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AN ARTIFICIAL NEURAL NETWORK BASED ANALYSIS METHOD FOR SKIN-STRINGER STRUCTURES

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ABSTRACT

Aim of this study is to develop a tool for fast determination of load carrying capacity and mass of skin-stringer structures. For this purpose 1440 different skin-stringer finite element (FE) models are created with a script written in Python 2.7 and analyzed by using commercial FE program ABAQUS. The script is utilized for creation of the model, analysis of the model, extraction of the buckling load, the collapse load and the mass of the assembly from ABAQUS analysis results. Model input parameters and analysis results of these 1440 models are used to create an artificial neural network (ANN) in MATLAB NNTOOL toolbox for a fast determination of the buckling load, the collapse load and the mass of skin-stringer assemblies other than already created 1440 different models. The performance of the trained ANN is demonstrated by comparisons with FE results.

INTRODUCTION

Stringer is the primary stiffening member fastened to skin of the aircraft in longitudinal direction. Stringers are used both to prevent buckling of the skin and collapse of the structure after skin buckling [Bruhn, 1973]. Buckling is an instability problem generally considered as the first failure mode of a stiffened panel. Buckling load is a function of material properties, panel thickness and panel length [Niu, 1999]. After buckling, loads on the buckled section of the skin panel are transferred to stringers and an effective section of the skin panel [Gustafson, 2009]. Stringers and effective skin panel section carries the excess load until collapse. Thus, load carrying capacity of an aircraft structure is significantly affected by design of a skin-stringer assembly [Mert & Kayran, 2015]. In Figure 1, there are images of fuselage skin-stringers (on the left) and tail boom skin stringers (on the right) of a helicopter.

To have an optimum skin-stringer assembly, the structure must be designed with maximum load carrying capacity and minimum weight. An optimization process with that objective involves many detailed structural analyses of a skin-stringer assembly with various combinations of design parameters. In this study, it is aimed to develop a methodology for a quick and accurate solution to obtain critical loads and mass of the system which can be used for an optimization process.

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Figure 1: Helicopter fuselage skin-stringers (left) and tail skin stringers (right)

An artificial neural network (ANN) can constitute an input-output relation between large data sets by observing and learning given data. Using an ANN, critical loads and mass of a skin-stringer assembly can be acquired significantly faster than building and analyzing a detailed FE model. Therefore, the optimization process can be much faster and include more trials to reach optimum parameters. In order to create an ANN, 1440 different skin-stringer finite element models are created with a script written in Python 2.7 and the models are analyzed by using the FE program ABAQUS. The assembly is subjected to an axial compression until failure. The reaction force-axial displacement curves are obtained from analysis results. The force-displacement result is used to determine the buckling load and the failure load of the skin-stringer assembly. The results and necessary inputs for 1440 FE analyses are collected by the script. MATLAB NNTOOL toolbox is used to create an artificial neural network that calculates load capacity and mass of a skin-stringer assembly without further use of finite element analysis.

METHOD

Skin-stringer model is chosen as flat skin panel stiffened by stringers with Z section due to its widespread use in aerospace industry [Ambri & Kaur, 2014]. The assembly is subjected to a compression loading. A rigid 2D shell part, which is shown in red in Figure 2, is used to model the frame. Compression load is introduced as displacement on the frame. A reference point, which can be seen as “RP” in Figure 2, is created on the frame to apply the displacement. Reference point “RP-1” is created to be symmetrical to mid-plane of stringers and is connected to each node on (0,y,z) plane via multi point constraint (MPC) connections. “RP-1” point is restrained in all directions and rotations as a boundary condition.

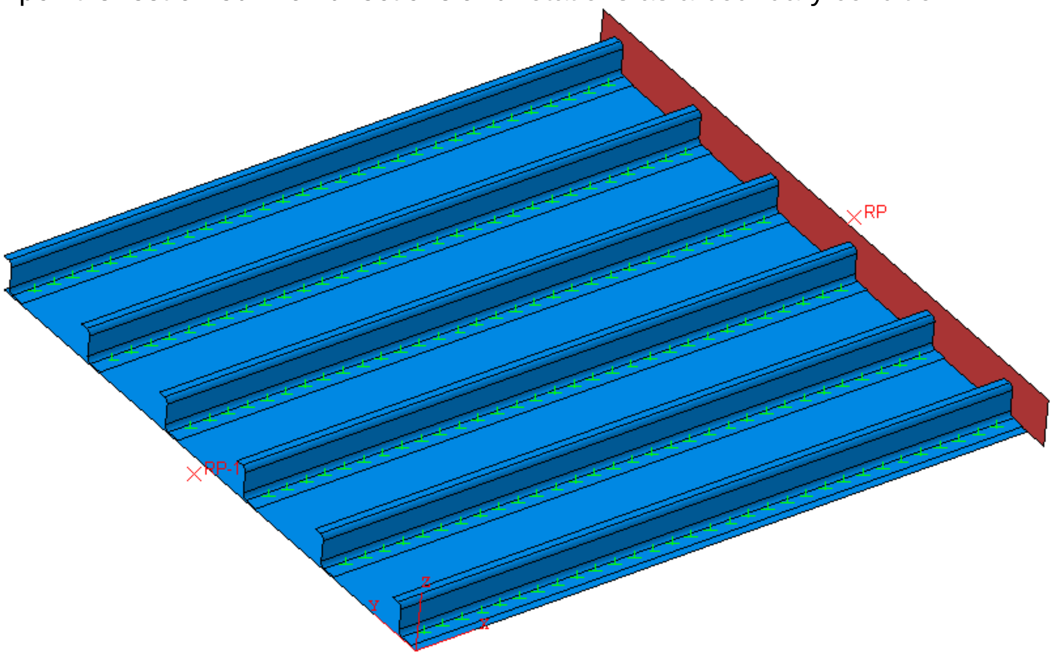

Figure 2: Finite element model of a skin-stringer assembly

All stringers and the skin panel are modeled as 2D shell elements with aluminum material properties. The mesh size and element type are determined after preliminary convergence studies. The average mesh size is determined as 4 mm and the element type is S4R (a 4 node shell element with reduced integration, hourglass control and finite membrane strains). Each stringer is connected to the skin by fasteners with diameter of 3.2 mm. Fastener spacing is determined as 4.5 times fastener diameter to represent a realistic design.

The model is solved using “Static, General” step of ABAQUS with enabled nonlinear geometry option (nlgeom=ON) and nonlinear (elastoplastic) material properties [Abaqus 6.13 Documentation, 2013].

Two types of materials are used in the analyses of the 1440 skin stringer assemblies: 2024-T3 clad sheet and 2024 T42 clad sheet. Both materials are 2024 series clad aluminum sheets, which are commonly used metals in aerospace industry. The properties of these materials are given in Table 1.

Table 1: Material properties

	2024-T3 Clad	2024-T42 Clad
Young’s Modulus (MPa)	72395	72395
Poisson’s Ratio	0.33	0.33
Density (g/cc)	2.768	2.768
Yield Strength (MPa)	310	241
Ramberg-Osgood Number	15	17

ABAQUS requires true stress-true strain relation data to model elastoplastic properties of a material. Thus, stress-strain relation of the two materials are obtained from Ramberg-Osgood equation [Ramberg & Osgood, 1943]

$$\boldsymbol{\epsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{\sigma_0}\right)^n}$$

where, $\boldsymbol{\epsilon}$ is the uniaxial strain, $\boldsymbol{\sigma}$ is the uniaxial stress, $\boldsymbol{E}$ is the elastic modulus, $\boldsymbol{\sigma_0}$ is the yield strength, and $\boldsymbol{n}$ is the Ramberg-Osgood number.

Obtained engineering stress-strain $\boldsymbol{\sigma_{eng} - \epsilon_{eng}}$ relation is converted to true stress-strain $\boldsymbol{\sigma_{tr} - \epsilon_{tr}}$ relation [Roylance, 2001] as

$$\boldsymbol{\sigma_{tr} = \sigma_{eng}(1 + \epsilon_{eng})}$$

$$\boldsymbol{\epsilon_{tr} = ln(1 + \epsilon_{eng})}$$

In the analysis of the finite element model that is described in this section, aluminum 2024-T3 clad sheet is used and the following data are extracted from the analysis results,

- Collapse load : 126.7 kN
- Buckling load : 37.1 kN
- Mass : 775 g

Finite element analysis results of the skin stringer assembly are also given as out-of-plane deformation contours and Von Mises contours in Figure 3 and Figure 4, respectively. Deformation scales of the figures are magnified five times. The figures show four levels of the load up to failure. The stages are shown in the figures as

a) Before buckling
b) At the moment of buckling
c) After buckling
d) At the moment of collapse

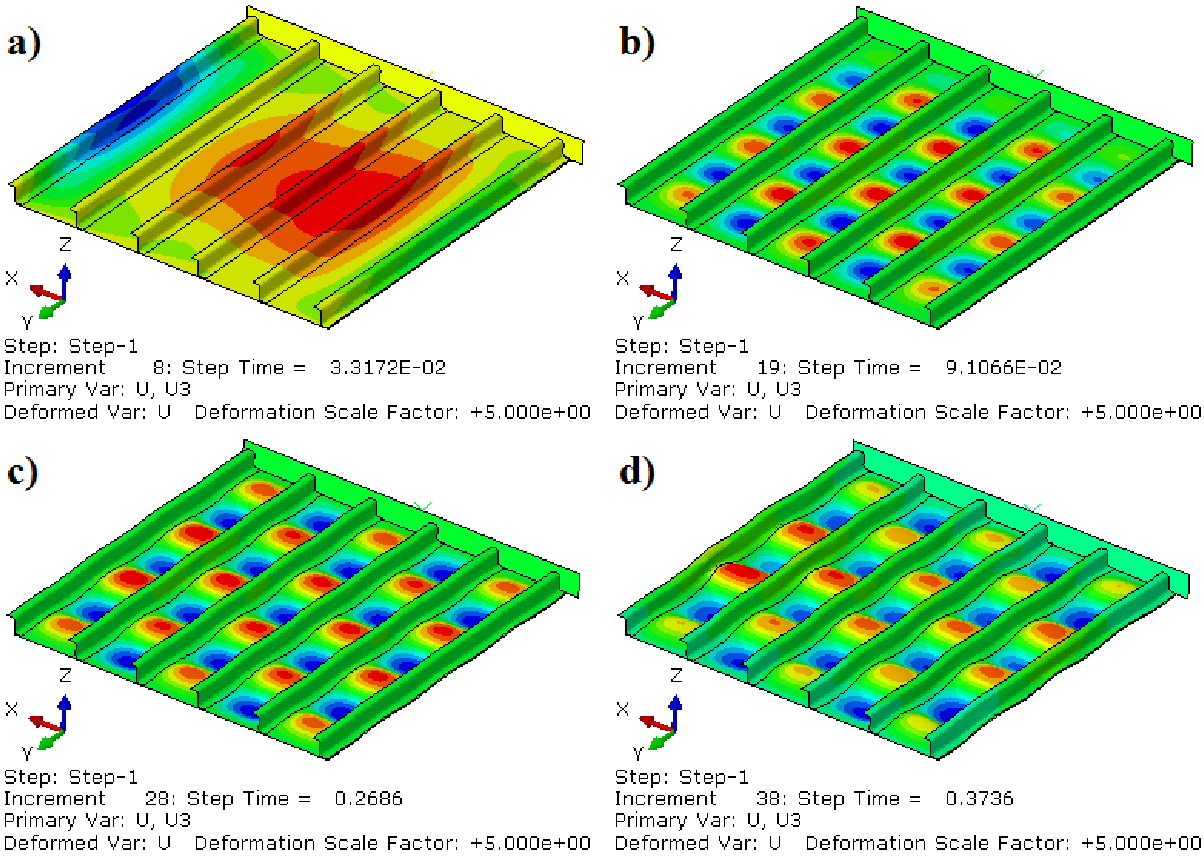

Figure 3*:* Out-of-plane deformation contours at four stages of the analysis

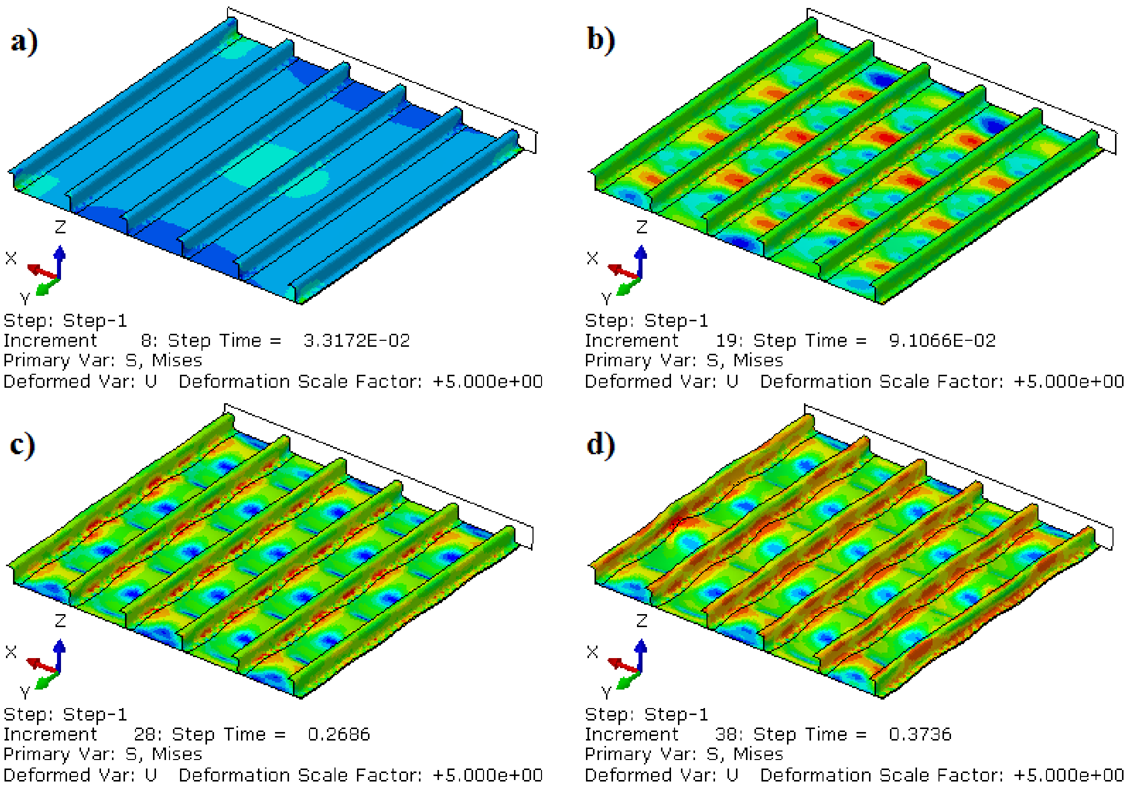

Figure 4*:* Von Mises stress contours at four stages of the analysis

A script is written in Python 2.7 to create an ABAQUS model, run the model and collect the buckling load, the failure load and the total mass of the system from the analysis results. The results are processed in MATLAB NNTOOL to create an artificial neural network (ANN).

Script

ABAQUS is capable of running scripts written in Python 2.7. Thus, a Python 2.7 script is utilized to create a finite element model (FEM), analyze it and collect the results.

Finite Element Model Creation and Analysis: Script is written in a way that allows the following parameters to be determined by the user,

- Skin panel thickness
- Stringer thickness
- Stringer height
- Stringer inner flange length
- Stringer outer flange length
- Stringer section inner radius
- Skin panel material
- Stringer material
- Skin panel length
- Skin panel width
- Distance between stringers
- Fastener diameter

The number of stringers is calculated by considering the skin width and the distance between stringers. Using the skin panel width and the distance between stringers given by the user, maximum number or stringers is determined. The remaining space of the panel is distributed evenly to each side of the panel.

To minimize the computation time, the script is not used in its maximum capacity. Some of the parameters are fixed to certain design parameters. Following parameters are considered to have marginal effect on buckling and post-buckling properties and therefore are fixed to given values:

- Stringer section inner radius = 2.5 mm
- Skin panel width = 350 mm
- Fastener diameter = 3.2 mm.

The values are chosen as average design values. The distance between stringers is a more critical design parameter than the panel width. The fastener diameter is not a parameter to consider during skin-stringer design but it should be chosen from standard fastener types to be suitable to skin-stringer load carrying capacity. The stringer section radius has an insignificant effect on sectional properties compared to flanges and height.

Following values of the parameters are used for the FE analyses. Consequently, the total number of analyses is calculated as 1440 with the following values,

- Skin panel thickness = [1.0, 1.27, 1.42, 1.6]
- Stringer thickness = [1.0, 1.27, 1.42, 1.6]
- Stringer height = [20.0, 30.0]
- Stringer inner flange length = [10.0, 15.0]
- Stringer outer flange length = [10.0, 20.0]
- Skin panel material = [AL2024 T3, AL2024 T42]
- Stringer material = [AL2024 T3, AL2024 T42]
- Skin panel length = [300.0, 350.0, 400.0]
- Distance between stringers = [60.0, 70.0, 80.0]

In order to minimize the number of analyses, total number of values for each parameter is kept at minimum. The skin and the stringer thicknesses have remarkable effects on the buckling load and the collapse load. Thus, relatively wide ranges of values are considered for these parameters. The stringer section properties are restricted to two values for each parameter in order to minimize the number of analyses.

Collection of Results: In Figure 5, and example force – displacement curve is given.

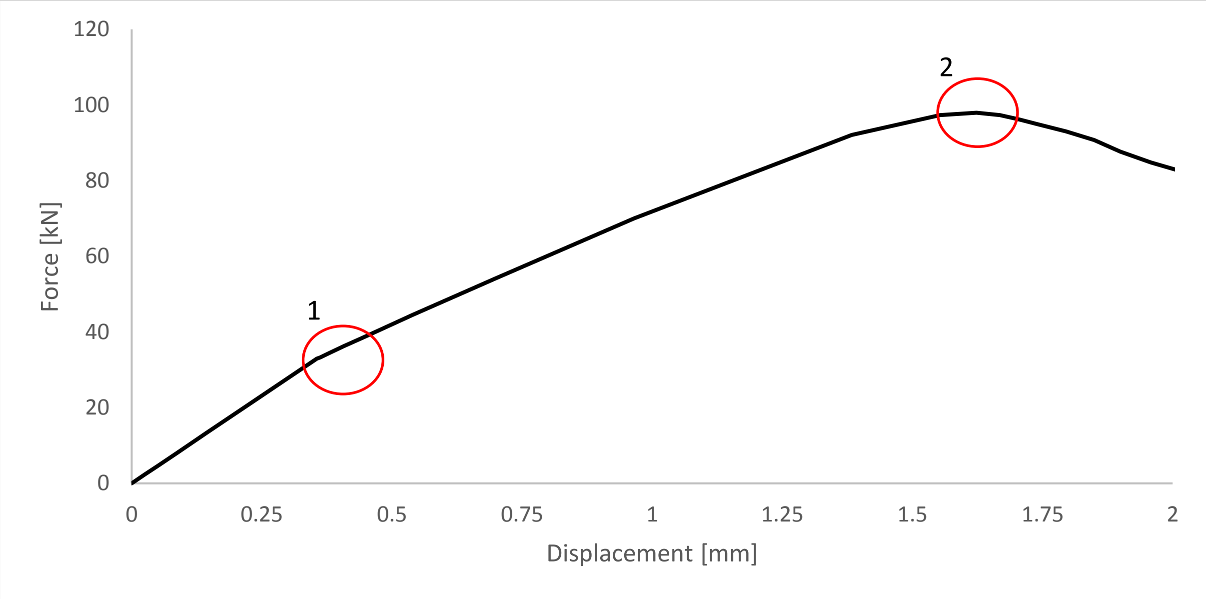

Figure 5: Typical force – displacement curve for a skin-stringer assembly

The slope change shown in circle-1 in Figure 5 represents the first buckling load, and the circle-2 corresponds to the collapse load of the assembly. By tracking the slope changes of the force-displacement curves, the buckling load and the failure load are obtained during the analysis. The mass of the structure is also extracted from the analysis results.

During the analysis, the force on the structure is tracked. In this way, the analysis is terminated at the peak value not to waste any unnecessary computation time.

Artificial Neural Network (ANN)

Input and outputs of the 1440 analyses are processed in MATLAB NNTOOL toolbox to create an artificial neural network (ANN). Objective of the ANN is to create a solution system between inputs and outputs, and return accurate outputs for any input set by applying the solution system.

To determine the number of neurons in the ANN, networks with 1 to 100 neurons are created. Output sets of each network are compared with the FEM results. It is found that network with 48 neurons gives the best performance.

90% of the analyses are used for training the ANN, 5% is used for validation and 5% is used for test. The network performance is measured based on the number of ANN results giving more than 5% difference to the FEM results. A large number of ANNs are created with different 90% training sets until 20 ANNs are obtained with desired performance.

Finally seven new models are created in addition to the initial 1440 analyses to check the performance of the ANNs. Then the ANN with the best performance is chosen.

RESULTS

From 1440 initial analyses, 95 of them (6.6%) show 5% or more difference in any of the three outputs to the FEM results. Only 8 of the analyses (0.56%) exhibit 10% or more difference. Maximum error is found to be 15.45% for the buckling load, 6.02% for the collapse load and 6.97 for the mass. ANN with the best performance tested with 7 additionally generated models. The maximum difference of ANN results for these 7 models to FEM results is found as 2.36%. Table 2 shows the input parameter set of 7 additional analyses, and Table 3 shows ANN results, finite element analysis (FEA) results and the corresponding percentage errors.

Table 2: FEA input parameters for additional analyses

FEA	1	2	3	4	5	6	7
Skin panel thickness	0.8	1	1	1	1.3	1	1
Stringer thickness	1.3	1.27	1.27	1.27	1.5	2	2
Stringer height	20	25	25	20	20	20	20
Stringer inner flange length	10	10	10	10	10	10	10
Stringer outer flange length	10	12	12	10	10	10	10
Skin panel material	2024T3	2024T3	2024T3	2024T3	2024T3	2024T3	2024T42
Stringer material	2024T3	2024T3	2024T42	2024T3	2024T3	2024T3	2024T42
Skin panel length	350	350	350	370	450	350	350
Distance between stringers	70	70	70	65	70	70	70
Stringer section inner radius	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Skin panel width	350	350	350	350	350	350	350

Table 3: ANN results, FEA results and error of ANN results for additional analyses

	Buckling Load (kN)			Collapse Load (kN)			Mass (g)		
FEA	ANN Result	FEA Result	% Error	ANN Result	FEM Result	% Error	ANN Result	FEM Result	% Error
1	53.18	52.90	0.53	98.10	97.34	0.78	924.66	931.89	0.78
2	66.00	65.03	1.50	106.12	105.58	0.51	924.10	931.89	0.84
3	53.12	52.90	0.43	108.68	109.94	1.15	909.94	931.89	2.36
4	64.85	65.03	0.26	119.05	119.25	0.16	948.98	931.89	1.83
5	36.68	37.29	1.63	84.14	83.77	0.44	893.02	873.45	2.24
6	38.08	37.29	2.11	91.08	92.72	1.77	859.66	873.45	1.58
7	36.51	37.29	2.11	92.38	91.56	0.90	868.26	873.45	0.59

CONCLUSION

An artificial neural network based analysis method is developed in this study. It has seen that use of ANN to conduct nonlinear structural analysis of skin stringer assemblies can provide fast and accurate solutions.

Performance of the ANN is tested with two different data sets. The first set is the data set used in training of the ANN, and the seconds set is the additional data samples that are created by input parameters not included in the training data set. Results of ANN and FEA for the two data sets are collected and compared. The comparison shows that the proposed ANN-based tool predicts the buckling load, the collapse load and the mass of the structure with a maximum 2.5% of error when compared with the FE results. However, the ANN tool is significantly faster than the FE analysis. Therefore, it is believed that the proposed tool can be used in the preliminary design.

References

Abaqus 6.13 Documentation. (2013, April). Dassault Systèmes.

Ambri, A., & Kaur, R. (2014). *Spars and Stringers - Function and Designing*. International Journal of Aerospace and Mechanical Engineering, 1(1): 58-61.

Bruhn, E.(1973) *Analysis and Design of Flight Vehicle Structures*, 1973 Edition, Jacobs Publishing INC., p: C5-1 – C12-1, 1973

Colier C., Yarrington, P., Gustafson, P & Bednarcyk, B.(2009) *Local Post Buckling: An Efficient Analysis Approach for Industry Use*, 50th AIAA/ASME/ASCE/AHS/ASC Structures, Stuctural Dynamics, and Materials Conference, Palm Springs, California, 4-7 May 2009

Mert, M., & Kayran, A. (2015). *Post-Buckling Load Redistribution of Stiffened Panels in Aircraft Wingbox Structures.* 8th Ankara International Aerospace Conference, METU, Ankara, 10 - 12 September 2015.

Niu, M.(1999) *Airframe Stress Analysis and Sizing*, 2nd Edition, Hong Kong Conlimit Press LTD., p: 451-468, Jan 1999

Ramberg, W., & Osgood, R. (1943). *Description of Stress-Strain Curves by Three Paramaters.* Washington: National Advisory Committee for Aeronautics, Technical Note, 902.

Roylance, D. (1999). 3.11 Mechanics of Materials. Fall 1999. Massachusetts Institute of Technology: MIT OpenCourseWare, https://ocw.mit.edu/courses/materials-science-and-engineering/3-11-mechanics-of-materials-fall-1999/modules/MIT3_11F99_ss.pdf. License: Creative Commons BY-NC-SA.