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"SIX SIGMA" AIDED DESIGN OF A FUSELAGE COMPOSITE PANEL

Six Sigma Method (SSM) is included in the "Robust Design" context and allows to reduce the sensitivity to external factors during design and manufacturing phase and during the product lifecycle, too. Organisations like Sony, Honda, Lockeed Martin, Motorola, Toshiba proved to be interested in this method but, only in 1979, Motorola first took into account this method for industrial problems, with the aim of improving product quality and reducing manufacturing costs. 'Six Sigma' ability of meeting customer requirements (in terms of costs and quality) and its intrinsic property of identifying and quantifying design parameters influence on final product performance, makes such method a valid and powerful tool for designers.

In the paper at hand, a design evolution for a composite fuselage panel is presented applying SSM. At first, basing on a Safety Margin optimized panel, the influence of the design parameters variation was estimated, assuming, as constraint, a deviation of the Safety Margin confined within ±5%. The most critical parameters resulted: the ply thickness, the material allowable strain, the lamina Young moduli along the main plane directions, the shear and Poisson modulus. By randomly varying these parameters, the FE models of novel panels, differing from the optimized one, were generated and, through the MSC\Nastran code, linear static and buckling investigations were performed. Predicted stress field and instability loads were used to compute the Safety Margin, thus achieving a normal distribution. Finally, allowed variation ranges of above mentioned parameters were found out, by verifying that the standard deviations fall within assigned Safety Margin range (i.e. within ±5%). The most critical parameter, both for the stress field generated and for the allowable instability load was the ply thickness, whose allowed excursion proved to be the narrowest one.

Keywords: **"Six Sigma", composite, margin of safety, mean value, deviation standard**

PROJEKTOWANIE SAMOLOTOWEGO PANELU KOMPOZYTOWEGO Z ZASTOSOWANIEM METODY „SZEŚĆ SIGMA"

Metoda „Sześć sigma" (ang. Six Sigma Method, SSM) zawarta w kontekście „Projektowania Wytrzymałej Konstrukcji" pozwala zredukować wrażliwość na czynniki zewnętrzne w okresie projektowania i wytwarzania oraz podczas eksploatacji produktu. Takie koncerny, jak: Sony, Honda, Lockeed Martin, Motorola, Toshiba wykazywały zainteresowanie tą metodą, lecz dopiero w 1979 r. Motorola jako pierwsza uznała tę metodę za odpowiednią do rozwiązywania problemów przemysłowych w celu poprawy jakości produktu oraz zmniejszenia kosztów produkcji. Zdolność metody „Sześć sigma" do zaspokajania wymagań klientów (w kategorii ceny i jakości) oraz jej wewnętrzna właściwość rozpoznawania i oszacowania wielkości wpływu parametrów projektowania na końcowe właściwości produktu czyni z niej ważne i potężne narzędzie dla projektantów.

W pracy zaprezentowano przebieg projektowania kompozytowego panelu samolotu z wykorzystaniem metody „Sześć sigma". Najpierw, bazując na panelu zoptymalizowaym ze względu na margines bezpieczeństwa, został oszacowany wpływ wariacji parametrów projektowania przy założeniu wartości odchylenia tego marginesu nie większej niż 5%. Najbardziej krytycznymi parametrami okazały się: grubość warstwy, dopuszczalne odkształcenie materiału, moduły Younga warstw wzdłuż głównych kierunków płatu, moduł ścinania i Poissona. Poprzez zmiany losowe tych parametrów wygenerowano modele MES nowych paneli, różniące się od zoptymalizowanego, oraz przeprowadzono liniowe badania statyczne oraz badania wyboczenia z pomocą kodu MSC/Nastran. Wygenerowane pole naprężeń i obciążenie wyboczeniowe zostały użyte do określenia marginesu bezpieczeństwa, osiągające w ten sposób rozkład normalny.

Na koniec zostały określone dopuszczalne zakresy zmian wyżej wymienionych parametrów poprzez weryfikację odchylenia standardowego w zakresie założonego marginesu bezpieczeństwa (±5%). Najbardziej krytycznym parametrem, zarówno dla wygenerowanego pola naprężeń, jak i dla dopuszczalnego obciążenia wyboczeniowego była grubość warstwy, dla której dopuszczalne odchylenie okazało się być najmniejsze.

Słowa kluczowe: **"Sześć sigma", kompozyt, margines bezpieczeństwa, wartość średnia, odchylenie standardowe**

INTRODUCTION

The new generation of aeronautical structures is characterized by light materials and high performance [1]. According to this trend, design efforts lead to use composite structure for envisaged weight and consumption cut down [2]. Due to their intrinsic nature, the investigations on buckling and strength behaviour of composites follows approaches generally different from traditional ones [3]. In this scenario, criteria able to highlight and quantify design parameters influence on final product performance, play a fundamental role, allowing for compliance to customer requirements. Within the quality optimization field, many groups, like Sony, Honda, Lockeed Martin, Motorola, Toshiba were interested in the Six Sigma Method (SSM), belonging to "Robust Design" typology and relating the Safety Margin of a structural component to the variation of some design parameters; Six Sigma originated as a set of practices designed to improve manufacturing processes and eliminate defects, but its application was subsequently extended to other types of business processes as well [3-5]; in Six Sigma, a defect is defined as any process output that does not meet customer specifications, or that could lead to create an output that does not meet the customer specifications [6]. In a manufacturing context the method is able to focus the possibility of a process to meet the customer need but in a design context, as presented in this work, it means to verify if standard deviation, of each considered design parameter, fall within assigned Safety Margin range (i.e. within ±5%). In this context the SSM is a sound opportunity to solve the problem, so that this approach is included in a "Robust Design" concept to optimize structural parameters during a composite structural design improving the manufacturing process and reducing costs. So that, SSM in a composite design concept leads to show the variation range of each structural parameter to have a desiderate output as presented in this work.

To solve this problem it is common use to introduce a safety coefficient in structural design variable, but, from this point of view, a "Robust Design" leads to deterministic hypothesis connected to variations during a lifecycle as aging of material. This is connected to an increasing uncertainty and a probability of structural failure apart from an increasing manufacturing, repairing and maintenance costs. So that, it is important to know and foresee structural performances for an optimum design concept [7, 8] and this work focuses this aspect. Through a probabilistic approach, based on SSM, by MSC Nastran solver and MSC Patran pre-post processor, a strength and a buckling FEM analysis for a fuselage composite stiffened panel, composed of 2 frames and 3 stringers, have been conducted. During the design phase, target structural parameters, as necessary condition for the application of SSM, have been defined. With a random parameter variation (skin ply thickness th_{skin}, the allowable values ε_{all}, the lamina Young modulus E_{11} and E_{22}, the shear modulus G_{12} and Poisson modulus ν_{12}, in a defined range, the normal distribution of Margin of Safety by strength analysis and eigenvalues found by buckling analysis, respectively, have been computed. In this way, the most critical design parameters have been determined and, on those ones, the SSM has been applied, determining reliability design requirements and information about design parameter "quality".

GEOMETRY DESCRIPTION AND MODELLING STRATEGY

The considered structure is a composite stiffened panel as in Figure 1 and about this one a strength and a buckling analysis have been conducted. In fact, for a weight saving purpose the added load capability before the ultimate strength of a composite panel is fundamental. A fuselage composite stiffened panel, by a FEM approach with real industrial requirements under Alenia Aeronautica S.p.A. property, has been designed.

The composite panel is a "stiffened" panel and it is composed of 3 omega profile (Fig. 2) stringers with a reinforcing rule for the structure along the longer side, and of 2 frames along the shorter side in a perpendicular direction to the stringers. Panel dimensions are: 1270 mm x 674 mm and 0.184 mm thick.

After defining geometry a FEM modelling has been created using cquad4 elements composed of 4 nodes and widely used for this type of approach because of this type of element is able to support in plane forces, bending and shear loads while strain shear out of plane is not considered. So that, this model has a FEM meshing as follows: 20784 nodes and 20940 elements as shown in Figure 1. For our purpose, in order to compare main results, always the same element n. 16584 (Fig. 3) between the 2 frames, has been considered. For this panel a composite material (CFRP) has been used composed of 13 plies with the following angular sequence: $45/-45/90/0/45/-45/0/-45/45/0/90/-45/45$ in degree with the following material property as in the Table 1.

TABLE 1. **Panel material property**
TABELA 1. **Właściwości materiału panelu**

th_{skin}	E_{11}	E_{22}	G_{12}	ε_{all}	ν_{12}
0.184 mm	115000 N/mm^2	7000 N/mm^2	3200 N/mm^2	3500 μstrain	0.3

A common fuselage panel is simultaneously loaded by distributed compressive load and also by shear load; so that the following panel has been loaded by a compressive load (50 N) on the longer side and by a shear flux (26.5 N/mm) on the shorter side. In order to have a static determinate structure, boundary conditions for the panel have been applied. On the longer front side in the FEM model (Fig. 1) the left node has been hinged and the right node has been embedded while along the four sides of the panel simply supported nodes have been included. In the following, two analysis, strength and buckling, shall be presented.

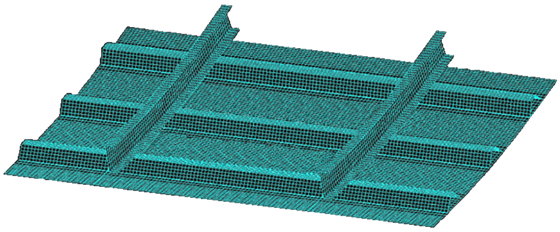

Fig. 1. FEM meshing of the panel

Rys. 1. MES siatki dla panelu

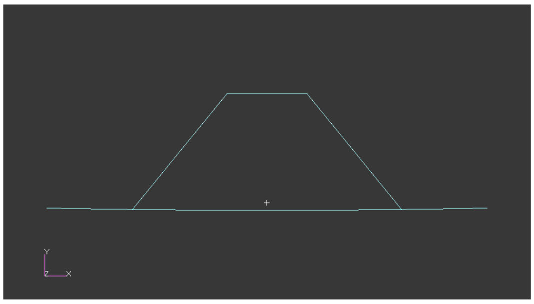

Fig. 2. Omega profile stringer

Rys. 2. Podłużnica o profilu omega

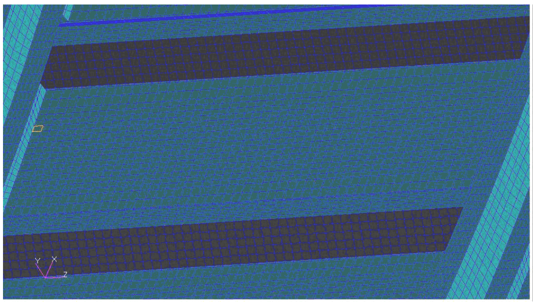

Fig. 3. Node n.16584

Rys. 3. Węzeł n.16584

STRENGTH ANALYSIS

At first, a strength analysis on the panel, using a FEM approach by a static linear analysis, through the Nastran SOL 101, has been conducted. The design parameters of the panel for the strength analysis are in Table 2.

TABLE 2. **Panel design parameter for strength analysis**
TABELA 2. **Parametry projektowania panelu dla analizy wytrzymałościowej**

Mechanical parameters	Design parameters
E_{11}, N/mm^2	115000
E_{22}, N/mm^2	7000
th_{skin}, mm	0.184
ε_{all}, µstrain	3500
G_{12}, N/mm^2	3200
ν_{12}	0.3

After this, the related Margin of Safety (MoS) have been evaluated for the element n. 16584 considering $MoS = 1.54$ as target value reference for the application of SSM.

In this analysis what is the influence of design parameters, in allowed variation range, on the MoS perturbation for a Robust Design, is the main purpose. So that, in order to apply the SSM, design parameters have been evaluated to determine which of these ones are critical for the MoS target value. In Table 3 a defined variation range for each parameter is shown.

TABLE 3. **Panel design variation for strength analysis**
TABELA 3. **Zmiany parametrów projektowania panelu dla analizy wytrzymałościowej**

Mechanical parameters	Variation range
E_{11}, N/mm^2	110000÷120000
E_{22}, N/mm^2	6000÷8000
th_{skin}, mm	0.175÷0.187
ε_{all}, µstrain	3500÷4100
G_{12}, N/mm^2	2500÷3900

According to a statistical approach in order to change randomly each of six parameters, by means of a numerical tool, a variation range has been defined. So that, 100 linear static analysis have been run for each parameter, so for 6 of these ones 600 SOL 101 analysis have been computed. This computational effort, according to the statistical approach, has been fundamental in order to have a more and more real result. The application of SSM is based on the requirement that standard deviation σ has to fall within $1/12$ of the requirement width as target Margin of Safety (MoS) for our purpose. Before applying the method the target value of $MoS = 1.54$, found for optimized panel, has been defined. From this target value upper and lower limits, respectively $1.54 + 5\%$ and $1.54 - 5\%$, according to this formula $\Delta = \frac{1.61 - 1.47}{1.54} = 0.1$, have been computed in order to verify the process capability in terms of bandwidth requirements. Standard deviation σ has to fall within $1/12$ of the requirement width, Δ, so finding the following reference value for the method application: $\sigma = \frac{\Delta}{12} = 0.008$. So that, a numerical tool has computed the MoS for each of 100 random value related to six design parameters (in all 600 values); then the MoS mean value μ and standard deviation σ have been estimated, in order to check if the process is centred $(\mu = 1.54)$ and is capable $(\sigma \le 0.008)$ so determining what design parameters are critical for a Robust Design concept, purpose of this work.

The tool, in Visual Basic language, selected the ply sequence and selected 100 values for the considered design parameters, automatically changes the values in the .bdf file and then generates other 100 .bdf files that can be analyzed by Nastran solver. By this procedure, for each of six parameters, in a more restricted range where the method is applicable, from 100 MoS values, the mean value μ, the standard deviation σ and normal distribution have been computed (Table 4).

TABLE 4. **Panel variation range and Six Sigma requirements for strength analysis**

TABELA 4. **Zakres zmian parametrów panelu oraz wymagania metody „Sześć sigma" dla analizy wytrzymałościowej**

Mechanical parameters	Variation range	Mean value (M.S.)	St. deviation	Six Sigma requirements
E_{11}, N/mm^2	114500÷115500	1.544	0.005685	yes
E_{22}, N/mm^2	6500÷7500	1.543	0.006765	yes
th_{skin}, mm	0.183÷0.185	1.543	0.009574	no
ε_{all}, μstrain	3790÷3810	1.544	0.00492	yes
G_{12}, N/mm^2	3000÷3400	1.544	0.00747	yes

Only ν_{12} is always centred (mean value $\mu = 1.54$) and capable (standard deviation $\sigma = 0$) and so it does not influence the panel design.

By the analysis of results it is evident that E_{11}, E_{22} and G_{12} have a smooth influence on mean value μ and standard deviation σ so that, they are not too critical for the application of the SSM and for a Robust Design. On the other hand, ply th_{skin} results critical, in fact, for this parameter, even if the allowed variation range is very small and the process is centred (mean value $\mu = 1.54$), however, standard deviation value is not acceptable ($\sigma = 0.009574 > 0.008$) and so, the process may not be considered capable.

So that, during the design process, this parameter shall be relevant for the panel and, on that one, in a Robust Design design concept efforts shall be focused.

BUCKLING ANALYSIS

In order to determinate the instability behaviour, after the strength analysis, on the composite stiffened panel, a buckling analysis has been conducted, too. Buckling analysis is based on the Eigenvalues computation, through SOL 105 Nastran solution, for the panel area between the two frames as in Figure 3. So that, design parameter effects, in terms of th_{skin}, E_{11}, G_{12} influence, has been evaluated. At first, on the optimized panel, a buckling analysis has been conducted considering the lowest Eigenvalue found in the area between the two frames as in the Figures 4 and 5. By the analysis, eigenvalue for optimized design condition is $\lambda = 1.0182$ and, for our purpose, this is the target value. As during the strength analysis, by randomly varying, in an allowed range, design parameters (ply th_{skin}, E_{11}, G_{12}) as shown in Table 5 mean value and standard deviation have been computed. By a batch file 300 runs (100 for each parameter) have been conducted so that, normal distribution has been found out. As in the strength analysis with MoS target value, in the buckling analysis the target Eigenvalue is $\lambda = 1.0182$. By this value the standard deviation shall fall within an assigned eigenvalues range (λ ±5%), so that, from this target value upper and lower limits, respectively $1.0182 + 5\%$ and $1.0182 - 5\%$, according to this formula $\Delta = \frac{1.07 - 0.97}{1.02} = 0.1$, have been computed, in order to verify the process capability in terms of bandwidth requirements. Standard deviation σ, as in the strength analysis, has to fall within $1/12$ of the requirement width, so finding the following reference value for the method application, $\sigma = \frac{\Delta}{12} = 0.008$. In the following the parameter variation range and, respectively, mean value and standard deviation.

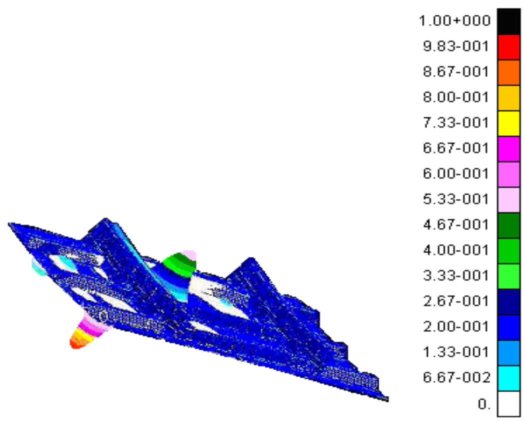

Fig. 4. Buckling analysis for optimized panel

Rys. 4. Analiza wyboczenia dla zoptymalizowanego panelu

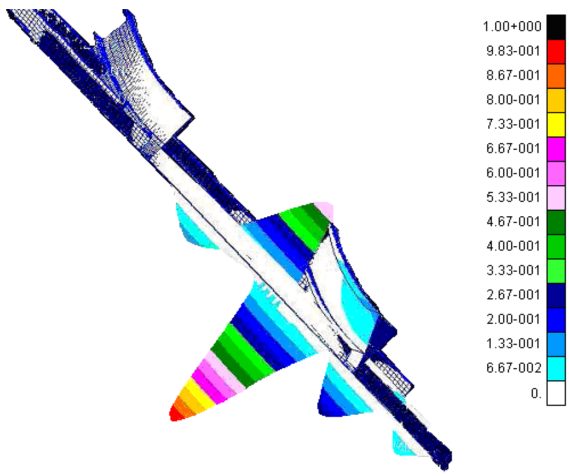

Fig. 5. Buckling analysis for optimized panel (particular)

Rys. 5. Analiza wyboczenia dla zoptymalizowanego panelu (szczegół)

TABLE 5. **Panel variation range and Six Sigma requirements for buckling analysis**
TABELA 5. **Zakres zmian parametrów panelu oraz wymagania metody „Sześć sigma" dla analizy wyboczenia**

Mechanical parameters	Variation range	Mean value (eigenvalue)	St. deviation	Six Sigma requirements
E_{11}, N/mm^2	114500÷115500	1.018	0.008	yes
th_{skin}, mm	0.182÷0.184	1.016	0.014	no
G_{12}, N/mm^2	3100÷3300	1.018	0.0001	yes

By buckling analysis ply th_{skin} is the most critical design parameter; E_{11} in a more restricted range is compliant to the requirements with a low standard deviation, as for G_{12} that in a restricted range respects the requirements with a standard deviation very low as shown in Table 5. For th_{skin}, even if in a small range $0.182 \div 0.184$ mm, through buckling analysis, a too high standard deviation value has been found. So that, for a composite stiffened panel design, during strength analysis and buckling analysis, this one is the most critical design parameter as presented during the investigation.

In a Robust Design concept, aim of this work, ply th_{skin} is the design parameter to be optimized to have a performance improvement.

CONCLUSIONS AND FURTHER STEPS

In this work a Six Sigma Method (SSM) application has been presented in a design approach.

SSM, in a Robust Design concept, leads to reduce the sensitivity to external factors during design and manufacturing phase and during the lifecycle, too. At first, while this method interested many groups (Motorola, Lockeed Martin etc.) to improve the product quality and to cut down manufacturing cost in order to meet the customer need, in a design concept, as presented in this paper, this method leads to estimate what are the most important design parameters and which of these ones are critical for the panel design. By knowing the critical design parameters a design improvement, weight reduction and cost cut down are possible before manufacturing phase.

The composite panel, under investigation, is a "stiffened" panel and it is composed of 3 omega profile stringers with a reinforcing rule for the structure along the longer side, and of 2 frames along the shorter side in a perpendicular direction to the stringer. In this paper two types of studies have been conducted on the panel: a strength analysis and a buckling analysis. The first analysis, by randomly varying design parameters, has shown that the ply thickness of the skin, th_{skin}, is the most important design parameter because it influences the method in terms of mean value and standard deviation and it does not respect the SSM requirements in terms of capability process. The target value for the method application is $MoS = 1.54$ for the optimized panel. Randomly varying parameters, by a numerical tool, MoS have been computed and for each design parameter has been verified if the standard deviation value falls within assigned Margin of Safety (MoS) range (MoS±5%). With respect to other parameters during strength analysis (ply th_{skin}, E_{11}, G_{12}, ε_{all}, E_{22}, ν_{12}) ply th_{skin} is the critical parameter on the MoS and for this reason, on that one, efforts shall be focused. For the buckling analysis in terms of computed eigenvalue, according to the target value ($\lambda = 1.0182$), the critical parameter is still th_{skin}, in fact, even if in a restricted variation range, it does not fall within assigned range (λ ±5%). Results show what is the panel sensitivity and provide indications for a design improvement. For the two analysis (strength and buckling) ply th_{skin} has been critical for the design; from this point of view the result acceptability confirms the correct approach and this leads to further application of the method. A future application could deal with a study on a stiffened composite panel with a different lay up sequence to show different behaviour on a design parameter. Other studies could be interested to a post-buckling analysis or to a mixed load conditions on the panel.

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