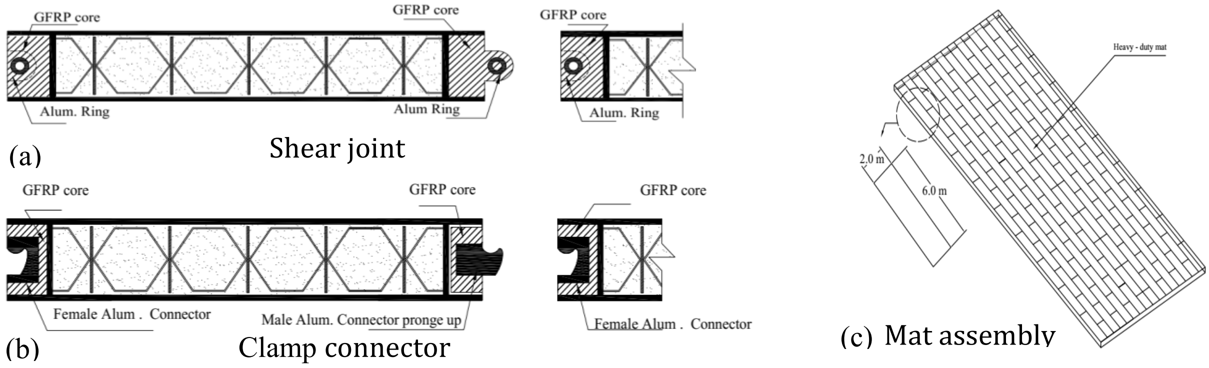

Figure 5. An illustration of the mat sandwich core design configuration

5. 3D FEM model and material properties description

The main carrying compression capacity of the sandwich composite mat is the vertical webs. These composite plates are modelled using the layered element type "SHELL181" in the FE package ANSYS. Moreover, upper, lower skins, and carbon fabrics wrapped around the hexagonal shaped foam beams are modelled using the same element type. The polyisocyanurate foam and the rich resin area in each core are modelled using the element type "SOILD186", the element type is functioned to behave as an elastic lateral spring with an equivalent lateral stiffness of each material. The two-sided hexagonal shape of foam beams around the vertical webs provides lateral supports at the mid-height of the carbon/epoxy laminate plates. Figure 6 shows a schematic drawing of vertical webs local boundary conditions. Based on A. Osman study, the shear failure of the sandwich core is examined by applying a three point load test [13].

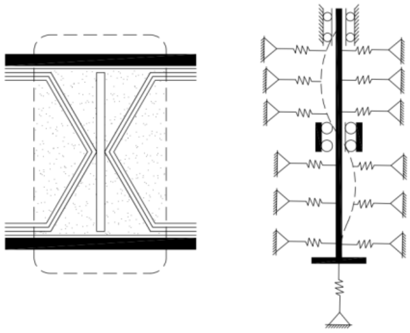

Figure 6. Schematic description of boundary conditions for the vertical laminated webs [13]

In the current study, the same test is applied numerically using the aircraft wheel loads on the composite mat. The three-point load test is modelled for only a part of the composite mat, which has a planar dimensions of 8 cm width and 75 cm length, the width represents a quarter core section of the composite mat with the vertical webs as well as the supporting hexagonal plate sides. Sandwich composite mat thickness including upper and lower skins is of 8 cm depth. The mat is rested from its ends on two thick steel plates of 7 cm thickness and 15 cm length, which are both restrained from a single line at their mid-bottom surface to behave as a simply supported beam. Given this, a free span of 60 cm from support to support is provided. The model is meshed using mixed quadrilateral and triangular shaped mesh of 10 mm size. Figure 7. a and 7.b shows the FE model boundary conditions and the meshing pattern of the composite mat, respectively.

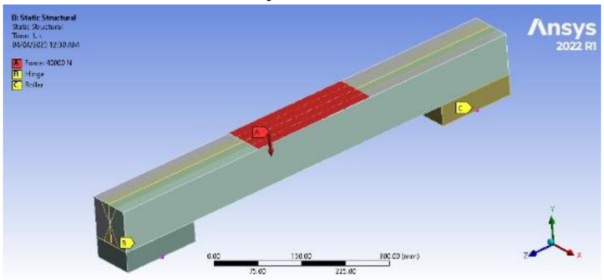

Figure 7.a model boundary condition

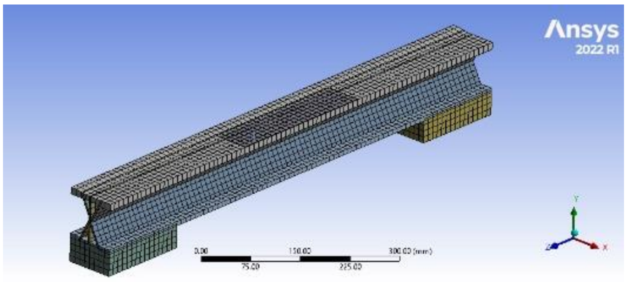

Figure 7.b model meshing pattern

The material properties of the used wet carbon/epoxy were characterized by A. Osman [13], whereas it were obtained from the manufacturer for the carbon prepreg MTM28-1/T700, resin matrix, and the polyisocyanurate foam. Table 2 lists the wet carbon/epoxy material properties, Table 3 illustrates the carbon prepreg mechanical characteristics. Table 4 tabulates the ultimate strength values for the 64 kg/m³ polyisocyanurate foam and the resin matrix.

Table 2. Wet carbon/epoxy mechanical properties

Property			Value
Tension [0°]	Tensile modulus	E_{1t} (GPa)	119
	Poisson ratio	υ_{12}	0.38
	Ultimate tensile	X_t (MPa)	1580
Compression [0°]	Compression modulus	E_{1c} (GPa)	96.6
	Ultimate compression	X_c (MPa)	322
Compression [90°]	Compression modulus	E_{2c} (GPa)	7.45
	Ultimate compression	Y_c (MPa)	90
Shear [±45°]	Shear modulus	G_{12} (GPa)	4.28
	Ultimate in-plane shear	S (MPa)	35

Table 3. Carbon prepreg MTM28-1/T700 mechanical properties

Property			Value
Tension [0°]	Tensile modulus	E_{1t} (GPa)	127
	Poisson ratio	υ_{12}	0.5
	Ultimate tensile	X_t (MPa)	2735
Compression [0°]	Compression modulus	E_{1c} (GPa)	116
	Ultimate compression	X_c (MPa)	1309
Compression [90°]	Compression modulus	E_{2c} (GPa)	16
	Ultimate compression	Y_c (MPa)	85
Shear [±45°]	Shear modulus	G_{12} (GPa)	3.7
	Ultimate in-plane shear	S (MPa)	127.0

Table 4. Ultimate strength properties of the foam and resin matrix and resin matrix

Property	Epoxy resin	(64 kg/m³) Polyisocyanurate
Compressive strength	86200 kPa	524 kPa
Tensile strength	72400 kPa	479 kPa
Shear Strength	123400 kPa	362 kPa

6. Maximization problem formulation

The objective function of the optimization problem is to maximize the safety factor of five failure criteria. the objective is subjected to a feasibility constraint of a safety factor greater than or equal to one, the minimum value obtained from the all the five analysis is considered the best achieved. The design variables are selected from a list of discrete values of ply orientations between -90 º to 90 º with a step size value of 15º. The aforementioned discrete optimization formulation can be formulated as follows:

Maximize: $\min S_F\left(x^1, x^2, \ldots, x^d\right) \qquad d = 1,2,\ldots,N_{dv}$

Subjected to: $-90^{\circ} \le g_q\left(x^1, x^2, \ldots, x^d\right) \le 90^{\circ} \qquad d = 1,2,\ldots,N_{dv}$

$$S_F \ge 1,$$

$$q = 1,2,\ldots,\mathrm{M},$$

$$x^d \in S_d = \{X_1, X_2, \ldots, X_{Dis}\}$$

where S_F (x^1,x^2, ..., x^d) is the safety factor function in terms of a set of design variables x^1,x^2, ..., x^d. A single design variable x^d has a scalar value that belongs to a vector S_d which includes all the scalar values {X_1, X_2, ..., X_{Dis}} corresponding to every discrete variable value. The optimization problem is subjected to a constraint function of the inequality g(x^1,x^2, ..., x^d). The symbols Ndv , M , and Dis are attributed to the numbers of design variables, inequality functions, and the number of all available discrete variables respectively. The hybrid variant Non-dominated Sorted Genetic Algorithm-II built in the FE package ANSYS is used in the current study for strength maximization of the laminated web [20]. The technique relies on creating a pareto ranking system that uses a quick non-dominated sorting, such that higher rank is assigned for feasible solutions rather than infeasible designs.

7. Results and discussion

The structure problem is simplified by applying the aircraft wheel tire pressure over the top skin of the vertical webs of the sandwich structure, such that the composite mat is examined under a three-point load testing. Two composite mats are examined with two different core material. A basic mat manufactured of wet carbon/epoxy for the core webs using VARTM infusion. The second mat is manufactured of MTM28-1/T700 carbon prepreg for the core webs. The numerical assessment of the basic fibre architectural design of both sandwich cores resulted in a minimum safety factor of 1.072 subjected to F4 wheel load tire pressure, and a maximum deflection of 2.63 mm. Figure 8.a and 8.b shows the obtained results of deflection, and safety factor of the numerically investigated basic design for the composite mats, respectively.

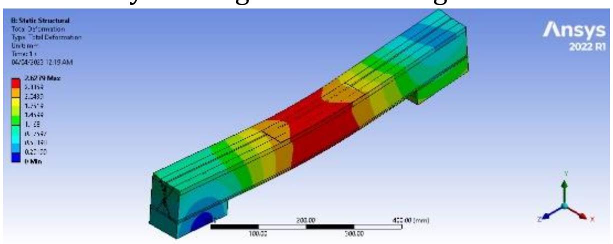

Figure 8.a model boundary condition

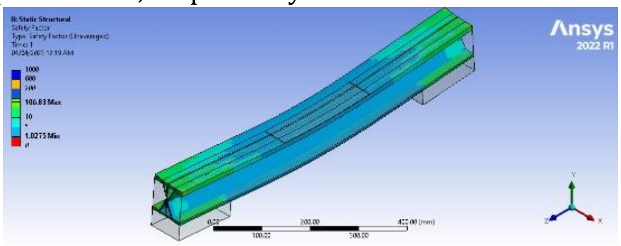

Figure 8.b model meshing pattern

Remarkable results are achieved after utilizing strength design optimization of the vertical laminated webs. Firstly, a safety factor of 1.424 is obtained for the wet carbon/epoxy laminated vertical webs having fibre architect of [90, -45,45,60] s for a symmetric balanced laminate. On the other hand, more enhanced value of 1.632 is achieved by the vertical webs manufactured of carbon prepregs. This value complies with building code provisions for having a factor of safety more than 1.5 for a composite structure. The final fibre orientation resulted in a symmetric laminate of [-45,90,602]s .Figure 9 represents the optimization history for maximizing the safety factor of both composite cores manufactured of wet carbon/epoxy and carbon prepreg.

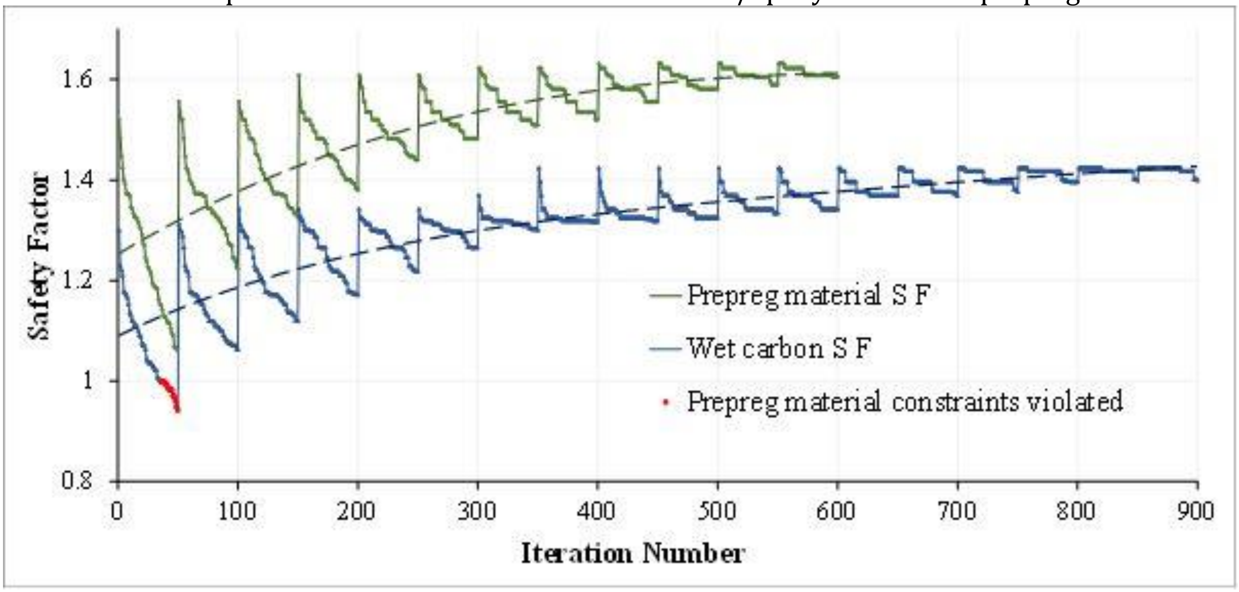

Figure 9. Optimization history for maximizing strength safety factor of wet carbon/epoxy and carbon prepreg composite mats

8. Conclusion

The current research proposes an alternative solution for rapid runway repair in order to retrieve damaged air transport fields to a full functional situation. The proposed alternative is a sandwich composite mat capable of replacing effectively precast or pre-stressed concrete systems, AM-2 aluminium systems, and cope the used FRP composite mats disadvantages for the needs of many bolts and plugs to fastened the mat, in addition the necessary need of underneath compacted soil which may not in some situation achieved due to rapid repair and timing. The sandwich composite mat is developed originally for decking bridges. The current study conducted a strength design optimization to investigate the adequacy of the composite mat to support multiple aircraft loads.

The strength design optimization showed a promising result in upgrading the mat bearing capacity to encounter all the aircraft wheel loading values, namely: F4, C130, C5, C141, and C17. Vertical laminated webs which are the main carrying capacity elements in the sandwich composite mat are examined once manufactured of wet carbon/epoxy and another time fabricated of MTM28-1/T700 carbon prepregs. Design is accomplished to satisfy the minimum safety factor of five failure criteria which are: maximum stress, Tsai-Wu, Tsai-Hill, Hashin, and Hoffman. Minimum safety factor of all failure criteria obtained is 1.424 for the case of wet carbon/epoxy webs having fiber architecture of, [90, -45,45,60]s, and 1.6 for carbon prepreg vertical plates with fiber orientation of [-45,90,602]s. The proposed sandwich composite mats are characterized with its superior weight to capacity ratio, such that a mat of the size 2m by 6m weights approximately 175 kgs including the aluminum joints, given this, the mat can be assembled by only 5 to 6 persons. The study of the sandwich composite mat must be experimentally studied against repeated loads, and joints have to be examined to fulfil the system computability.

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