DOE for Hybrid Plies Characterization

Design of Experiment(S) using THE j2-optimality algorithm

Document Release

This document of a design sub-process for Cambio describes the intricacies of design and outlines, broadly as well as in detail, the necessary sequential actions for achieving the intended design result. On the parallel, it is also meant to aid in work breakdown structure creation and project finance planning. By signing this document, members acknowledge that they have read, understood and accepted implications, requirements and outcomes of taking the design and planning actions recommended in this document. This document may be released upon obtaining all relevant signatures.

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List of Relevant Documents

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1 Introduction and Rationale

1.1 Choice of experiment design methodology

The OA/NOA design algorithm (programmed based on the J2-optimality criterion) will choose the appropriate level combinations for number of plies from the values obtained in Table 2 in Section 2.2.

2 Experiment Design

Automotive parts and panels are subject to various loading conditions, many of which occur simultaneously. In light of this, it is sought to find out the performance trends of pure and hybrid composites for the following parameters.

* Elastic modulus, tensile yield strength, ultimate tensile strength for:
  + Axial tension
  + Transverse tension
  + Compression
  + Edge Compression
* Shear modulus, shear yield strength, ultimate shear strength for:
  + In-plane shear
  + Interlaminar shear
* Bending (delamination, shear crimping, etc.)
* Toughness
* Hardness
* Elastic/Transition/Plastic Moduli (where applicable)
* Fatigue life (S-N curve at different stress ratios)
* Heat transfer coefficient
* Thermal fatigue (S-N curve at different stress ratios)
* Behaviour under vibration
* Hygrothermal behaviour

The following section describe how the experiment is proposed to be designed to characterize the general behaviour of hybrid plies.

2.1 Factor and Level Definitions

The following variables should be set at the allowable options, to fully define a glass-carbon hybrid laminate:

1. Number of plies
2. Laminate character (symmetry, balance)
3. % hybridization (% carbon plies in a base glass laminate)
4. Type of ply (unidirectional, biaxial, triaxial, quadriaxial, etc.)
5. Material type
   1. Glass: S-glass, E-glass
   2. Carbon: High Strength (HS), Intermediate Modulus (IM), High Modulus (HM), Ultra-High Modulus (UHM)
6. Tow size (2K, 3K, 12K, etc.)
7. Core type
   1. Coreless
   2. Core: Polyurethane (PU), Polyvinyl chloride (PVC), Polystyrene (PS), aluminium honeycomb, Nomex honeycomb, Balsa wood, etc.
8. Core thickness (increments in mm)
9. Ply angles (increments in degrees)

These factors and their corresponding levels have been defined in Table 1, with number of levels, degrees of freedom and level values specified.

*Table 1: Table of Design Degrees of Freedom*

|  |  |  |  |
| --- | --- | --- | --- |
| FACTORS | NO. OF LEVELS | LEVEL DESCRIPTION | DOFs |
| Number of plies (Odd) | 11 | 1 3 5 7 9 11 13 15 17 19 21 | 10 |
| Number of plies (Even) | 11 | 2 4 6 8 10 12 14 16 18 20 22 | 10 |
| Laminate Character (Odd) | 3 | Non-symmetric, Symmetric-Unbalanced, Antisymmetric | 2 |
| Laminate Character (Even) | 4 | Non-symmetric, Symmetric-Unbalanced, Symmetric-Unbalanced, Antisymmetric | 3 |
| % Hybridization | Dependent on number of plies (Up to 22) | % hybridization is defined as amount of carbon in a base glass laminate.   * One: 100% * Two: 0%, 50%, 100% * Three: 0%, 33.3%, 66.6%, 100% * Four: 0%, 25%, 50%, 75%, 100% * And so on… | Up to 21 |
| Type of ply | 4 | Unidirectional, Biaxial, Triaxial, Quadriaxial | 3 |
| Material type (Glass) | 2 | E-glass, S-glass | 1 |
| Material type (Carbon) | 4 | High Strength (HS), Intermediate Modulus (IM), High Modulus (HM), Ultra-High Modulus (UHM) | 3 |
| Tow | 8 | 1K 2K 3K 4K 6K 12K 24K 50K | 7 |
| Resin | 3 | Epoxy, Polyester, Vinylester | 2 |
| Core material | 10 | None (coreless), PU, PVC, PS, PMA, PEI, SAN, Al. honeycomb, Nomex honeycomb, Balsa | 9 |
| Core thickness | 9 | 1 mm, 2 mm, 3 mm, 5 mm, 7.5 mm, 10 mm, 12 mm, 15 mm, 20 mm | 8 |
| Honeycomb thickness | 3 | 10 mm, 20 mm, 30 mm | 2 |
| Honeycomb cell size | 3 | 3.2 mm, 6.4 mm, 19.1 mm | 2 |
| Honeycomb foil gauge | 8 | 0.0007 in, 0.001 in, 0.0015 in, 0.002 in, 0.0025 in, 0.003 in, 0.004 in, 0.005 in | 7 |
| TOTAL | **105** |  | **90** |

This table immediately makes apparent the extreme amount of design flexibility available at the composite designer’s hands. It also makes obvious the problems faced in testing and characterization of composite laminate materials.

It should be noted that ply angle for each ply is a factor that has been purposely left out of the design matrix, because keeping it increases multi-fold the complexity of the design as well as the design generation process.

2.2 Design Simplification

It can be easily recognized that running an experimental design of the type, e.g. 1121019182433321, is highly impractical due to the associated costs and time, even if a full factorial design is rejected for its ridiculously large size in favour of a reduced orthogonal design. Due to these cost and experimental size constraints, the following table is proposed to be used for the final experimental design. Some factor levels have been reduced and some factors have been broken down and simplified for ease.

*Table 2: Description of Chosen Factor Levels*

|  |  |  |  |
| --- | --- | --- | --- |
| FACTORS | NO. OF LEVELS | CHOSEN LEVELS - DESCRIPTION | DOFs |
| Number of plies (Odd) | 5 | 1, 5, 9, 15, 19 | 4 |
| Number of plies (Even) | 4 | 4, 10, 16, 22 | 3 |
| Laminate Character (Odd) | 3 | Non-symmetric, Symmetric-Unbalanced, Antisymmetric | 2 |
| Laminate Character (Even) | 4 | Non-symmetric, Symmetric-Unbalanced, Symmetric-Unbalanced, Antisymmetric | 3 |
| % Hybridization | Dependent on number of plies (Up to 8) | % hybridization is defined as amount of carbon in a base glass laminate.  Refer Table 3. | Up to 7 |
| Type of ply | 2 | Unidirectional, Biaxial | 1 |
| Material type (Glass) | 2 | E-glass, S-glass | 1 |
| Material type (Carbon) | 4 | High Strength (HS), Intermediate Modulus (IM), High Modulus (HM), Ultra-High Modulus (UHM) | 3 |
| Tow size | 3 | 3K, 6K, 12K | 2 |
| Resin | 1 | Epoxy | 0 |
| Core material (Foam) | 2 | None (coreless), PU/PVC/PS | 1 |
| Foam core thickness | 5 | 3 mm, 7.5 mm, 10 mm, 15 mm, 20 mm | 4 |
| *\*Factors related to honeycomb core not included for design simplification* | | | |
| TOTAL | **43** |  | **31** |

With this reduction and simplification, it is sought to minimize the number of tests needed to be performed to characterize hybrid plies with a reasonable level of statistical reliability. The simplification proposed in Table 3 reduces the design to a type 52433223. When inserted into the design generation algorithm, the designer should take care to sequence the factors in a descending order according to the associated number of levels. This eases the stress on the algorithm and improves its efficiency and performance. This design with reduced factors and their levels can now be introduced into the design generation algorithm to obtain various designs. The process adopted for the same is describes in section 2.4.

**% Hybridization** is defined here as the % content of carbon plies in a base glass laminate. E.g. In a 20-ply glass laminate, if 5 plies replaced with carbon plies resulting in a 15-glass and 5-carbon ply laminate, then % hybridization = 5/20\*100 = 25%. It can immediately be observed that the value % hybridization depends on the number of plies in a laminate, because it is driven by the allowable replacements of plies within a laminate. E.g. A 4-ply laminate can only have % hybridization values of 0%, 25%, 50%, 75% and 100%, by sequentially replacing each glass ply with carbon. It should be observed that a 4-ply laminate can’t have a % hybridization value other than the five specified, e.g. it can’t have a value of 30% or 60%. To account for this, Table 4 lists all the possible fractions for the chosen factor levels for the factor “number of plies”. Against that, the table lists the % hybridization levels chosen to simplify and reduce the design. The level values are chosen to keep the design reliable, able to estimate the main effects and trends, yet small enough in size. Therefore, at least 5 levels are chosen for each step of number of plies to keep the experiment fidelity reasonably high.

**Note**: For a laminate with ‘n’ plies, a % hybridization level of (2\*100/n) % is always chosen, keeping in mind the need for characterizing a laminate made of a glass material on the inside with outermost skin layers of carbon each.

*Table 4: % Hybridization Levels Chosen for Different Number of Plies*

|  |  |  |  |
| --- | --- | --- | --- |
| NO. OF PLIES | FRACTIONS OF PLY HYBRIDIZATION POSSIBLE | % HYBRIDIZATION LEVELS CHOSEN | NO. OF LEVELS CHOSEN |
| 1 | 0/1, 1/1 | 0%, 100% | 2 |
| 4 | 0/4, 1/4, 2/4, 3/4, 4/4 | 0%, 25%, 50%, 75%, 100% | 5 |
| 5 | 0/5, 1/5, 2/5, 3/5, 4/5, 5/5 | 0%, 20%, 40%, 60%, 80%, 100% | 6 |
| 9 | 0/9, 1/9, 2/9, 3/9, 4/9, 5/9, 6/9, 7/9, 8/9, 9/9 | 0%, 11.11%, 33.33%, 55.55%, 77.77%, 100% | 6 |
| 10 | 0/10, 1/10, 2/10, 3/10, 4/10, 5/10, 6/10, 7/10, 8/10, 9/10, 10/10 | 0%, 30%, 50%, 70%, 100% | 5 |
| 15 | 0/15, 1/15, 2/15, 3/15, 4/15, 5/15, 6/15, 7/15, 8/15, 9/15, 10/15, 11/15, 12/15, 13/15, 14/15, 15/15 | 0%, 13.33%, 33.33%, 53.33%, 86.67%, 100% | 6 |
| 16 | 0/16, 1/16, 2/16, 3/16, 4/16, 5/16, 6/16, 7/16, 8/16, 9/16, 10/16, 11/16, 12/16, 13/16, 14/16, 15/16, 16/16 | 0%, 12.50%, 50%, 68.75%, 81.25%, 100% | 6 |
| 19 | 0/19, 1/19, 2/19, 3/19, 4/19, 5/19, 6/19, 7/19, 8/19, 9/19, 10/19, 11/19, 12/19, 13/19, 14/19, 15/19, 16/19, 17/19, 18/19, 19/19 | 0%, 10.52%, 31.58%, 52.63%, 73.68%, 100% | 6 |
| 22 | 0/22, 1/22, 2/22, 3/22, 4/22, 5/22, 6/22, 7/22, 8/22, 9/22, 10/22, 11/22, 12/22, 13/22, 14/22, 15/22, 16/22, 17/22, 18/22, 19/22, 20/22, 21/22, 22/22 | 0%, 9.09%, 22.72%, 50%, 68.18%, 72.72%, 90.90%, 100% | 8 |

2.3 Isolated Treatment of Honeycomb-Cored Laminates

In view of the inherent complexity of including honeycomb panels in the characterization, it is chosen to isolate the testing of honeycomb cored panels completely; therefore, only foam cores are included in the above table. Testing is proposed to be performed on these panels separately, using 8-ply symmetric balanced UD laminate (e.g. [0/0/0/0]s).

*Table 3: Factors for Aluminium Honeycomb Panels*

|  |  |  |  |
| --- | --- | --- | --- |
| FACTOR | NO. OF LEVELS | CHOSEN LEVELS - DESCRIPTION | DOFs |
| Core material (Honeycomb) | 1 | Aluminium honeycomb | 0 |
| Honeycomb thickness | 3 | 10 mm, 20 mm, 30 mm | 2 |
| Honeycomb cell size | 3 | 3.2 mm, 6.4 mm, 19.1 mm | 2 |
| Honeycomb foil gauge | 8 | 0.0007 in, 0.001 in, 0.0015 in, 0.002 in, 0.0025 in, 0.003 in, 0.004 in, 0.005 in | 7 |
| TOTAL | **60** |  | **45** |

2.4 Process of Design Generation

The process described herein is meant to clarify the logical steps of factor sequencing and usage within the design matrix. As discussed earlier, the factors need to be introduced in the algorithm in a descending order according to the associated number of levels. Keeping this in mind, the following process is proposed. (Once factor settings are chosen at the start of one iteration, the factors should be sorted in descending order as required before introducing them to the algorithm.)

1. Choose one factor level of factor “type of ply” among unidirectional and biaxial.
2. Choose one factor level of factor “core type” among coreless and cored.
   1. By performing step 1 and 2, the pressure on the design matrix is relieved slightly, because now 4 different design matrices can be obtained for the different combinations of (UD, biaxial) and (coreless, cored), which are given by (UD, coreless), (UD, cored), (Biaxial, coreless) and (Biaxial, cored). Experiments are designed for each of these four combinations separately.

To define the laminate, the following steps are required after the choice of one of the above combinations. The following factors are the only ones that go into the algorithm. The algorithm can be run for each of the four above mentioned combinations to obtain the full experiment design.

1. Evaluate factor “core thickness” with 5 levels.
2. Choose odd or even number of plies.
   1. If odd is chosen, evaluate factor “number of plies” with 5 levels.
   2. If even is chosen, evaluate factor “number of plies” with 4 levels.
3. Depending on number of plies chosen, evaluate factor “% hybridization” with 2, 5, 6, 6, 5, 6, 6, 6 or 8 levels.
4. Depending on number of plies chosen, evaluate factor “laminate character”.
   1. Odd number of plies: 3 levels
   2. Even number of plies: 4 levels
5. Evaluate factor “material type” according to factor “% hybridization”.
   1. 0%: evaluate factor “material type” with 2 levels (glass material types)
   2. 100%: evaluate factor “material type” with 4 levels (carbon material types)
   3. Between 0% and 100%: evaluate factor “material type” for both carbon and glass with 2 and 4 levels respectively.
6. Evaluate factor “tow size” with 3 levels.

After all factors are evaluated for a given experiment design, the factors should be sorted in descending order according to number of levels of each. This step is necessary because the above process guides the experiment designer through the various laminate design options available for characterization. This leads to multiple combinations of factor-level values, all of which need to sorted in descending order when come across.

2.4.1 Options of Factor-level settings possible

As an example, choosing core thickness (5 levels), odd number of plies = 9 (5 levels), % hybridization (6 levels), laminate character (3 levels), and tow size (3 levels) results in a design of type 615132(2141). Choosing even number of plies would result in a design of a different type. Table 4 list all possible combinations of factor-level settings, applicable to each of the four initial combinations of factors “type of ply” and “core material”. Thus, the number of experiments is equal to the total number of factor-level settings in Table 4 multiplied by four.

*Table 4: Possible Factor-Level Settings*

|  |  |
| --- | --- |
| Sr. No. | Factor-Level Settings |
| 1 | 3121(2141) |
| 2 | 5232(2141) |
| 3 | 5132(2141) |
| 4 | 615132(2141) |
| 5 | 6132(2141) |
| 6 | 615132(2141) |
| 7 | 6132(2141) |
| 8 | 615132(2141) |
| 9 | 6132(2141) |
| 10 | 524131(2141) |
| 11 | 514131(2141) |
| 12 | 524131(2141) |
| 13 | 514131(2141) |
| 14 | 61514131(2141) |
| 15 | 614131(2141) |
| 16 | 81514131(2141) |
| 17 | 814131(2141) |

Thus, with the choice of 2 levels of the factor “type of ply” being chosen outside the domain of the design, and 17 experimental designs for the other factors, the total number of experiment designs will be 17\*2 = 34. The highest number of runs for any experiment is expected to be 30 (for experiment designs containing factors with 5 and 6 levels), although the number could be smaller still.

2.4.2 Discussion

To reduce the problem further, it is possible to eliminate the “material type” factor altogether by choosing a single glass fabric type (S-glass) and a single carbon fabric type (e.g. high modulus). This would remove all the corresponding (2141) terms from the experimental designs shown above, thus easing the design. But doing so would likely keep the experimenter away from the actual results that are required, i.e., material characterization in all possible cases. Since laminate material properties will differ for the same type of fabric and tow sourced from different manufacturers, it is necessary to at least understand the performance trend between different types of fabric (preferably sourced from the same manufacturer, or produced by the same process, if at all it is possible).

3 Experiment Cost Estimation

|  |  |  |  |
| --- | --- | --- | --- |
| CATEGORY | ITEM | INCURRING UNIT | ESTIMATED COST (₹) |
| Raw material | Carbon fibre cloth (UD) | m |  |
| Carbon fibre cloth (Biaxial) | m |  |
| Glass fibre cloth (UD) | m |  |
| Glass fibre cloth (Biaxial) | m |  |
| Core material (foam) | m^3 (or blocks) |  |
| Core material (honeycomb) | m |  |
| Epoxy resin | l |  |
| Hardener | l |  |
| Release agent | l |  |
| Breather cloth | m |  |
| Separator | m |  |
| Mould material (e.g. steel) | m^3 |  |
| Manufacturing | Vacuum pump | units |  |
| Vacuum bag | - |  |
| Test coupon mould manufacturing | units |  |
| Foam core machining | machine uptime (hours) |  |
| Testing | Universal testing machine – operating rental | units of use (or hours) |  |
| Fatigue testing machine – operating rental | units of use (or hours) |  |
| Bending flexural testing machine – operating rental | units of use (or hours) |  |
| V-notch beam (shear) testing machine – operating rental | units of use (or hours) |  |
| Impact testing machine – operating rental | units of use (or hours) |  |
| Logistics | Travel | - |  |
|  | Procurement logistics – raw material transport, transport to testing facility, etc. | - | 10000 |
|  | Documentation - experiment guidelines, coupon labelling, etc. | - | 500 |
|  |  |  |  |
|  |  |  |  |
| TOTAL |  | | |

5.25 spice5.30 air 6.30 jet 7.20 indigo 8 indigo 4.45 ind