AFRL-ML-WP-TP-2007-444

DECKS FOR RAPID RUNWAY MAT APPLICATION (POSTPRINT)

Dean C. Foster

APRIL 2007

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
April 2007	Conference Paper Postprint	

4. TITLE AND SUBTITLE
DECKS FOR RAPID RUNWAY MAT APPLICATION (POSTPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62102F

6. AUTHOR(S)
Dean C. Foster

5d. PROJECT NUMBER
4347

5e. TASK NUMBER
RG

5f. WORK UNIT NUMBER
M03R1000

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Structural Materials Branch (AFRL/MLBC)
Nonmetallic Materials Division
Materials and Manufacturing Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7750

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-ML-WP-TP-2007-444

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Materials and Manufacturing Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7750

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL-ML-WP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-ML-WP-TP-2007-444

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Conference article published in the Proceedings of the 2007 Polymer Composite Conference. This is a work of the U.S. Government and is not subject to copyright protection in the United States.
PAO Case Number: AFRL/WS 07-0574, 15 Mar 2007. Paper contains color content.

14. ABSTRACT
Since the 1960s the Air Force has employed an aluminum matting system, AM-2, for rapid aircraft parking ramp expansion (RPRE) in austere environments. While functional and durable, AM-2 is heavy and cumbersome to install. The restrictive weight of AM-2 and its tedious installation complicate the process of deploying aircraft. The Air Force Research laboratory (AFRL) is developing an AM-2 alternative made from composite materials. This next generation matting system, AM-X, consists of a lightweight foam core sandwiched between composite face sheets. The critical key performance parameters (KPP) for AM-X are a unit weight between 154.7 N/m^2 (3.23 lbs/ft^2) and 232.7 N/m^2 (4.86 lbs/ft^2), and a useful life requirement between 1500 and 1000 passes by a tire carrying a 133,733N (30,000 lb) load creating a surface pressure of 241.9N/cm^2 (350 psi) over a soil with a California Bearing Ration (CBR) value of 6 with no more than 3.81cm (1.5 in) deflection in the panel. In addition, the panel size is also critical for transportability requirements enabling the use of the standard 463L pallet. Successful proof-of-concept tests were completed in June 2003 demonstrating that the panel deflection requirement can be met. Design iterations focusing on optimizing the panel properties and geometries with respect to deflection are complete. Further mat tests took place in August 2005, June 2006 and September 2006. Results of the design iterations, full scale field testing, and a comparison of design vs. actual deflection of the panels will be reported.

15. SUBJECT TERMS
Composite materials, sandwich structures, pultrusion, resin transfer molding (RTM)

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			
Unclassified	Unclassified	Unclassified	SAR	28	Dean C. Foster **19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Decks for Rapid Runway Mat Applications

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ABSTRACT

Since the 1960s the Air Force has employed an aluminum matting system, AM-2, for rapid aircraft parking ramp expansion (RPRE) in austere environments. While functional and durable, AM-2 is heavy and cumbersome to install. The restrictive weight of AM-2 and its tedious installation complicate the process of deploying aircraft. The Air Force Research Laboratory (AFRL) is developing an AM-2 alternative made from composite materials. This next generation matting system, AM-X, consists of a lightweight foam core sandwiched between composite face sheets. The critical key performance parameters (KPP) for AM-X are a unit weight between 154.7 N/m^2 (3.23 lbs/ft^2) and 232.7 N/m^2 (4.86 lbs/ft^2), and a useful life requirement between 1500 and 1000 passes by a tire carrying a 133,733N (30,000 lb) load creating a surface pressure of 241.9N/cm^2 (350 psi) over a soil with a California Bearing Ration (CBR) value of 6 with no more than 3.81cm (1.5 in) deflection in the panel[1]. In addition, the panel size is also critical for transportability requirements enabling the use of the standard 463L pallet[1]. Successful proof-of-concept tests were completed in June 2003 demonstrating that the panel deflection requirement can be met. Design iterations focusing on optimizing the panel properties and geometries with respect to deflection are complete. Further mat tests took place in August 2005, June 2006 and September 2006. Results of the design iterations, full scale field testing, and a comparison of design vs. actual deflection of the panels will be reported.

KEY WORDS: Composite Materials, Sandwich Structures, Pultrusion, Resin Transfer Molding (RTM)

1. Introduction

Rapid parking ramp expansion (RPRE) is critical to the military for rapid global mobility. The limiting factor in deploying aircraft to austere environments is the amount of suitable taxiways and parking space for aircraft. As more and more aircraft enter a bare base environment, they must land quickly and exit the flight line in order for the next aircraft to be able to touch down. Under these conditions, with enemy fire in some situations, it is critical that suitable taxiways and parking ramps can be constructed quickly and reliably.

The United States Air Force and Marine Corps currently use a matting system known as AM-2 for RPRE, as shown in Figure 1 and detailed in Figure 2. Developed in the early 1960s, AM-2 is an extruded aluminum mat that is 3.8cm (1.5in) thick, comes in a nominal 0.607m x 3.66m (2ft x 12ft) panel size and weighs roughly 310.1N/m^2 (6.46lbs/ft^2). The transport requirements for AM-2 are very taxing, requiring 48 dedicated C-130 aircraft sorties for a standard 18,580.6m^2 (200,000ft^2) parking apron[2]. The mats are also transported on unique non-uniform pallet configuration creating further mission complications. Additionally, the matting system is complicated and difficult to construct. The panels interlock with overlapping and interlocking edge connections, and on rough or uneven surfaces the aluminum edge connections are often difficult or impossible to align properly for interlocking. The weight of the panels also requires a very specific preparatory routine for assembly. This routine requires pallets of the matting to be laid out with a specific offset distance and assembly direction which, if not followed precisely, will require lifting and replacement of the pallets. Finally, the AM-2 matting system consists of many more parts than just the panels themselves including locking bars, edge stiffeners and tie-down parts. These additional parts add complexity and weight to the system.

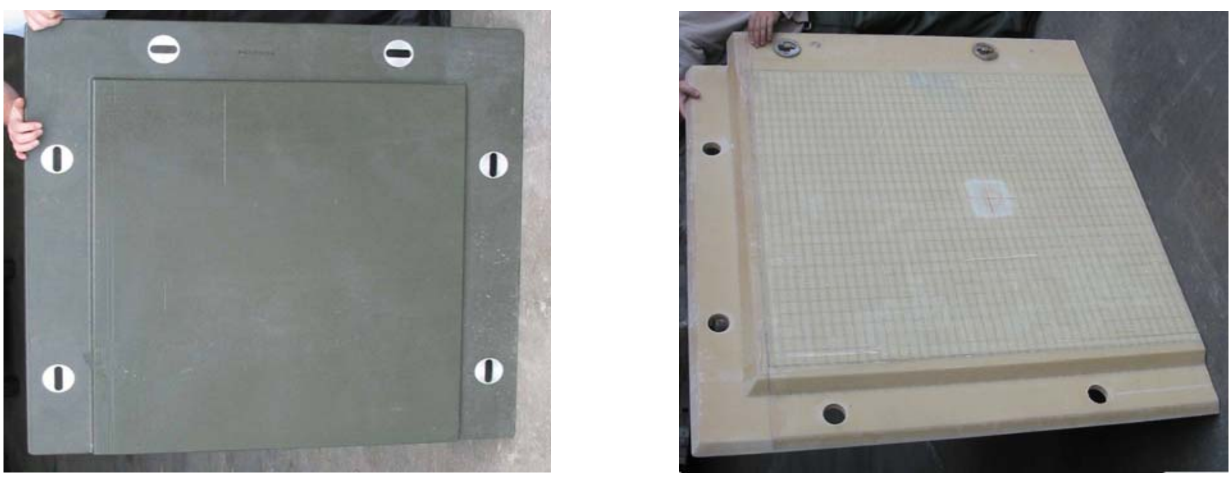
Figure 1: AM-2 matting being assembled

With all of these detractors, AM-2 matting is still known as a sturdy and reliable matting system that gets the job done. And having been produced for nearly 40 years, the cost is low at roughly \$193.75/m^2 (\$18/ft^2). However, the Air Force Air Combat Command (ACC), the Air Force Air Warfare Battlelab (AWB), the Air Force Civil Engineering Support Agency (AFCESA), has seen the need and benefits for a lighter, simpler yet cost effective matting system to replace AM-2. These units have the primary responsibility of constructing the RPRE at austere airfields. Under the developmental name AM-X, many metal and composite alternatives to AM-2 have been in development in conjunction with the Air Force Research Laboratory (AFRL) Materials and Manufacturing Directorate (AFRL/ML) since 2001.

- Interlocking pieces, 3.81 cm (1.5in) thick
- Long Panels: 0.607m x 3.66m (2ft x 12ft), 346N (155lbs)
- Half Panels: 0.607m x 1.83m (2ft x 6ft), 173N (77.5lbs)
- Panel weight: approx. 310.1N/m^2 (6.46lb/ft^2)
- 35 rows of matting: 351.2m^2 (3,780 ft^2)
- Standard C-130 load: 175 pieces (140 long, 35 short); 108,855N (24,412lbs, 12.2tons)
- Standard "patch" = 16.46m x 23.6m (54ft x 77ft 6in)

Figure 2: Details on the AM-2 panels and overall system[2]

Two private companies responded to an Air Force Broad Agency Announcement (BAA) in 2001 to develop composite alternatives to AM-2. Both contractors use a fiber/matrix composite sandwich panel with a closed cell foam core as their prototype mats. These panels are commercial off-the-shelf products modified for the required loading mentioned above. Contractor A's half panels is shown in Figure 3(a) whereas Contractor B's is shown in Figure 3(b). Both prototype panel face sheets are fiberglass fibers in a vinyl-ester matrix, and the foam core is a commercially available closed cell insulating foam as shown in Figure 4. Contractor A uses pultrusion for the manufacture of their matting. Pultrusion is similar to extrusion, but instead of forcing material through a die with a pushing force, all panel materials are oriented, initially fed through a heated die, cured in the die and subsequently pulled. Contractor B uses a more traditional Resin Transfer Molding (RTM) process in which panels are laid up dry, vacuum bagged with resin pulled through the dry preform cured. Both contractors reinforce their core material by a proprietary process of either stitching or filament winding using fiberglass fibers.



(a) (b)

Figure 3: Contractor A's half panel (a) and Contractor B's half panel (b)

Figure 4: Fiberglass/vinyl-ester face sheets and stitching with foam core

An overview of the most important analytical work completed and the corresponding testing of the subsequent design development iterations for the next-generation airfield matting will be outlined here.

2. Capability Development Document Requirements

The requirements set forth in the Acquisition program's Capabilities Development Document (CDD) are extensive. The total CDD requirements for this project are too numerous to list here. However, the Key Performance Parameters (KPPs) are those critical requirements that carry precedence over the other requirements in the CDD. Table 1 lists the AM-X KPP requirements. For any DoD Acquisition program, requirements are constructed with Threshold and Objective values. The Threshold value is the minimum acceptable value for a given requirement, while the Objective value is a desired value for the requirement based on additional effort and trade-off of other requirements. As with the nature of any engineered system, the requirements in the CDD are often competing. Therefore, it is impossible to achieve the objective values of all requirements. Thus, the requirements are inherently "tradable," i.e., meeting the objective or threshold value on one requirement at the expense of another can help achieve greater overall program success.

The critical KPP's are the panel unit weight, number of passes of the controlling aircraft and the overall panel dimensions. Because the goal is between a 25% to 50% weight reductions over the existing AM-2, composite materials offer the best materials choice to accomplish his feat. For these efforts the most severe aircraft loading is the F-15E having a tire pressure of 2.4 MPa (350 psi). It is a single tire assembly concentrating the load over an area of 0.055 m^2 (85.8 in^2). Due to the Transportability KPP and to a lesser extent the lifting capability of military personnel, the panel dimensions are limited to no greater than 2.44 m X 1.22 m (8ft X 4ft). The standard USAF 463L pallet is the controlling criteria for panel dimensions. The pallet has usable area dimensions of 2.64m X 2.13m (104 in X 84 in). Analysis and design efforts were focused on optimizing the panel unit weight against deflection with the F-15E loading. As will be shown below, various subcomponents of the mat system are analyzed for optimization of the panels.

Table 1: Key Performance Parameters (KPPs)[1]

KPP	Developmental Threshold	Developmental Objective
Controlling aircraft for load bearing design and evaluation	C-17, F-15E, and V-22.	Same
Number of C-17 passes before subgrade reaches a 7.62cm (3in) sag over a 148.6m^2 (1600ft^2) area [approx. 12.2m x 12.2m (40ft x 40ft)]	1000 ** Projected capability – to be determined. This number remains to be validated by comparison testing with AM-2 matting.	1500
Number of F-15E passes before subgrade reaches a 3.18cm (1.25in) sag over a 148.6m^2 (1600ft^2) area [approx. 12.2m x 12.2m (40ft x 40ft)]	1000 ** Projected capability – to be determined. This number remains to be validated by comparison testing with AM-2 matting.	1500
Reusable Panels	Mats must be recoverable and suitable for reuse after being cleaned and repacked.	Same
Weight	232.9N/m^2 (4.85lbs/ft^2)	155.1N/m^2 (3.23lbs/ft^2)
Interoperability with adjacent pavements	Must accommodate transition of aircraft between existing airfield pavement (and/or AM-2 matting) to LAM and provide a secure method of anchoring while ensuring that there are no tire hazards or safety issues.	Same
Transportability	2 bundled configurations: 463-L and ISO, 2.44m x 2.44m x 6.10m (8ft x 8ft x 20ft) flat-rack containers. 463L configuration moveable by "10K" forklift.	Same

3. AM-X Development – Proof-of-Concept

Analysis and Design

Each contractor performed their own analysis to modify their respective matting concepts. Both did coupon level testing to validate their designs. Most modifications consisted in densification of their foam core reinforcement and increasing the panel's skin thickness. Contractor A also investigated the cam-lock panel-to-panel connection detail that was provided to each contractor by AFRL engineers.

Load Testing

The proof-of-concept tests for both prototype mats occurred at Tyndall AFB, Panama City, Florida in June of 2003. The tests were done on a soil with a 10 CBR because of constraints of the testing bed at Tyndall. A load cart, as shown in Figure 5 was fitted with an F-15E strike fighter landing gear wheel. This aircraft generates the critical surface load for all Air Force aircraft, having a wheel load of 133,733N (30,000lb) over a contact patch of approximately 548.4cm^2 (85in^2), resulting in a 241.9N/cm^2 (350psi) surface stress. All proposed mat solutions were laid out in a brickwork pattern, as shown in Figure 6. AM-2 patches were laid as transitions from the soil to the first matting field, in between each mat test section, and as a run-out after the last matting field to facilitate load cart maneuvering. The load cart was driven with the loaded wheel traveling along the lines indicated in Figure 6. The load lines spanned a total of 177.8cm (70in), and a normal distribution of passes was generated across the load lines. Test results were very promising in the ability to utilize composite materials for the next generation of airfield matting, AM-X. Contractor B's panel failed after 68 passes, halting the loading. The failure mode was a top face-sheet buckling failure propagating outward from a locking cam in a direction parallel to the loading path. The failure was considered sufficient to halt the test because the cam at the failure point was disbanded from the panel and floated freely under loading. Contractor A's panel, while showing cracking near the cam locks, did not demonstrate any failures sufficient to stop the test. Overall it was concluded that the failure mode from aircraft loading would be near the stress-concentrating discrete cam-locks, as anticipated.

Figure 5: Load cart with F-15E tire and loaded to 133,733N (30,000lb)

The panels themselves showed satisfactory resiliency and load carrying capability away from the stress concentrations. Based upon the success of the modified commercial off-the-shelf products two design iterations have since been accomplished. In these mat development iterations, robust analysis and design of the system were accomplished via finite element models (FEM) and further testing on CBR 6 soils.

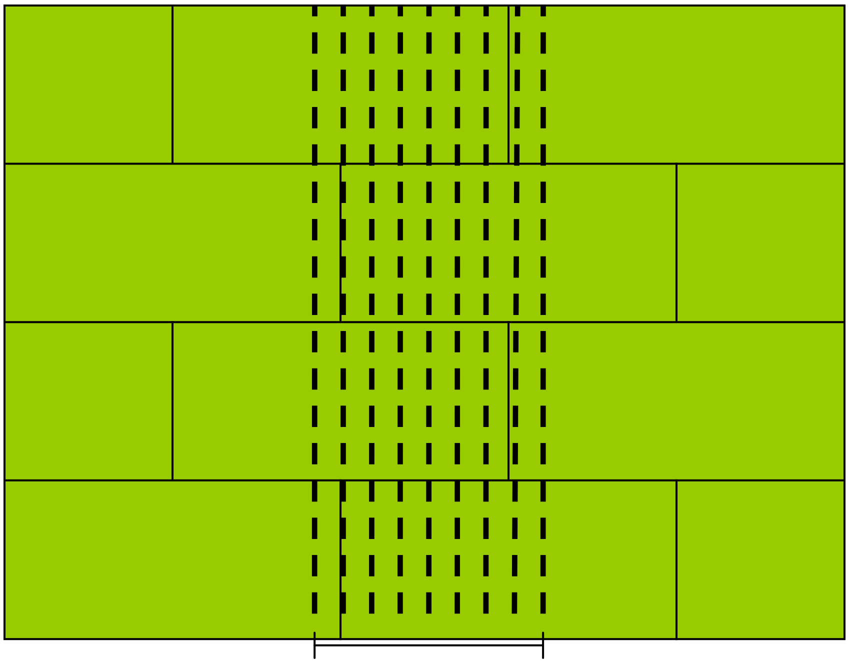


Figure 6: Testing layout with brickwork design and load cart paths

4. AM-X Development – Second Iteration

Analysis and Design

After the proof-of-concept test a thorough analysis and design effort commenced for both contractor prototype mats. Due to the limited capabilities of each contractor the University of Dayton Research Institute (UDRI) was employed as an independent design and analysis agency for all iterations on the composite matting alternatives. UDRI utilized 3-D finite element model for all design and analysis employing the commercial Abaqus software. For both matting contractors the tire loading on the mats was essentially the same for each FEM. All models employed between two and four full size mats depending on the particular detail being considered. The mats were explicitly modeled as skins and cores using material properties supplied by each contractor. The panel-to-panel connection utilized a cam-lock connector. These cam-lock connectors were also explicitly modeled. In addition, a very detailed model of the panel joints was developed using contact elements where appropriate to capture the stresses at the joint and their effects on the core and skins. The mats were modeled as resting on the soil and the soil was modeled using regular hexahedral elements near the mats and infinite elements representing the far-field soil, as shown in Figure 7[3]. Developing an accurate FEM of a CBR 6 soil was beyond the scope of this project but extremely important for accurate analysis and design results. Critical to the success of the design is to capture the soil mat interaction for proper sizing of the core and skin strengths. To accomplish this secant moduli at 1% and 8% deformation were obtained from load-penetration curves for a standard soil having a CBR of 100[4]. Scaling these values to a CBR of 6 resulted in high soil modulus of 31.01 MPa (4,500 psi) for 1% deformation curve and a low soil modulus of 10.34 MPa (1,500 psi) for 8% deformation curve. Preliminary analysis of the soil assumed an isotropic elastic material predicted maximum strains in the soil of less than 3% using the low modulus and less than 1.5% using the high modulus. Consequently, the high modulus is considered to be representative of a typical soil response while the low modulus is considered to be more conservative. Therefore in light of a more developed soil model and the desire to be conservative for design, it was decided to use the low modulus value of 10.34 MPa (1,500 psi) and a Poisson's ratio of 0.33 for all design cases[3].

The design effort for Contractor A focused on the mat edge and to assess the influence of core stiffness on skin stresses and panel deflection. One edge design case resulted in a lapped edge configuration where at the flange and panel intersection a near vertical step exists tapering down to half the panel thickness over the 165.1 mm (6.5 inch) lap or flange length. The other design involved a tapered edge having a 15° vertical angle over a 165.1 mm (6.5 inch) flange length. For all analysis cases six loading locations, as shown in Figure 8, were used. Loading cases 1 through 3 positions the load at the midpoint between panel connections where load case 1 has the load on the panel with its flange on top thus causing the top flange of the loaded panel to push against the bottom flange of the unloaded panel. Load case 2 has the load directly over the flanged edge while load case 3 is position on the panel having its flange on the bottom thus trying to separate or open the panel joint.

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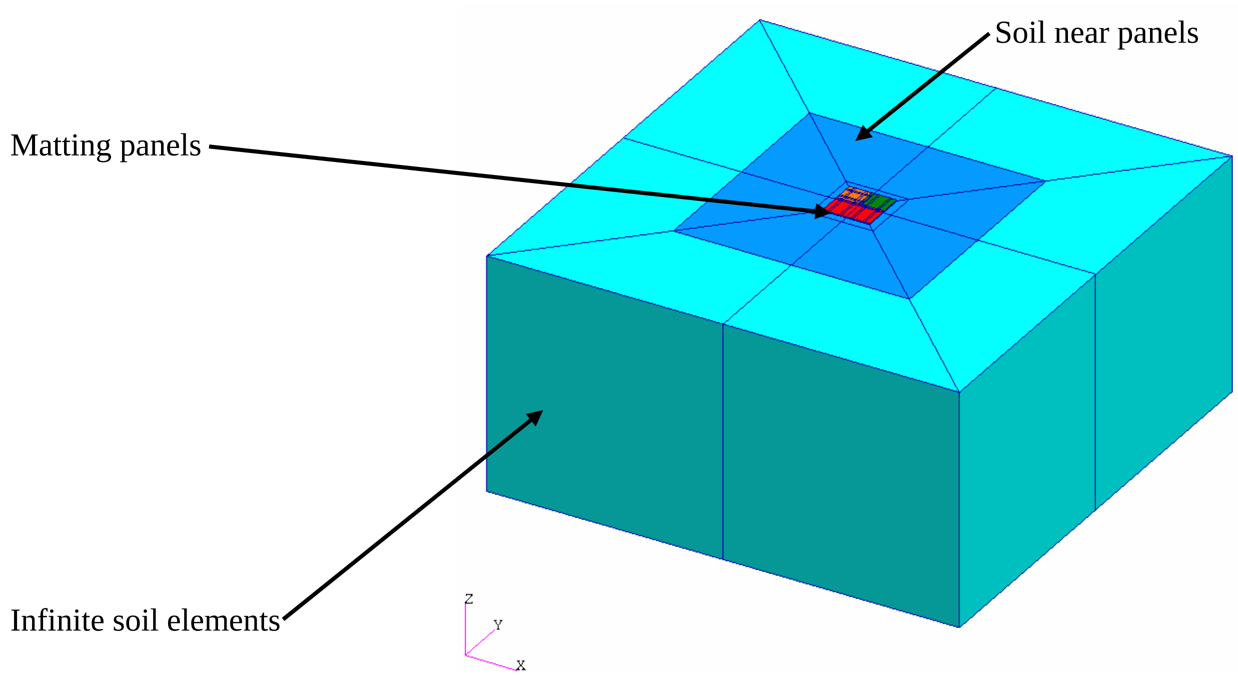


Figure 7: Representation of soil model used for all design and analysis cases

Loading cases 4 through 6 are in line with the panel connections where load case 4 is positioned the same as load case 1, load case 5 is positioned the same as load case 2 and load case 6 is positioned the same as load case 3. Thirty design iterations were completed for Contractor A.

Key findings from the lapped edge design cases are that the margin of safety in the skins away from the panel edges are relatively high, however, at the edge they are low. In addition the margin of safety in the core at the edge is also low. Results from the tapered edge analysis show that the margin of safety for the skins away from the edge and at the panel edge is high. However, the margin of safety for the core in the edge is negative[3]. This coupled with the difficulty of manufacturing the tapered edge and the cam-lock panel connection mechanism eliminated this joint from any further consideration. Thus the joint the as shown in Figure 3(a) having the lapped edge of 155.7 mm (6.13 inches) wide was used for the test specimens evaluated for this second iteration.

In addition to the edge design two different core moduli were supplied by Contractor A while using the same composite skin material properties for analysis to compare core stiffness to panel deflection using the lapped edge design. Results of this analysis are

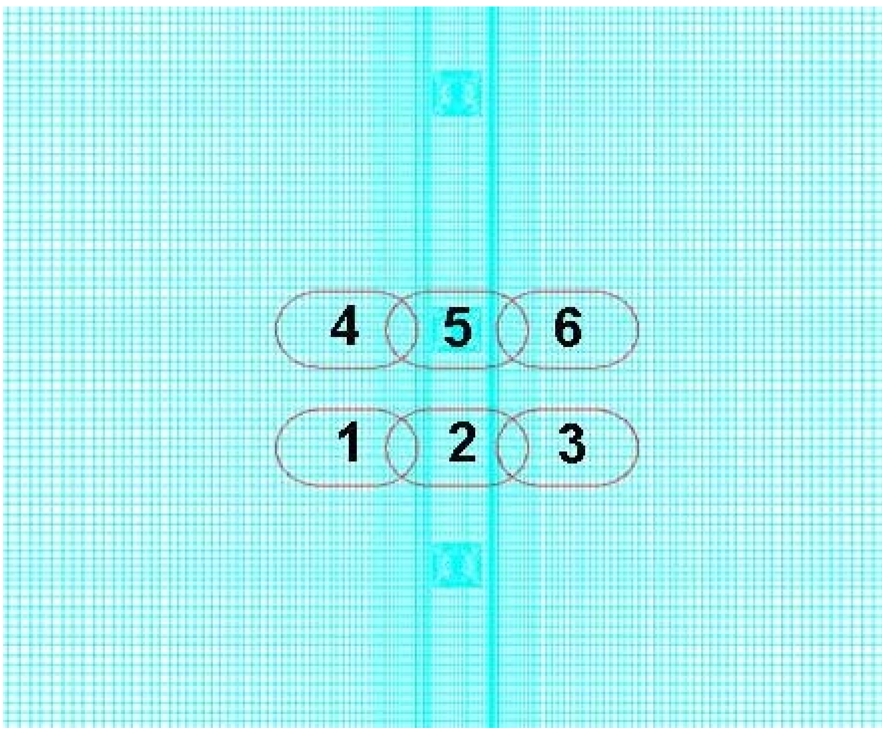


Figure 8: Loading diagram showing position of tire for Contractor A analysis and design

shown in Figure 9. As expected stiffening the core reduces the deflection, however, in this case it is less than what would be computed for an unsupported beam or plate[3]. This indicates that a higher portion of the load is being carried by the soil. Due to the simplified soil model employed for analysis this result could be a double edge sword where testing will validate the design assumptions.

After the proof-of-concept test as described above Contractor A changed the panel edge connection detail to a tongue and groove type connection, as shown in Figure 10, using plastic locking cams. This change was intended to reduce panel field assembly difficulties encountered in the proof-of-concept tests. In addition, internal analysis results indicated a more robust panel connection. Internal field testing validated their results.

For Contractor B the design and analysis effort focused on evaluation of various skin and core materials as well as analysis of their lapped edge joint. In addition they investigated varying the panel width similar to that of the existing AM-2. A total of thirty-eight design/analysis cases were completed for Contractor B, 24 investigating the skin/core stresses, 8 design cases investigating the lapped edge and 6 analyzing a narrow panel configuration. As previously mentioned the panel dimensions were set at a nominal 2.44 m X 1.22 m (8ft X 4ft) for efficient utilization of the 463L pallet. However, the critical dimension with the 463L pallet is the length of the panel. Thus keeping the panel length no longer than 2.44 m (8ft) accomplishes optimized utilization of the 463L pallet per the CDD requirements. Results of the narrow panel analysis offer no benefit over the nominal 2.44 m X 1.22 m (8ft X 4ft) mat dimensions, therefore the narrow panel configuration was removed from further consideration.

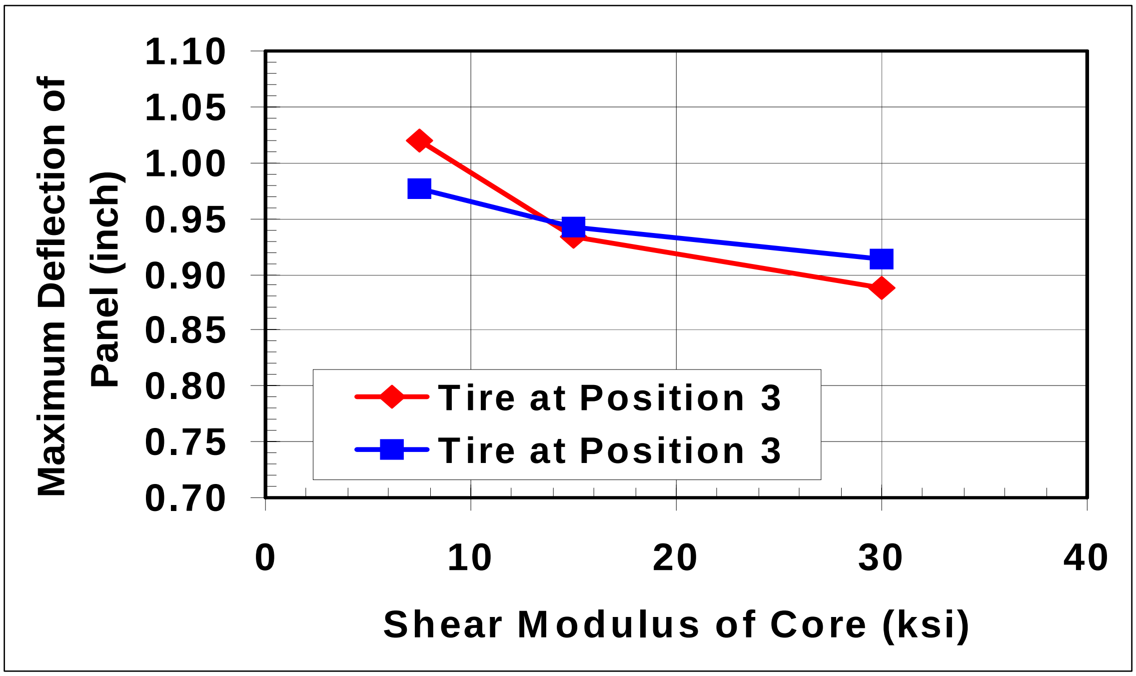


Figure 9: Influence of core stress on panel deflection for Contractor A

Figure 10: Contractor A panel edge modification from lapped edge to tongue and groove

Results of the skin/core analysis are shown in Figure 11. The baseline analysis was that of the commercial off-the-shelf product used in the proof-of-concept tests in June of 2003. Switching the core direction with respect to loading path resulted in approximately 8% reduction in deflection over the range of core thickness. However, traffic over the mats will not be directional and since the analysis indicated the deflection is under the CDD requirements of 31.8 mm (1.25 in) no benefit is obtained orienting the core to one particular direction. Also no benefit was obtained using a hybrid bottom skin. Analysis results do show a reduction in deflection by incorporating carbon fiber plies in the lower skin for bending stress but the benefit to cost was not enough for further consideration. The largest gain was utilizing a 3.18 mm (1.25 in) skin thickness for both the upper and lower skin of the panel. The range of skin thickness considered was from 1.19mm to 3.18 mm (0.0467 in – 0.125 in) in various combinations as the top and bottom skin. Additionally from the analysis results there is no further gain in reducing deflection with increasing core thickness. Therefore the decision to set Contractor B nominal core thickness at 50.8 mm (2.0 in) for the duration of this round of development was made.

Contractor B's lapped edge geometry is shown in Figure 12. The lapped edge is approximately 152.4mm (6 in) long and tapers at a 45° angle from the full panel thickness to half panel thickness and finishes with another 45° taper over the remaining half panel thickness. Analysis of the lapped edge configuration for Contractor B resulted in two loading configurations. The first load configuration is shown in Figure 13(a) where load case 1 is in the center of the panel, load case 2 is on the panel having the lapped edge on the bottom tending to open the joint, load case 3 is directly over the joint and load case 4 is on the panel having the lapped edge on top tending to keep the joint closed. The second configuration is shown in Figure 13(b) and is situated at the corner where three mats come together. Load case 7 in on the panel having both lapped edges on the bottom of panels 1 and 2 tending to open the joint, load case 8 is on the panel having one lapped edge on top of panel 3 and the other on the bottom of panel 1 and load case 9 is directly over the corner of the three panels. Key findings in this investigation are:

- Deflections and skin stresses are maximum for load case 3 and 9
- Maximum joint open of 5.1mm (0.2 in) occurs at load case 4
- Vertical core stresses significantly exceed the tire loading indicating core crushing for all load cases
- Joint openings are less for load cases 7-9 than for 1-4

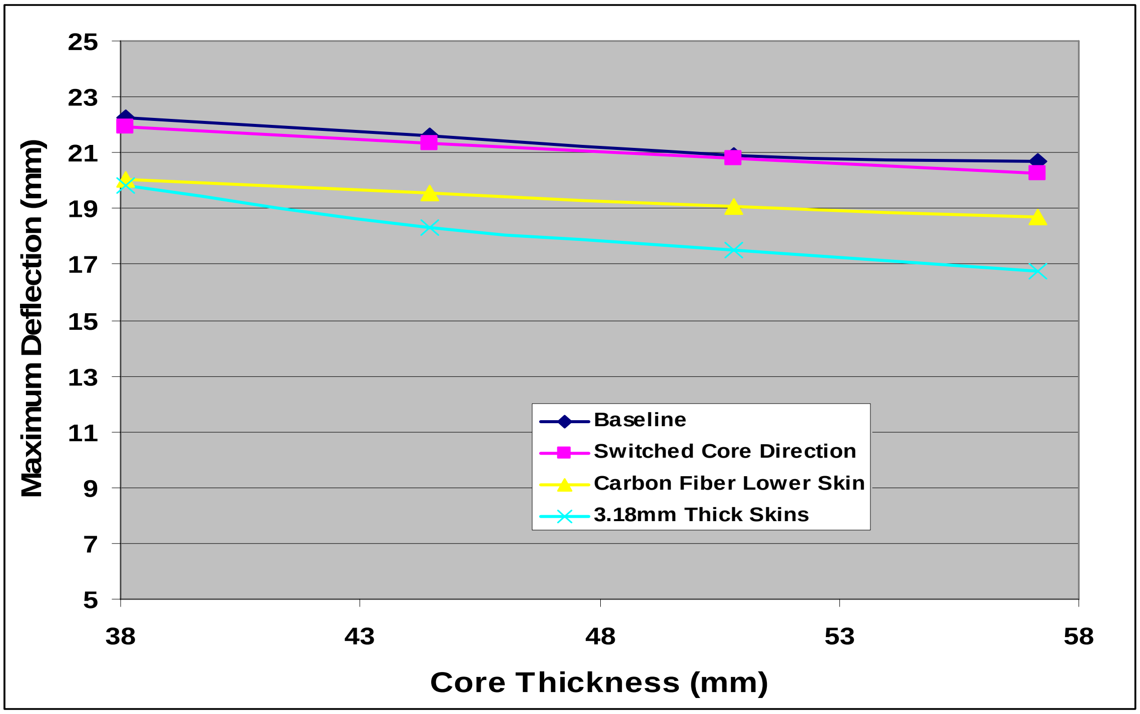


Figure 11: Results on skin/core analysis for Contractor B.

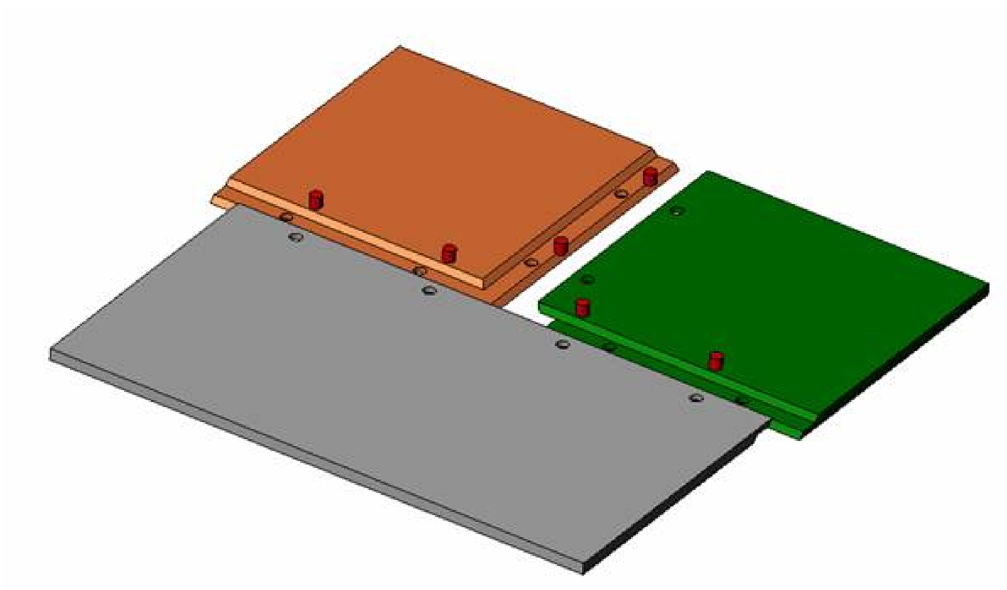
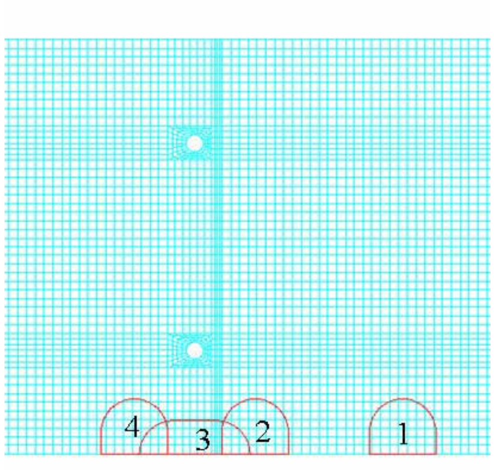
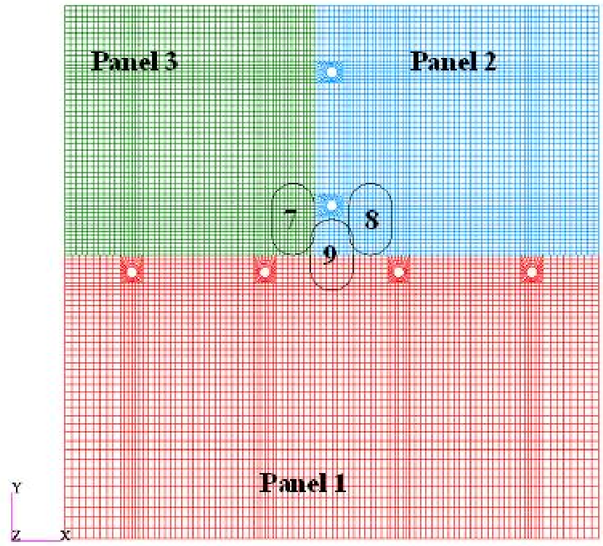


Figure 12: Contractor B lapped edge geometry.





(a) **(b)**

Figure 13: Panel edge load configuration 1 (a) and load configuration 2 (b) for Contractor B

Load Testing

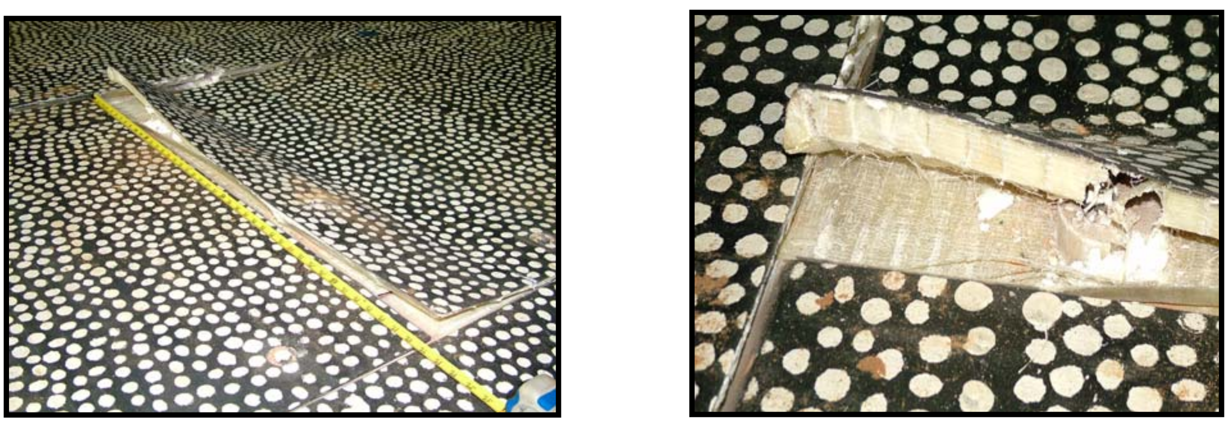
Testing for the second development iteration for both composite panel contractors as well as several metallic mats took place in August 2005 at Tyndall AFB, FL. The same setup as used for the proof-of-concept tests was employed again except the maximum load on the load cart was increased to 156,125N (35,100 lbs). Digital image correlation was used to collect in-situ deflection data as the load moved across each test section. The soil was prepared to an average CBR of 6 over a 0.61m (2.0 ft) depth. After panel failure was achieved the CBR values of that particular test section were obtained to observe the change in soil structure. The load cart was incrementally loaded to the maximum weight of 156,125N (35,100 lbs). This was done to ensure the digital image correlation test method was working properly. In addition to the digital image correlation data collection a total station surveying instrument was also utilized to obtain static deflection data.

Contractor A panels failed after a total number of passes of 30, two passes at a maximum load of 107,731N (24,220 lbs). The failure was located at the top flange of the tongue and groove edge connection detail as shown in Figure 14(a). The top flange debonded after the second pass in the test. The loading at this point was less than half the load at final panel failure. The panel system maximum deflection was 25.4mm (1 in) as shown in Figure 14(b). The average unit weight of the panels was 284.53 N/m^2 (5.94 lbs/sf).

(a) (b)

Figure 14: Contractor A top flange failure (a) and maximum panel system deflection (b)

Contractor B panels failed at 41 passes with 5 passes having the maximum load of 138,600N (31,160 lbs). Failure initiated as the top flange of the lapped joint delaminated and fractured as shown in Figure 15(a). The delamination occurred at a load of 123,121N (27,680 lbs) and zipped down the edge leaving the cam-lock intact, as shown in Figure 15(b). The average unit weight of the panels was 284.44 N/m^2 (5.98 lbs/sf).



(a) (b)

Figure 15: Contractor B top flange lapped edge failure (a) with cam-lock intact (b)

The baseline mat, AM-2, survived a total of 74 passes with 29 being at the maximum load of (35,100 lbs). The failure of the AM-2 also occurred in the joint, as shown in Figure 16(a) and (b). It sustained a maximum deflection of 64mm (2.52 in). The significance of the AM-2 test results indicated other factors were at play in the test since prior testing of the AM-2 yielded quite different results in satisfying the 1,500 pass requirement under the load of an F-15E. It was determined that the CBR, although and average of 6 through the soil depth, was incorrectly prepared and should have been a constant CBR 6 through out its depth. In addition since the majority of the mats failed in the joint, where historical testing has proven this to be the weakest link, and considering that the CBR at the mat soil/interface most likely was 1 the decision was made to progress to another round of matting development. The next round, however, would consider one composite and one metal alternative solution.


(a)


(b)

Figure 16: AM-2 failure in the joint rail (a) and relative deflection between panels (b)

5. AM-X Development – Third Iteration

Analysis and Design

Observation of the baseline AM-2 performance concluded that a dramatic change in the panel joint needed to be investigated. In addition, a general increase in panel stiffness was identified as a strategic goal. The University of Dayton Research Institute was retained for all analysis and design work. All prior analytical work was taken full advantage of plus full 3-D FEM models of the baseline, AM-2, mat as well as an older version using aluminum honeycomb core with aluminum face sheets were developed and analyzed on the elastic soil described above. The honeycomb mat, designated M19, was first developed in the late 1950's and early 1960's by the U. S. Army for airfield matting. However, the development evolved into the AM-2 version over concerns about its robustness and durability. The F-15E tire geometry was also slightly changed increasing its foot print area to 0.07 m^2 (100.9 in^2) from 0.06 m^2 (85.7 in^2)[5]. Request for proposals were sent out for this next iteration of development. Contractor B was then selected for the third iteration of development based upon their performance in the second iteration tests.

To accomplish the goal of increased stiffness, initial analysis efforts focused on optimizing the skin of the sandwich panel to achieve margin of safety, based on stress, of 40% in the skins. Skin materials ranged from carbon bi-directional and quasi-isotropic fabric to E-glass bi-directional and quasi-isotropic fabric plus a hybrid carbon/E-glass fabric. The core was also varied in thickness and included carbon and E-glass fibers for reinforcement. One other panel concept was also evaluated that involved two thin sandwich panels field bonded one on top of the other in an overlapping arrangement that eliminated all fasteners[5].

Unlike prior development efforts this effort combined a vast amount of laboratory coupon testing in combination with FEM analysis to achieve optimum properties. Extensive coupon level testing of the material combinations was done for FEM inputs. A combination of long beam bending tests and short beam shear-critical bending tests were performed to obtain skin and core shear strength properties. A total 15 composite panel concepts resulting in 71 FEM analysis cases were evaluated for the panel skin optimization. Interpolation functions were used with the analysis results to obtain an optimum skin thickness for each concept evaluated[5]. Each concept was further analyzed based upon component weight with the results shown in Figure 17. Due to the successful tests of both the AM-2 and the M19, i.e. both mat systems achieved the objective number of passes with the F-15E loading; Figure 17 reveals several composite material concepts at or below the target weight of both the AM-2 and M19. Furthermore, M19 being the lightest system having achieved successful load testing it is now the target for the composite system to meet or exceed.

Figure 18 compares the panel concepts to the amount of pressure on the soil and panel deflection from the F-15E loading. Again several promising concepts are below the results of the baseline AM-2 and M19. From these analysis cases several candidate panels were manufactured and tested on a foam bed. The M19 baseline panel was also tested on the foam bed for side by side comparisons. The foam bed test was used to simulate the

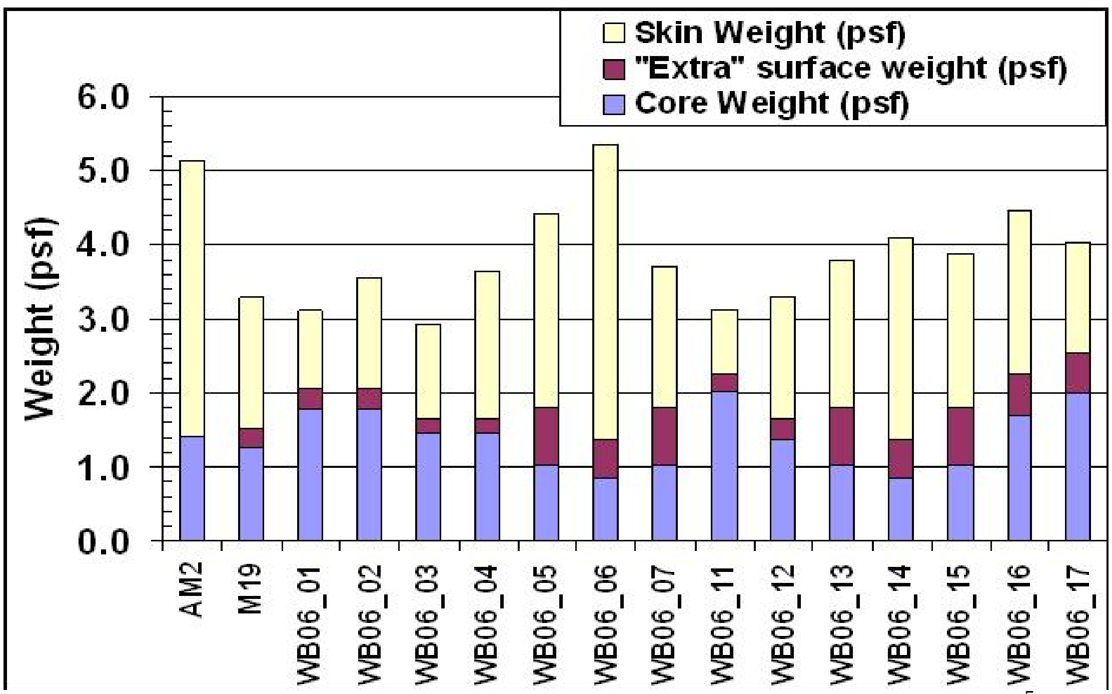


Figure 17: Optimized panel analysis cases and there projected unit weight[5].

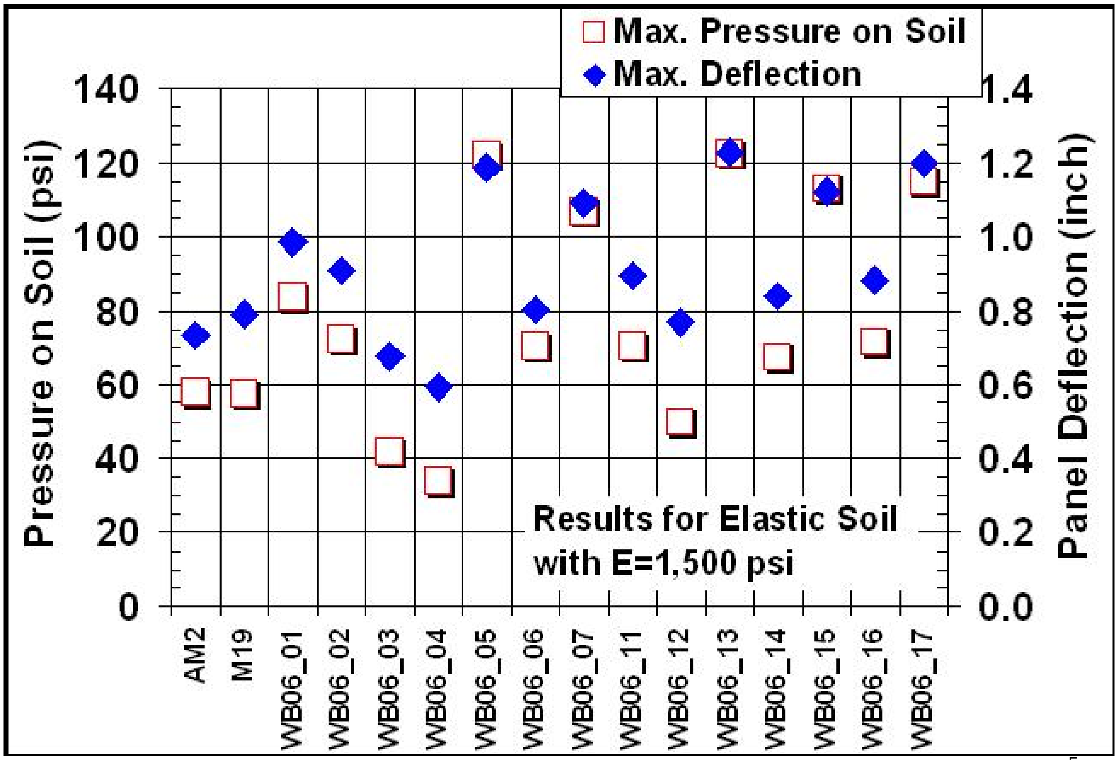


Figure 18: Panel concept pressure on soil and panel deflection from F15 loading[5].

modeled soil conditions and consists of a stack of foam sheets having total dimensions of 1.22m X 1.22m X 0.6m (4ft X 4ft X 2ft) and having a modulus of 103.4 MPa (1,500 psi). A total of 9 different panel concept designs were tested where the load was incremented at 44.5 kN (10K) from 44.5 kN (10K) to 202 kN (45K) and cycled at each increment for 50 cycles[5]. From the results of the foam bed test three concept designs were selected for further scrutiny and they consisted of two E-glass designs and one carbon design. Further analysis of these concepts yielded the carbon design as the optimized panel for further prototype testing. The carbon design consists of quasi-isotropic panel skins and a carbon fiber reinforced core.

Concurrent to panel optimization, new panel connection designs were being evaluated. Observations on how the AM-2 and M19 behaved under load lead to a complete overhaul of the current lapped edge connection to one that mimics the movement of the baseline panels. The AM-2 and M19 use very similar joint configurations allowing some rotation as the load traverses the panel. Analysis of this joint revealed a rotation of 7° between joined panels[5]. In addition the joint was not tight or rigid allowing almost 6.35 mm (0.25 in) of in-plane movement[5]. The joint system used for the M19 panels made a frame for the honeycomb core where the face sheets bond to the core but are welded to the joints. Gaps exist between the honeycomb and joint and are filled with a potting compound. The AM-2 joint was very similar in that the extruded edges have relatively more section that the interior panel and the transverse edges, also having more section, are welded to the panel creating a relatively stiff frame for the AM-2 mat. To this end engineers at AFRL devised a concept utilizing a dog-bone shaped connector inserted into matching keyways that form a frame around the panel. This style of connection allows for similar rotational and in-plane movement as the AM-2 and M19 connections. This system was optimized around six variables. Extensively laboratory testing at the coupon level of the joint system considered keyway materials, connector key materials, joint bending, joint shear, joint tension, bonding keyway to panel skins, bonding keyway to panel core and prototype testing utilizing one full panel and two half panels to replicate the worst case loading at a corner joint. For this development iteration the decision was made to manufacture the keyway via aluminum extrusion since bonding the keyway frame to the panel proved capable of handling the required loads from the testing and analysis completed. The optimum connector key material for this development iteration as determined by analysis and testing is nylon. Nylon provides the necessary strength and flexibility for ease of mat assembly.

To fully understand the impact of the relatively stiff dog-bone keyway frame on the panel finite element models of the composite panel having a stiff frame were analyzed to investigate the effects on the core, face skins and panel behavior on the soil. To accurately model the effects a rectangular array or field of panels was used. The field consisted of four rows of matting with the load applied in the center of the field. Five loading conditions were used to evaluate the stresses in the skin and core, as shown in Figure 19.

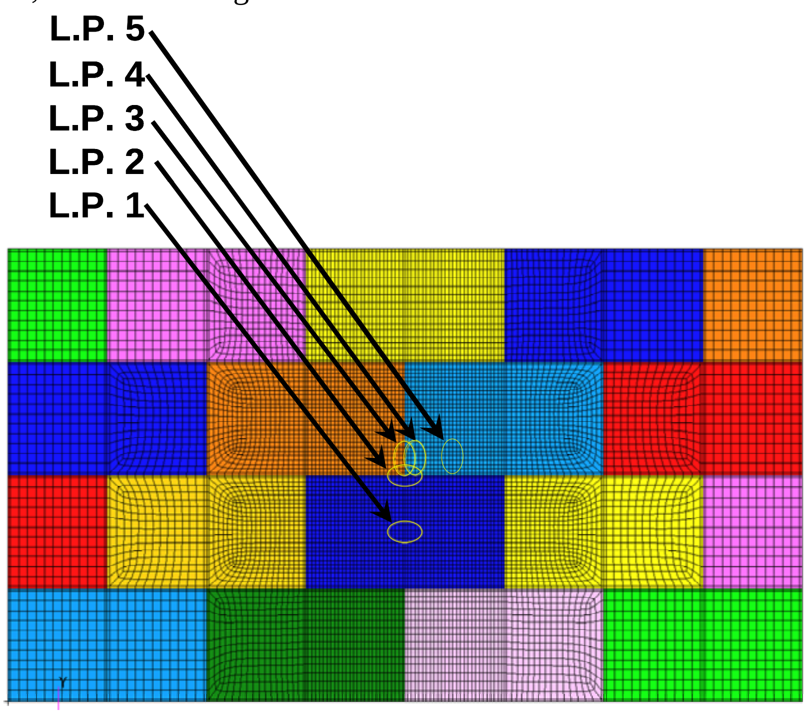


Figure 19: Loading conditions for stress evaluation in matting field[5].

A total of 27 FEM analysis cases were performed. The models had a 25.4 mm (1 in) wide edge around the perimeter of each panel where the element stiffness was increased to simulate the frame[5]. The panels were modeled side by side with vertical edges and the dog-bone connection existing at the mid-plane of the panel thickness. The general trends indicated by the analysis for edge stiffening include reduced stress in the skins at the panel edges, an increase in load transfer between the panels and a reduction on the soil pressure[5]. The analysis also investigated changing the stiffness of the panel-to-panel dog-bone connector. These analysis results indicate that a stiffer connector concentrates the load in a smaller area. In addition, allowing in-plane movement between the panels from 0 mm (0 in) to 3.18 mm (0.125 in) does not have a significant affect on the load transfer from panel to panel and panel stresses do not change dramatically with a stiffer panel-to-panel connection[5].

Additional analytical investigations were done to measure the effects of panel liftoff from the soil bed and well as panel size, panel thickness for the E-glass panels and panel layout pattern. For the sake of brevity the results of these analytical efforts will not be discussed, however, their results were utilized in the material and panel geometry optimization.

Load Testing

In June of 2006 two sets of one full size and two half size prototype panels were tested at Tyndall AFB, FL on a CBR 6 soil. The only difference between the two sets was that one set had supplemental reinforcement of the skins in area at the joint where analysis indicated highly stresses areas. The prototype test results verified most panel analysis in that system response under load matched fairly well with the analytically derived deflections. From these results the panel skins were slightly modified and 93.2 m^2 (1,000 sf) of mat having carbon fiber quasi-isotropic skins, carbon reinforced foam core and aluminum keyway frames using nylon connector keys were produced for the program test at the U. S. Army Engineering Research and Development Center (EDRC) in Vicksburg, MS in September 2006. The average unit weight of the mats manufactured for the EDRC tests were 196.4 N/mm^2 (4.1 lbs/sf), slightly above the midpoint between the objective and threshold weights. The panels were arranged the same way as in previous tests at Tyndall AFB as shown in Figure 13 above. Five traffic lanes were used for this test instead of nine lanes as shown in Figure 13. Figure 20 show the composite panels in place with the lane lines painted down as the load cart is traversing the mats. The edges of the mats are weighted by lead ingots to simulate a larger field of mats. Under deployed conditions a typical area would be over 18,580.6m^2 (200,000ft^2) as mentioned above.

Figure 20: Composite AM-X mat layout with traffic lanes and weighted edges.

The soil was prepared to a constant CBR 6 through out its depth. Deflections were measured using a total station after 25 passes under load or when failure occurs prior to removing the panels. The load was not ramped up as in the previous test but started at the full load of 156,725 N (35,235 lbs). Figure 21 shows the load cart with the F-15E wheel at full load trafficking across the center of the panels. Five total AM-X concept mats were laid out creating a 74.1 m (243 ft) long test setup. Trafficking took approximately one month to complete. As test sections of various concept mats failed they were removed and replaced with AM-2 and trafficking continued. Figure 22 shows rutting after pass number 384 in the soil after the concept panels placed next to the composite mats failed. Failure of the mats was determined by 10% of the area of the test section. Since approximately 93.2 m^2 (1,000 sf) of mat was supplied for each test section, the test section was determined failed if a 9.3 m^2 (100 sf) area failed or, in the case of the composite mat being 2.44 m X 1.22 m (8 ft X 4 ft), 4 mat sections failed. A failure of a panel was determined to be such that the load cart could not traffic across the mat safely without completely punching through to the soil or damaging the tire or load cart in any way. The composite mat failed after 4,132 passes of the full F-15E loading of 156,725 N (35,235 lbs) surpassing the objective of 1,500 passes by 2.75 times.

Figure 21: Load cart with full load of 156,725 N (35,235 lbs) trafficking across center of mats

Figure 22: Rutting after pass 384 in test section next to the composite mat test section.

6. Conclusions

Starting with a commercial off the shelf product with little modification proved the concept that composite materials have the ability to offer a solution to the demanding requirements for the next generation airfield matting. After optimizing the composite panel system for weight and strength, employing extensive FEM analysis and coupon level testing, the results prove the unique taylorability of the composite material system. Due to its success at the September 2006 test, the requirements for the next generation AM-X airfield matting system have under gone dramatic changes to become a joint program with the U. S. Navy. The updated requirements restrict the mat thickness to 31.75 mm (1.25 in) with a unit weight no greater than 182 N/m^2 (3.8 lbs/ft^2). In addition, several new aircraft loading requirements were added. Upon completion of this next round of development AFRL engineers along with the ACC/DR and AFCESA program managers will likely recommend selection of a single AM-X matting system for system demonstration and development within the acquisition framework. This new matting system will be a critical force multiplier in the United States military's mission achieving rapid global mobility.

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8. Acknowledgments

This program is a joint effort by the Air Force Research Laboratory Materials and Manufacturing Directorate (AFRL/ML), United States Marine Corps NAVAIR, the Air Force Air Combat Command (ACC/DR), the Air Force Air Warfare Battlelab (AWB), the Air Force Civil Engineering Support Agency (AFCESA), and the Air Force Agile Combat Support System Program Office (AAC/YBC). Additional testing and consultation was provided by the United States Air Force's 823rd Red Horse Civil Engineering Squadron and the United States Army Engineer Research and Development Center (ARMY/ERDC).