Publ. Astron. Obs. Belgrade No. 101 (2021), 117 – 124 *Contributed Paper*
DOI: 10.5281/zenodo.5645393

ON THE NUMERICAL STRUCTURAL CALCULATION METHODS OF THE SPACE STRUCTURES AS A RELIABLE REPLACEMENT FOR EXPENSIVE TESTING, STILL A COMMODITY AND WHY

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Abstract: From the perspective of specific techniques and procedures for design, manufacturing, deployment, installation, service, and maintenance, there are three different types of space structures: satellites (structures that orbit the earth), habitats (the buildings erected on other planets or moons or geostationary orbits), and vehicles (structure made for transport of goods, equipment, and passengers). All these space structures are exposed to different sets of loadings, like extremely high temperatures range, high acceleration, space radiation, and others. Ultimately, as on Earth, we must take care that their structural integrity is maintained, while additionally, in habitats (space stations, Moon-habitats, geostationary space hotels, etc.) we must also provide the comfort for humans, plants or animals. To decrease the design and maintenance costs, and provide service away from Earth resources, the goal is the use of virtual reality in their life cycle management. Such a virtual reality should be based on 1) reliable numerical simulation tools for calculating the structural response under loadings, and 2) artificial intelligence decision making. So, it is a future! But what about the present status of numerical methods in space engineering, as the Finite element method? Why FE software is still seen as a commodity, instead of a reliable tool for testing? How the energy needs to attain comfort is simulated. And finally, why the development of numerical simulation tools for calculation of the thermo-mechanical response of the space structures, are not favored and heavily supported by the space sector, as many other innovations? The present paper will try to answer some of these questions.

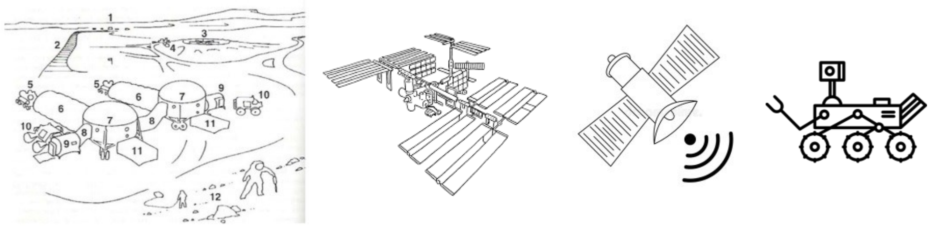
Keywords: space structures, structural integrity, finite element method

1. INTRODUCTION

As may be defined there are three types manmade of structures in space: habitats Fig.1a (Cohen 2015), space stations Figure 1. b., and satellites Figure 1. c., and vehicles Figure 1. d. Let us briefly enplane these structures from its various aspects.

The habitats in space follow the similar requirements as that on Earth. The common words are comfort (Bluyssen 2010), sustainability health and cost.

Comfort in buildings from physical point of view is usually seen from the measurement of temperature, pressure, and humidity.



(a) (b) (c) (d)

Figure 1: Types of space structures: habitats, space stations, satellites, and vehicles

On the other hand, sustainability is mostly related environmental impact. Healthy building is one which maintains and impacts no harm on human health. The most frequent cause of unhealthy condition of building is mold, and others may be related physical quantities in comfort measurement. And lastly, cost is usually not prevailing factor, but it is advised that it be minimal related building performance versus structural and energy efficiency. Let us now define what is habitat in space (other names are: building in space, or out-of-terrestrial building). That is confined human or equipment habitat in space or another planet or moon. In this paper we will consider the most economic tools in design and erections of such buildings.

Satellites are manmade structures that are put in orbit around Earth or another planet or moon; usually they are grouped in space stations or satellites. They require or not artificial gravity, depending on, if they are designated for human living, they are usually called space stations. On the other hand, if they are designated for equipment, they are usually just called satellites. They either can be erected on site or lunched in its simplest form or parts from earth. In that instance they are exposed for re-entry physics, and they are imposed to very high temperature levels. The issue or thermo-dynamics is then to calculate extensively.

Space stations (or human inhabited space stations) are in that point of view orbital confined spaces in which humans spend their time for working and living. It should follow the same requirements for structural and energy efficiency and comfort. They can have artificial gravity or not. For example, International Space Station is in constant none or low gravity state. It is now recognized that absence of gravity can impose severe change in usual blood flow path in human body (Goebel et al. 2019), but it is still unclear how much and how long human can sustain reverse in blood flow. Nevertheless, the calculations are related design, proof-of-strength, thermal resistance, energy efficiency, and other. Present author field of study in this instance is considered to thermo-elasticity and calculation of comfort and energy efficiency.

Space vehicles are designated for transport or humans, animals or biological samples or instruments or machines. They design and manufacturing follow usual prerequisites for any other vehicle that we made on Earth, except gravity and environmental issues. They should be optimized per structural integrity and life cycle pattern and cost. The calculation used are under solid and fluid mechanics theory and tools.

In the rest of the paper, we will be concerned with design and manufacturing or building, based on type of space structures. Specifically on computational numerical (software) tools available contemporary and its effectiveness. It will be shown that in addition to completely correct simulation process from discretization to applying of boundary conditions, loads and material input data, the results are to be expected to be not totally correct if the use of standard displacement-based approach, and that the use of mixed FEM approaches or advanced user expertise is required, before validation, prototyping or manufacturing or construction.

2. ON THE ACCURACY OF THE FINITE ELEMENTS IN SPACE ENGINEERING

In the present paper we are addressing the accuracy of the computational modelling and simulation, of the abovementioned structures, using traditional and new approaches. It is shown in (Mijuca 2010) that using standard displacement based Finite element approach (FE displacement based) or hand calculation, if uniform material structure is loaded only mechanically results are on safe side, while for composite material structures result is on unsafe side. It will mislead the responsible engineer to either overweight the structure, or declare that structure safe for even increased loadings, respectively. In both cases it is not what is wanted in spaces.

The situation is even worse in the case of the thermo-elastic computations. Namely, in finite element displacement-based approach, there is an issue of non-consistency between thermal and mechanical strains. That leads to calculation of the results that will be on unsafe side that is, underestimated. It is a big drawback because the real structure will collapse before calculated time. This malignancy is proven with the comparison with primal-mixed finite element approach (FE HC8/9) in (Mijuca 2008) and experiment. It is probably that in space structures finite element calculation are seen as commodity, and never replacing expensive prototype testing.

In this investigation we will narrow our attention to beam or the plate like structures that are traditionally calculated with dimensional reduction theories. It is for expected that it will deteriorate results, but nobody expected that it will be so detrimental in the case of the standard FEM approach in the setting of thermo-elasticity. That malignancy will be simplest as possible explained here on the also simple set of examples, over the simple coarse meshes. More, it will be explained why in space industry computational engineering is seen as a commodity, rather than confidential tool.

3. PRESENT NUMERICAL SIMULATION SCHEME

Motivated by the shortcomings of the standard thermo-mechanical displacement finite element based scheme widely used in commercial software (FE H8), one of the goals of the present paper is to recommend superior primal – mixed finite element FE (HC8/9), on the rather simple model problems.

A mixed coordinate independent hexahedral finite element HC 8/27 scheme in solid mechanics introduced in (Mijuca 2010), presently is used for the calculation of thermo-elastic structural response. Essentially, it allows straightforward introduction of thermal strains, thus enabling overcoming of the so-called consistency error (Miranda & Ubertini 2001) between thermal and mechanical deformation fields, mainly responsible for spurious oscillations of displacement variable. Present finite element is reliable, even when it is slandered, distorted, or used for the analysis of nearly incompressible or orthotropic materials, up to 7 orders of magnitude, and up to angle of 180 degrees, respectively. Therefore, transition problem of connecting finite elements of different types and dimensions is overcome also. To test convergence of the results, the standard model problems made of homogeneous, orthotropic, or multi-materials are considered. The present approach has a great potential to be reliably used in analysis of simple or complex structures, or to be used for macroscopic analysis in the straightforward conjunction with the numerical analysis on microstructural base in life estimate analysis.

4. BIMETALLIC BEAM-LIKE STRUCTURAL PART SUBJECTED TO THE TEMPERATURE LOAD

The cantilever bimetallic strip of length $l = 10$, arbitrary width $w = 0.1$, and thickness $t = 0.1$, where symmetric part is shown in Figure 2, is presently analysed. The beam is stress free at $T_R = 70$ and subjected to a uniform temperature$T_0 = 170$. Both materials have the same modulus of elasticity and Poisson's ratio, which are $E = 3 \cdot 10^7\ MPa$ and $\nu = 0.3$, respectively. The difference is in coefficients of thermal expansion, which are $\alpha_1 = 1 \cdot 10^{-5}$ and $\alpha_2 = 2 \cdot 10^{-5}$, respectively for the upper and lower material.

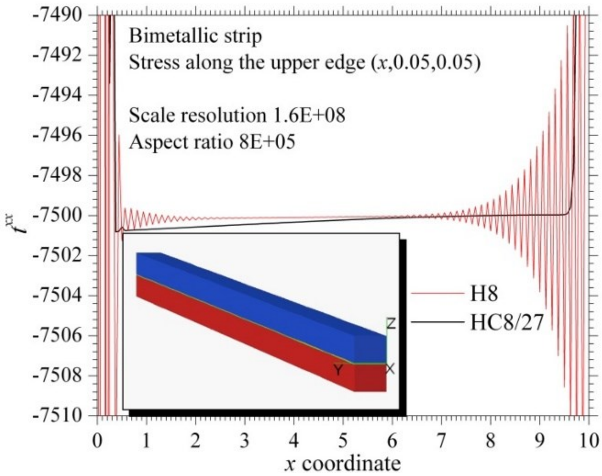


Figure 2: Target results obtained by the dimensional and full finite element theory

The analytical solution at the fixed end for a top surface is obtained by the hand-out simple beam theory (see Roark & Young (1975), page 114) and it is $t^{xx} = -7500$. The dimensional reduction (curve H8) theory gives unrealistic spurious results on the upper edge, while in present case (curve HC8/27) result is smooth, as shown in Figure 2.

5. UNIFORM MATERIAL PLATE LIKE STRUCTURAL PART UNDER SUDDEN TEMPERATURE CHANGE

This model problem is taken from (Mijuca 2008), page 583, case 9. It is an isotropic rectangular solid body of the plate like shape fixed on its physical boundaries. The reference temperature is $T_R = 294.15K$ and the upper face is suddenly exposed to a temperature $T = 350K$. Its dimensions are $8 \times 4 \times 0.25$ $[m]$ in x, y and z axes direction, respectively. The Young's modulus is $E = 34290\ MPa$, the Poisson's ratio is $\nu = 0.2$, while coefficient of thermal expansion is $\alpha = 0.00001°/K$. The plate would normally assume a spherical curvature with radius $\frac{t}{\nabla T\alpha}$, where t is the distance between the hot and cold face. If the edges are fixed, the plate will be held flat by uniform edge moments and the maximum bending stress $t^{xx} = \frac{\nabla T\alpha E}{(1-\nu)}$, obtained by the modified Kirchhoff plate theory (that is: $t^{zz} = t^{xy} = t^{xz} = t^{yz} = 0$) (Mijuca 2008), is $t^{xx} = -23.93871\ MPa.$

It should be noted that thermal loadings through thickness are introduced intrinsically, because no dimensional reduction is used. Namely, heat transfer is natural, not extrapolated, as when using 2-dimensional plate theory. The verification of the presently used numerical technique HC8/9 for the case of the fixed edges is completed with comparison by the modified (Mijuca 2008), in which it is assumed that $t^{zz} = t^{xy} = t^{xz} = t^{yz} = 0$ and plate is held flat by uniform edge moments and the maximum bending stress $t^{xx} = \frac{\nabla T\alpha E}{(1-\nu)}$. The theoretical Kirchhoff plate theory result is for the present model problem given by $t^{xx} = -23.93871\ MPa.$

On the contrary, present approach HC8/9, gives us rather higher maximal stress (see obtained stress distribution, Fig. 3). Therefore, it is significant finding, that deserves further investigation, because it could explain premature failing of real thermally loaded structures that are calculated and proven by standards based on plate theory or standard FE displacement approach.

The results with present approach, primal mixed HC8/9, for two types of topology discretization, are shown in Tables 1 and 2.

It should be perceived that maximal compressive and tension stresses are obtained on the fixed edges (see Figure 3), so we may conclude that thermal protection system in re-entry vehicles should be continuous, and not made of tiles, because they may fall-off.

Table 1: Fixed plate under temperature gradient: Stress t^{xx} convergence, reduced and full HC8/9 approach

Fixed Plate loaded by transversal temperature gradient, FE HC8/9, t^{xx}		
$8N \times 4N \times 2N$	if $t^{zz} = t^{xy} = t^{xz} = t^{yz} = 0$	*full theory*
1	-23.93871	*-32.645*
2	-23.93871	*-32.492*
3	-23.93871	*-32.284*
Target	*-23.93871*	-

Table 2: Fixed plate under temperature gradient: Stress convergence of FE HC8/9 for meshes $8N \times 4N \times 2$, $N = 1,2,3,4$

Fixed plate loaded by transversal temperature gradient, FE HC8/9						
$8N \times 4N \times 2$	t^{xx}_{max}	t^{yy}_{max}	t^{zz}_{max}	t^{xy}_{max}	t^{xz}_{max}	t^{yz}_{max}
1	-32.645	-32.551	-34.033	-0.73360	-1.9245	-1.9597
2	-32.699	-32.694	-33.810	-0.87241	-3.8111	-3.8115
3	-32.764	-32.764	-33.918	-1.27110	-7.4198	-7.4199
4	-33.821	-33.823	-34.404	-2.0495	-12.5330	-12.5330

Present approach shows that if all stress components are unknown and unsuppressed (which is realistically), target solution is substantially different, as shown in Table 1. It should be emphasized that present approach is reliable in thin plates like structures discretized by 3D finite elements, see (Mijuca 2004), and it would not lock under any circumstances.

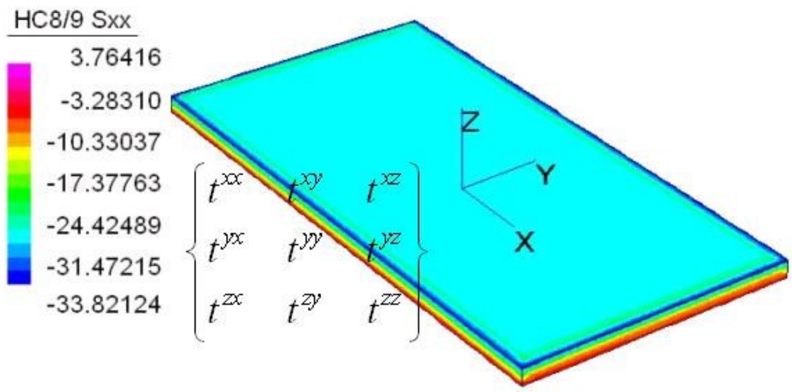


Figure 3: Fixed plate loaded by temperature gradient through its thickness. FE HC9/9 (full theory).

Thus, without doubt, it can be stated that dimensional reduction or neglecting of some stress components leads to substantial underestimation of thermal stresses in structures under thermal loading. This explains premature collapse of structures under fire calculated with plate theory hand-out or finite element approach based on displacement, also.

6. COMPOSITE STRIP UNDER 3-POINT BENDING

Present goal is to show that in reality, in composites maximal stresses are much higher than one calculated by plate theory.

A simply supported 5-layer symmetric composite strip under central line load of $10\frac{N}{mm}$, reported in Taig (1992) is presently analysed. Material lay-up is 0/90/0/90/0. All plies are of the same thickness. Only one half of the model is analysed due to the geometrical central and load symmetry. For the ply rotated by 0 degrees the material constants are: $E_x = 100000$, $E_y = E_z = 5000$, $G_{xy} = 3000$, $G_{xz} = G_{yz} = 2000$, $\nu_{xy} = 0.4$, $\nu_{yz} = 0.3$ and $\nu_{zx} = 0.015$. For the ply rotated by 90 degrees, material constants are: $E_x = E_z = 5000$ and $E_y = 100000$, $G_{xy} = 3000$ and $G_{xz} = G_{yz} = 2000$, $\nu_{xy} = 0.02$, $\nu_{zx} = \nu_{yz} = 0.3$. We emphasize that present FEM HC9/9 approach is not sensitive to mesh quality and shape, so thin layer of finite elements is put on each side of the material interfaces. The central line load is discretized as normal pressure $p[MPa]$ over the long, small area A around centerline. Each inner pile is approximated by four finite elements per thicknesses, as shown in Figure 4.

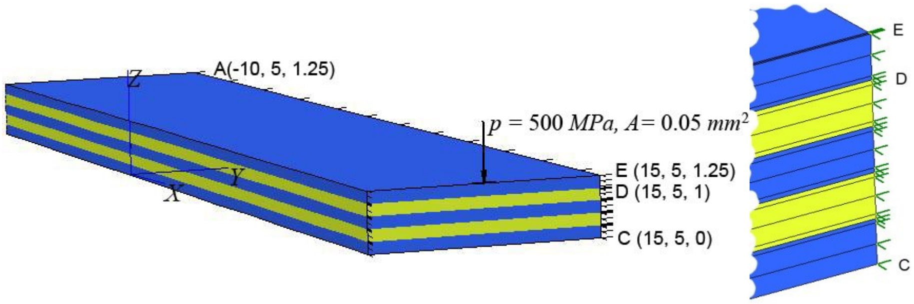


Figure 4: Composite Strip under midspan continual load.

The analytical solution obtained by the modified uni-material simple beam theory, are $t^{xx}(E) = -359$, $t^{yz}(D) = -4.88$ and $u_z(E) = -0.458$. The convergence of the present results stresses in nodes E and D, are given respectively, in Table 3, and converge to substantially higher results than theoretical.

Table 3. Composite strip: Convergence for $p = 50MPa$ and $A = 0.5mm^2$

Composite strip, load $p = 50MPa$ and $A = 0.5mm^2$				
N	$NEL\ (12N+2) \times 1 \times 18$	$t^{xx}(E)$	$t^{xz}(D)$	$u_z(E)$
1	252	-447.7511	-1.5685	-.5670
2	468	-448.3428	-1.5327	-.5667
4	900	-454.2073	-1.5297	-.5668
8	1764	-457.2082	-1.4943	-.5673
16	3492	-458.9545	-1.3591	-.5679
	Target	-359	-4.88	-0.458

We may see that in both cases results normal stress and deflection results converge to a higher value than target ones. The intensity of interlaminar shear stresses at node D depends on the value of the area A over pressure is applied, but it converges to a target value for the smaller value of A. It is shown in (Mijuca 2010) that plate theory underestimates the maximal stress result. Thus, we may assume that by neglecting normal and shear stress components in each of the layer, as usual in plate theory, our result will converge to analytical (plate theory) solution.

7. CONCLUSION

The present paper tries to explain why standard finite element displacement-based simulations (dFEM) are seen as a commodity rather than reliable replacement for expensive and extensive prototype testing, by space industry. First, there is simple lack of trust in simulation, and on the top of that there is always enough money for testing (i.e., investors do not know mechanics), and everybody tends to be on a safe side regarding decisions and responsibility.

Traditionally, dFEM is used by engineers as a *black box* with no proper mathematical education and understanding of its deficiencies. Accordingly, when used improperly, the results obtained will be inconsistent and spurious. Nevertheless, even with all possible knowledge in numerical methods, dFEM is simply incapable to go multiscale, and can be highly inaccurate in thermo-mechanical calculations. There have been myriad cases where bad simulation results resulted in rejection of a good engineering design. And vice versa, structural designs approved by simulations using dFEM failed prematurely. Some of dFEM deficiencies are shown in the present paper through numerical examples.

New era of simulation-driven structural design in space industry should be based on available (Mijuca 2010) mixed finite element approach (FEMIX) that is reliable and validated, and above all beam and plate theories should be abandoned completely. This is presently shown through a few simple numerical examples as well. There is no excuse to consider 3D structure with billions of atoms confined in 3D space, as 2D object.

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