EXPERIMENTAL INVESTIGATION OF SPRING-BACK BEHAVIOR OF COMPOSITE SANDWICH STRUCTURES: PART ONE

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ABSTRACT

Spring-back has been known as one of the major challenges in the composite structure manufacturing that often set the constraints on part manufacturability. The spring-back is thought to occur due to a combination of several factors: the non-symmetric or imbalanced structure of the part, thermal stresses that occur during the composite cure due to incompatibility of composite materials or due to the mismatch in the thermal expansion of the part and mold. The purpose of this paper is to present the experimental result from a case study that investigates the spring-back effects due to non-symmetric and imbalanced of a carbon fiber reinforced plastic (CFRP) composite sandwich structure. The study was conducted with both non-metallic and metallic cores. This paper also provides a methodology developed to evaluate the effects of the spring-back and discusses manufacturing solutions to reduce or eliminate the spring-back effects. Specific material and processing information are excluded in this paper to protect the proprietary data.

1. INTRODUCTION

In current commercial aircrafts design the nacelle, which houses the aircraft engine, is an assembly of multiple components that have complex surface profiles and construction. The nacelle provides structural support and protects the engine as well as incorporates the features that improve the aerodynamic performance, reduces excessive noise generated by the engine, and reverses the thrust to slow down the aircraft during landing. The components of the nacelle that surrounds the engine are often manufactured from composite sandwich structures for weight reduction. In addition, the nacelle structure also designed to reduce the noise generated from the engine by adding the acoustic treatment to meet the noise requirement by federal regulation. Manufacturing of acoustic sandwich structure is a complex process that often requires multiple stages of fabrication. This paper presents the test results from a case study that investigated the spring-back effect, which is a major challenge in the manufacturing of aircraft nacelle's sandwich structure.

In general, a sandwich structure consists of honeycomb cores that are sandwiched between two face sheets. The bonding of face sheets to honeycomb core often requires a structural adhesive film layer in order to effectively control the bond area between the honeycomb core cell walls and the face sheets. Depending on the Engineering Drawing requirements, an

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acoustic treatment may be needed for one side of the sandwich structure's face sheet and/or the honeycomb core detail. The acoustic treatment on a face sheet is often done by creating holes on the face sheet, which is called perforation. The perforation is a complex process and is highly controlled. In general, three perforation processes are in practice: fabrication from the perforated CFRP prepreg, fabrication from the unperforated CFRP prepreg on a pin mat, or layup the unperforated CFRP prepreg, then cure and drill the face sheet. The acoustic treatment of the honeycomb core detail is often done by inserting a perforated film layer into the core detail prior to bonding the panel. The acoustic treatment of core details is also as complex as the perforation of the skin and is highly controlled. There are two methods of creating the acoustic treated core details: insert the perforated film directly onto core then cure; or insert a non-perforated film, cure, then drill the holes.

Due to the complexity of the surface profile and surface finish requirements for aerodynamic and acoustic performance, the nacelle structures are often fabricated by a hand layup technique that utilizes a sequential fabrication process approach. The optimization of manufacturing is usually accomplished by using multiple stages in the layup process depending on the complexity of the geometric features, limitation of currently available technology, operation cost, tooling cost, limitation of resources, and etcetera. The two-stage fabrication typically requires a pre-fabricated perforated skin and bonded pre-fabricated core details (made to Engineering design) that are bonded together with an uncured face sheet. The three-stage fabrication typically requires formed core details (not made to Engineering design) bonded onto a precured pre-fabricated perforation skin, cured, and machined (to Engineering design), then bonded onto an uncured face sheet. The two-stage layup requires high precision of perforated skin layup and core detail profiles to the Engineering requirements, which is often hard to achieve due to the complexity of the geometry and limitations of core forming techniques. As such, a three-stage fabrication process is the preferred approach as it mitigates the challenges with the tight tolerance requirement of the core's surface profile.

Three-stage fabrication maintains its own challenges when compared to a one or two-stage fabrication, which is often less susceptible to the spring-back effect. The spring-back is thought to occur due to a combination of several factors: the non-symmetric or imbalanced structure of the part, thermal stresses that occur during composite curing due to incompatibility of composite materials or due to the mismatch in the thermal expansion of the part and the curing mold. Three-stage fabrication contains all of the aforementioned characteristics that contributed to the spring-back factor. The case study was designed to evaluate the potential affects with measurable values to construct solutions to overcome the effects of spring-back.

2. EXPERIMENTATION

2.1 Methodology

The initial approach used a finite element method (FEM) to evaluate the effects of spring-back. However, the approach using FEM was soon abandoned due to additional testing to obtain the key parameters to input into the FE models and high computing power to conduct the analysis. As manufacturing operations demanded a solution to overcome the spring-back effect, a case study was then developed using an experimental study approach. At first, a

design of experiment (DoE) was formulated to account for all causes and effects of the manufacturing process. The DoE resulted in a large number of test cases due to various parameters involved in the materials and the part manufacturing process.

Since the project required a solution that would support the budget and schedule, a simplified test matrix using engineering justification was created instead of the DoE approach. Literature research on the effects of spring-back on non-symmetrical and imbalanced sandwich structure yielded limited prior studies as there is no literature available to address the spring-back effect for one side face sheet sandwich panels. An exercise was done to list all key process parameters that were believed to be the greatest factors contributing to the spring-back effect. They are listed below:

1. The non-symmetric or imbalanced structure of the part: This study limits to the core-to-skin bonding stage only since the layup of the skin at the bonded panel stage is considered as balanced and symmetric structure in the three-stage fabrication.

2. Cure cycle: Prior study on the solid laminate showed that the spring-back occurs predominantly during cure due to the expansion and shrinkage of the material [1-2]. A higher curing temperature may result with a higher amount of spring-back. A modified cure cycle was selected and kept as a constant variable for the study.

3. Thermal stresses that occur during cure due to incompatibility of the materials: Two types of core material had been selected for comparison: high-density aluminum versus high-density fiberglass honeycomb cores. The prepreg, adhesive film, and core-splicing materials remained the same to reduce the amount of variables.

    a. Effect of the layup configurations: This study used two skin layup configurations to compare the spring-back due to thick and thin skin layups. Configuration 1 had a symmetric and balanced precured skin that was made from 10 plies of plain-weave fabric prepreg with 8 additional plies of eight harness satin added at the core to skin bonded stage. Configuration 2 has a symmetric and balanced precured skin that was made from 12 plies of plain-weave fabric prepreg with no additional prepreg plies added at the core to skin bonded stage.

    b. Honeycomb core thickness variations had been theorized to affect the spring-back. Aluminum core with three different thicknesses were used to evaluate this effect.

4. The cure tool has been known to affect the spring-back factor due to thermal stresses that occur due to the mismatch in the thermal expansion, contraction of the part, and the curing mold during cure [2]. Two different tools were used in this study: one was a curved aluminum tool and the other was a flat invar tool.

Spring-back is an after cure effect that the structure has deviated from the tool's surface profile. The spring-back is often measured by the maximum distance between the tool's and the structure's surfaces. However, in practice the spring-back is only concerning when it requires a high amount of force to restrain the part to its intended contour. The engineering requirement typically allows a minor gap between a bonded detail part and its checking

fixture, when measured using a localized force. This study considered the gap of 0.76 mm and localized force of 44 N as the maximum allowance for the bonded panel. As such, any spring-back or pushdown force in excess of this requirement at the core to skin cure could cause issues at the final assembly stage. This paper evaluates the spring-back effect by the lift off (or spring-back) distance and pushdown force (restraint force) required to restrain the part to the contour.

The spring-back measurement was performed by using a consistent process to all test coupons. After completion of the cure, all core-to-skin coupons were removed from the autoclave and cooled down in a restrained method using the vacuum bag. The debagging occurred only after the coupons had cooled down to room temperature. After demolding, the edges of the test coupons were de-flashed prior to moving to the test lab for spring-back measurements.

The spring-back distance was determined by dimensional measurement of the test panels and tools using the measurement system chosen by the Spirit Research and Development (R&D) Dimensional Measurement team. Using an ATOS III Blue Light Scanner, each coupon was scanned on the tool side face and compared back to the surface scan of the tool, based on the coupon's location and orientation on the tool. The deviation between the surfaces indicated the amount of spring-back (distance) from the tool.

The pushdown force was measured using an ergoFET™ Dynamometer, an example of which can be seen in Figure 1, which records the load required to physically push the part down to the table. The measurement was performed by securing the lowest spring-back area of each individual test coupon to a fixture that had the same surface contour as the cure tool. The force was measured by exerting a force onto the dynamometer until it reached 0.127 mm gap as determined by the feeler gage.



Figure 1: ErgoFET™ Measurement Device

2.2 Materials

The materials used for this study are described in the subsections. Specific material designations and vendor's information are excluded in this paper; however, the basic detail of each material used is included for reference purposes.

2.2.1 Prepreg Materials

The prepreg materials used were plain weave (PW) and eight-harness satin (8HS) fabric that were constructed from 3K carbon fiber yarns and untwisted. The fabrics were impregnated in a toughened epoxy resin system that was designed for autoclave cure at 177°C. The nominal thicknesses for PW and 8HS fabrics were 0.18 mm and 0.34 mm, respectively.

2.2.2 Adhesive Films

Adhesive film materials used was supported and unsupported films. Both types of films were made from the same modified epoxy resin that was intended for structural bonding application. The supported structural film adhesive had an areal weight of 391 gsm and a nominal thickness of 0.25 mm with a mat carrier. The unsupported film adhesive had an areal weight of 269 gsm and a nominal thickness of 0.13 mm with no mat carrier.

2.2.3 Honeycomb Core Materials

Honeycomb core materials used in the study were aluminum and fiberglass. The detail of each honeycomb core material is provided in Table 1. All honeycomb core details were cut to a dimension of 102 mm wide by 610 mm long from the core sheets. Core thicknesses of 25.4 mm, 34.3 mm, and 61.7 mm were selected for aluminum core. Only one core thickness of 24.5 mm was selected for fiberglass core. Each core detail was inspected to ±0.25 mm of the nominal thickness prior to coupon fabrication. All core details were cut with ribbon direction parallel to its width. All core details that were laid up on the Al – Curved Tool were individual formed using a proprietary core forming process developed by Spirit AeroSystems, Inc.

Table 1. Honeycomb Core Materials

Core Types	Foil Material	Nominal Core Density (kg/m^3)	Nominal Core Cell Size (mm)
Al High Dense	5056 Aluminum Alloy	192	3.18
FG High Dense	Fiberglass fabric stabilized by phenolic resin	256	4.76

2.2.3.1 Core Splicing Materials

A core splicing material was used to bond two core details together. The selected core splicing material was an epoxy syntactic paste adhesive that was designed for a 177°C cure.

2.3 Cure Tool

Two cure tools were utilized for the study: an invar flat tool and aluminum male curved tool. The curved aluminum tool determines the worst case of CTE (coefficient of thermal expansion) differences between the curing tool and the prepreg material or the fiberglass honeycomb core. The flat invar tool determines the effect of the current production tool,

which was believed to produce a less spring-back effect due to its similar CTE with the prepreg material and the fiberglass honeycomb core.

2.4 Test Coupon Fabrication

Two face sheet layup configurations were selected for layup. Configuration 1 was to simulate the layup configuration of an edge of the nacelle inlet panel. Configuration 2 was to simulate the layup configuration of an edge of the nacelle thrust reverser panel. Note that the layup configurations in this study do not represent the layup configuration of the entire nacelle's inlet or thrust reverser. The purpose of selecting two layup configurations was to create a quantitative measurement plan comparing the spring-back effects of a thin versus a thick layup while able to use part of the data to support the development of the project.

The fabrication of test coupons involved two stages as it assumed to simulate a proposed production process. The first stage comprised two skin layups of 10-ply and 12-ply plain-weave fabric prepregs. Both of the skins were laid up, final bagged (using the best shop practices), and cured in the autoclave. After partially cured, the first stage layup was machined and extracted to individual skins with a dimension of 1.2 m in length by 0.10 m in width. The second stage comprises a surface preparation of the first stage skin, layup of a ply of structural adhesive film, and then additional plies and/or core details. See Table 2 for the complete layup configurations of the test coupons. After the second stage layup, the test coupons were final bagged using best shop practices and then cured in the autoclave.

Table 2. Test Coupons Layup Configuration

Layup Configuration	**Stage**	**Stacking Sequence**
Configuration 1 (See Figure 2)	Stage 1	$[45/0/0/45/0]_S$ PW plies / unsupported film
	Stage 2	Stage 1 / unsupported film / [45/90/45/90/45/90/45] 8HS plies / unsupported film / supported film / core Details
Configuration 2 (See Figure 3)	Stage 1	$[0/45/0/45/0/45]_S$ PW plies / unsupported film
	Stage 2	Stage 1 / unsupported film / supported film / core Details

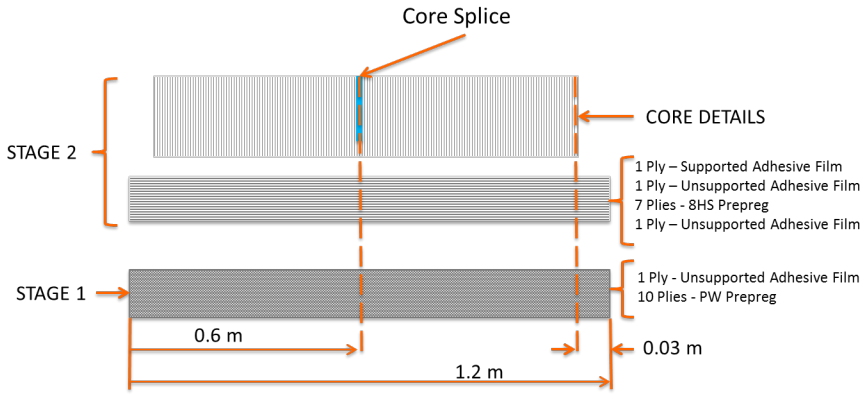


Figure 2: Configuration 1 Fabrication Scheme

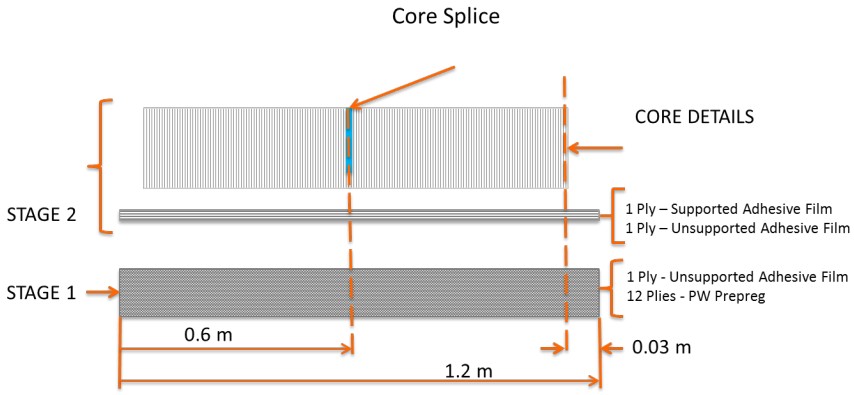


Figure 3: Configuration 2 Fabrication Scheme

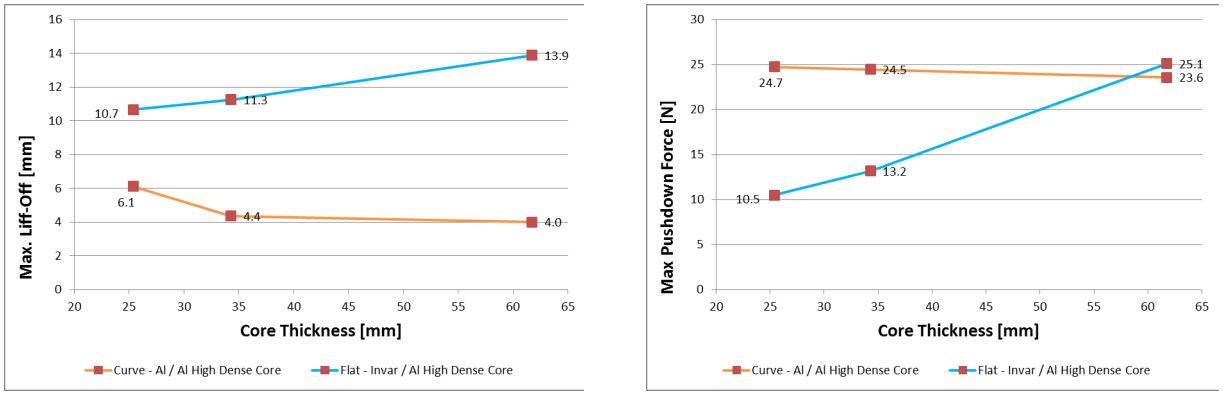
3. RESULTS

As the spring-back effect is a combination of various processing parameters, the quantitative characteristic of spring-back must be looked at case by case. As given by the fact that the spring-back developed at the core to skin bonding stage, due to the interaction of a non-symmetric and non-balanced structure, with mismatched CTEs of the constituent materials and the cure tool; a quantitative measure was developed to better understand spring-back theory to formulate the manufacturing solutions. The results were broken down into subsections to compare the contribution of a set of process parameters and the interaction between them. The effects of spring-back were evaluated by (1) the maximum distance where the test coupon departed from the tool surface and (2) the maximum pushdown load required to restrain the test coupon to the tool surface. The detail of dimensional measurements is not included in this paper, however, it is noted that not all spring-back or lift-off distance occurred at the ends of the coupon for the curved tool.

3.1 Core Thickness versus Cure Tool

The contribution of core thickness and cure tool to the spring-back effect was investigated using coupons fabricated with aluminum core laid up on Configuration 1 skin. The spring-back effect due to core thickness and cure tool variation is shown in Figure 4. The results

showed that the spring-back effect response with respect to core thickness was different between the cure tools. The spring-back increased as aluminum core thickness increased for coupons that cured on the flat – invar tool, while the same coupon configuration that was cured on a curved – aluminum tool showed otherwise. The results also showed increasing the core thickness has negligible effect to the spring-back factor (only a slight change in the maximum pushdown force) for aluminum core when laid up on a thick face sheet (Configuration 1) and cured on a curve-aluminum tool.



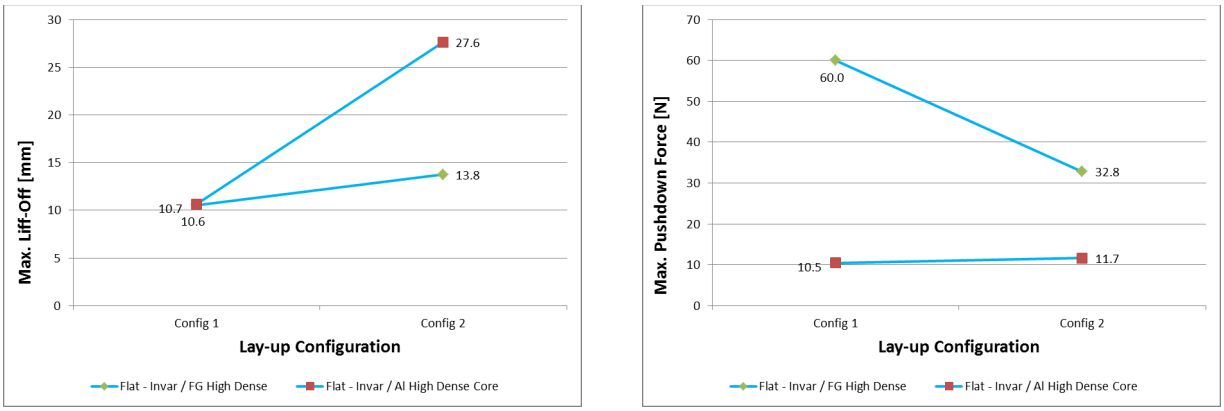
a. maximum lift-off

b. maximum push down load

Figure 4. Spring-back effects by core thickness and cure tool

3.2 Skin Layup Configuration and Core Material

The contribution of core material and skin layup configuration to the spring-back effect was investigated by evaluating the test coupons fabricated using 25 mm thick fiberglass and aluminum cores with two different layup configurations. All coupons were laid up, final bagged, and cured using the same Flat – Invar tool. The summary of the test results is presented in Figure 5. Test results indicated that the maximum spring-back distance was higher for aluminum core in almost every case. The exception was Configuration 1 (thick) layup, in which the aluminum core panel sprang back 0.1 mm less than the fiberglass core. The spring-back difference was insignificant and should be considered as equivalent in this case. Although the aluminum core had a higher spring-back distance, the fiberglass core required a higher pushdown force in every case. This result is quite interesting as the initial thought process was the amount of force required to restrain the part to the tool has a direct correlation with the amount of spring-back distance. It was always focused on reducing the amount of spring-back and did not regard the amount of force required to constrain the part to the tool.

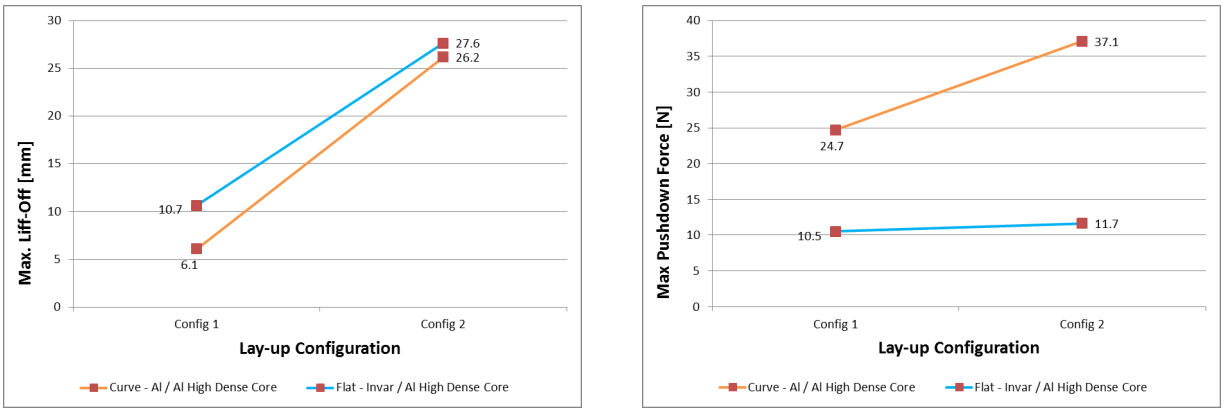


a. maximum lift-off b. maximum push down load

Figure 5: Comparing spring-back effects between aluminum and fiberglass cores

3.3 Cure Tool

The contribution of cure tool to spring-back effect was evaluated on the test coupons fabricated using 25 mm thick aluminum cores on two different layup configurations. The coupons were laid up, final bagged, and cured using two different tools: flat – invar and curved – aluminum. All coupons were cured under the same cure load. The summary of the test results is presented in Figure 6. The test results showed the amount of pushing down force increased as the spring-back distance increased. The thicker skin required less amount of restraint load than the thinner skin. Although the flat-invar cure tool showed higher lift off distance, the force required to pushdown was significantly less than the curve-aluminum tool.



a. maximum lift-off b. maximum push down load

Figure 6: Spring-back effects on 25 mm thick aluminum core

3.4 Correlation of Processing Factors

Several observations are drawn from correlating the processing factors:

1. The amount of force to constraint the coupon from spring-back is independent to the amount of lift off. The effect of spring-back should not be evaluated solely by the amount

of lift off, but in some cases, the amount of force to constraint the spring-back is even more critical. Nevertheless, the effect of spring-back should be evaluated by both the amount of lift off and pushdown force.

2. The following are observed for the flat – invar tool:

    a. For aluminum core: core thickness has a direct correlation to the spring-back effect. Both lift off distance and pushdown force increase as core thicknesses increase. The layup configuration (as a function of the face sheet thickness and stiffness) has a direct correlation to the amount of spring-back distance, but has insignificant effect on the pushdown load.

    b. For fiberglass core: the contribution of core thickness to spring-back effect will be included in future studies as the test results showed no direct correlation between aluminum and fiberglass cores. Layup configuration shows opposing effects on the amount of lift off distance and pushdown force. A thicker face sheet reduces the lift off distance, but requires more restraint force. A thinner face sheet showed an opposite effect compared to the thicker face sheet.

3. The following are observed for the curve – aluminum tool:

    a. It is not possible to draw any definite lessons learned on the fiberglass core.

    b. The following are observed for aluminum core:

        i. Increasing core thickness shows a slight decrease in spring-back distance and pushdown force.

        ii. Layup configuration (as a function of face sheet thickness and stiffness) play a major role to the spring-back effect for both distance and pushdown load.

4. The results show that fiberglass core behaves differently than aluminum core. The test results indicate that the layup configuration might have significant impact to the spring-back for fiberglass core and the amount of pushdown force and lift off distance may not follow any trend. Additional studies are needed to evaluate how the core thickness and cure tool contribute to the spring-back effect.

4. CONCLUSIONS

The challenges in controlling the spring-back effect in composite structure manufacturing have been presented. This paper shows comprehensive results of how honeycomb core materials, core thickness, layup configuration, and cure tool type contributes to the spring-back of a non-symmetric and imbalanced part. Conclusive observations have been drawn for a high-density aluminum core, but further studies will be needed for fiberglass cores and other aluminum core densities. Other processing factors such as core direction, splicing, and acoustic treatments may be needed in order to fully understand and draw a definite conclusion on the spring-back effect and to develop risk mitigation plans for the

manufacturing of nacelle structures. The influence of processing parameters to spring-back in sandwich structure fabrication is quite complex and requires extensive studies.

5. REFERENCES

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