

A METHODOLOGICAL APPROACH FOR NUMERICAL ANALYSIS OF UPHOLSTERED SOFA WITH FINITE ELEMENT METHOD (FEM)

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ABSTRACT

Engineering design of furniture is an important issue for modern industry and it can be accomplished by means of creating a model structure and analyzing by a convenient software. A fair strength analysis of furniture structure is a computationally complex process since various types of member types, e.g. springs, upholster plates and complicated mechanisms type connections, are included in modelling. Finite element method (FEM) is the most convenient approach to analyze furniture systems because of the member variety and the furniture's, in general, complex geometry. In this study, an improvable methodological approach was recommended for numerical analyses. Upholstered sofas are tested under backrest frame loads according to the principles of FNAE 80-214 General Services Administration Upholstered Furniture Test Method (GSA), then numerical analysis is carried out to simulate the performance tests on virtual platform. 3D modelling of sofa is made with SpaceClaim 3D solid models software and analyses are performed with a Finite Element Software, Ansys Workbench. Entire system of the sofa, including all members, joints, connections and springs are defined with convenient parameters related to mechanical properties of the material and the resulting deformations of the experiments. In this study, the sofa model is developed in a methodological manner, in three different ways. The model is improved with small details and it is observed that small changes in the model resulted in essential outcomes such that consistent results are decided to be achieved by means of tuning some parameters, e.g. spring constants, upholster thickness and elasticity. According to the results, reasonable estimates are obtained from the numerical analyses by using this methodological approach.

Key words: numerical analysis, upholstered furniture, furniture performance test.

INTRODUCTION

Engineering design and strength analysis of furniture are relatively new concepts and not systematically applied in Turkey as almost like in other countries. Until the mid1950's furniture had not been investigated structurally and design of members and joints had never been a subject in mathematical theories despite the fact that furniture by

definition is a structural construction. Contrary to this, past experiences and aesthetic factors influenced the determination of member sizes and joint constructions of furniture. Engineering design is a significant step in the production process of furniture including all aspects of economical, aesthetical and technical factors such that it should be definitely performed based on the scientific norms.

Development of new products in the wood industry in the past was mostly based on empirical information. The data about construction properties were usually obtained by testing prototypes of the final product. The development of computer technology and numerical methods have made the research much easier and enabled obtaining information of what is happening inside a loaded chair already at the design phase. Computer use in the industry saves the time for the product development and improves its quality (Horman et al., 2010). Smardzewski (1998) developed a computer program designed for rigidity/strength analysis of furniture side frame constructions. The results indicated that the computer program allowed accurate, rapid, and multiple rigidity/strength analyses of furniture side frames constructed of wood. With the development of technology, modern management and production techniques, integrated with mathematical optimization techniques, are quickly established for furniture design, as like in the case of other manufacturing processes of many other devices. Therefore, businesses are required to catch up with the technological development by using computer and optimization techniques as a tool for maintaining their existence within the intensely competitive market (Koç et al. 2011). In another study, it is stated that, prototyping and research-development costs could be reduced by utilizing virtual design (Kasal, 2004).

FEM is extensively used for many other aims in furniture calculations. The study carried out by Hajdarevic and Martinovic (2014) presented numerical analyses of the effects of tenon length on the flexibility of mortise and tenon joints. The results of the study indicated that mortise and tenon joints became stiffer as tenon length increased. Furthermore, the results revealed that the stiffness of

the joints in a frame had a considerable impact on the structure deflection. Numerical analysis of the specimens as three-dimensional frame structures provided reasonable estimates consistent with the actual testing results (Kasal et al., 2016). The best source of cyclic loading comes from the “GSA Test Method for Upholstered Sofas” (Eckelman and Erdil, 2001). This is a cyclic stepped load test method in which the strength and durability of one part of the sofa is determined independently of the other parts. The test procedure is carried out as follows: A part of the sofa is subjected to a given load for 25,000 cycles at a rate of 20 cycles per minute. Once 25,000 cycle have been completed at this load level, the load is increased a specified amount and testing continued for another 25,000 cycles. This procedure is repeated until the sofa suffers disabling damage or until a desired acceptance level has been reached (Eckelman and Erdil, 1999).

A fair and accurate approximation in the strength analysis of furniture frames costs expensive computationally because of various types of member types, e.g. springs, upholster plates and complicated scissors type links, forming the furniture structure. Technology has developed very rapidly. As with other industrial products, the developments in technology have influenced the furniture in each phase from design to production. The use of technological developments is very important to strengthen the design of furniture. The engineering design of furniture can be accomplished by utilizing solid modeling and structural analysis software. FEM provides a convenient tool for analyzing furniture systems. Furniture members, joints, and the entirety of the system can be modelled parametrically via FEM. Minor changes in the parameters of the materials in the model can cause major changes in the results. By

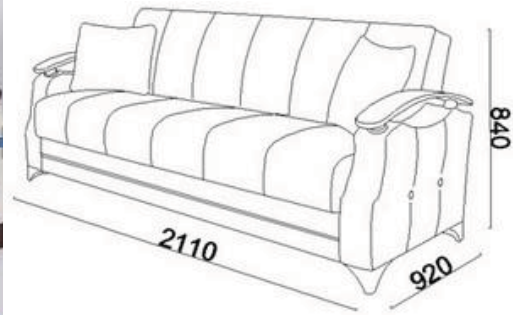
making changes in the computer environment, in other words; tuning for the appropriate parameters, it is very easy to obtain results close to real results as a methodological approach. Furniture model can be renewed in the direction of continual improvement and convenient results can be reached. After all, member forces, forces at joints, can be calculated to determine the optimum member sizes. The aim of this study is to develop a new approach for definition of upholstered furniture structural system in the digital platform. For this purpose, a model upholstered furniture was chosen from a commercial company in Turkey and tested under backrest frame loads according to the principles of FNAE 80-214 General Services Administration Upholstered Furniture Test Method (GSA) and then numerical analysis was carried out to simulate the performance tests.

EXPERIMENTAL

Test Sofa and Actual Performance

Tests

The test sofa selected for the needs of the present study, is an upholstered coach which is shown in Fig. 1. It has a length of 2.11 m, a width of 0.92 m and a height of 0.84 m. It can be classified as a heavy furniture, weighting 100 kg approximately. It has a well-qualified upholstery made of synthetic fabric. Test sofa was tested under backrest frame loads, according to the principles of FNAE 80-214 General Services Administration Upholstered Furniture Test Method (GSA)(Fig. 2). Three replications were used in the tests.



Width :2110 mm

Depth : 920 mm

Height : 840 mm

Figure 1: Upholstered sofa chosen for this study

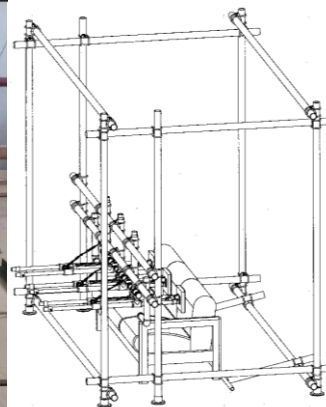


Figure 2: Test setup

In this method, a specified initial load is applied to the furniture at a given cyclic rate for a specified number of cycles. When the prescribed number of cycles is completed, the load level is increased by a given increment, and the procedure is repeated until a desired load level has been reached or until the furniture fails (Eckelman, 1988; Erdil, 2002).

According to FNAE 80-214, the test was started at a load level of 333.6 N. Loads were increased at an amount of 111.2 N, incrementally, at each level and 25000 cycles are completed at every single level step. Here, in these tests, load was increased until the failure of the furniture. None of the critical members were observed to be failed except for the upholstery. At the end of the test, the upholstery was deformed distinguishly and test was stopped.

There are two main critical factors for the performance tests; stress and deformation. For backrest frame tests, top of the

backrest deformation and stress of backrest members give significant values. Stress values were not obtained during experiments but deformations of backrest were kept recorded and compared with FEM results.

Structural Analyses with FEM

Three different furniture models were studied and the model is improved to get accurate results. Improvements were mainly caused by the upholstery of the back frame. According to actual performance tests, it is understood that upholstery of the furniture absorbs important proportion of applied force. In other words, upholstered sofas resist to the forces better than the sofa frame without upholstery. In this manner, sofa frame and upholstery should be defined on virtual platform in details. For this purpose, 3 types of finite element model (FEM types) were prepared for an approximation to the actual performance test results. FEM type-I is shown in Fig. 3.

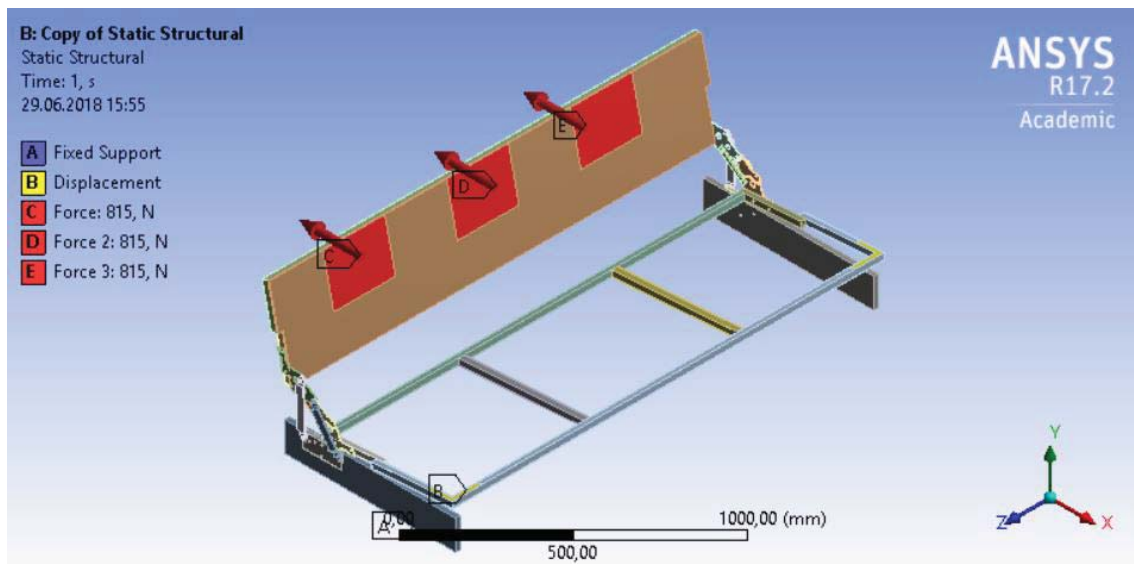


Figure 3: FEM type-I for Backrest test

As seen in Fig 3, all boundary condition has a letter. Point A is fix support which applied at both side rails of sofa frame. Point B refers to the center of the small area at the corner of the sofa frame which is designated

for pin supports. Point C, D and E refers to the center of the area of the force that applied at same time and same magnitude.

In FEM type-I upholstery was defined by means of actual test results. Upholstery,

which has 1 cm thickness, was defined as an isotropic material. Modulus of Elasticity (MOE) of the upholster was determined by actual performance tests. Since upholstery members are hyperelastic materials, the mechanical properties, e.g. modulus of elasticity, shear modulus, should be function of displacement. Here in this study, the upholster was defined with a constant MOE which is just a linear approximation in the computer model. At the end of the analyses, FEM type-I gave high stress values in the members of sofa. In the product catalogue (Erdemir, 2017), the maximum value of yielding is given as 420 MPa, but the stress value of

analysis was 597 MPa. Therefore, that prediction values are not accepted for the FEM analysis. Thus, a second FEM type is prepared to take better results from FEM. In this context, FEM type-II was prepared with some difference from FEM type-I.

In Fig 4, FEM type-II is given. All boundary conditions and the application points of forces remain same, except for the thickness upholstery which is increased from 1 cm to 15 cm. In this case, the displacement values are better than the previous one. The effect of upholster is included much well by means of increased thickness.

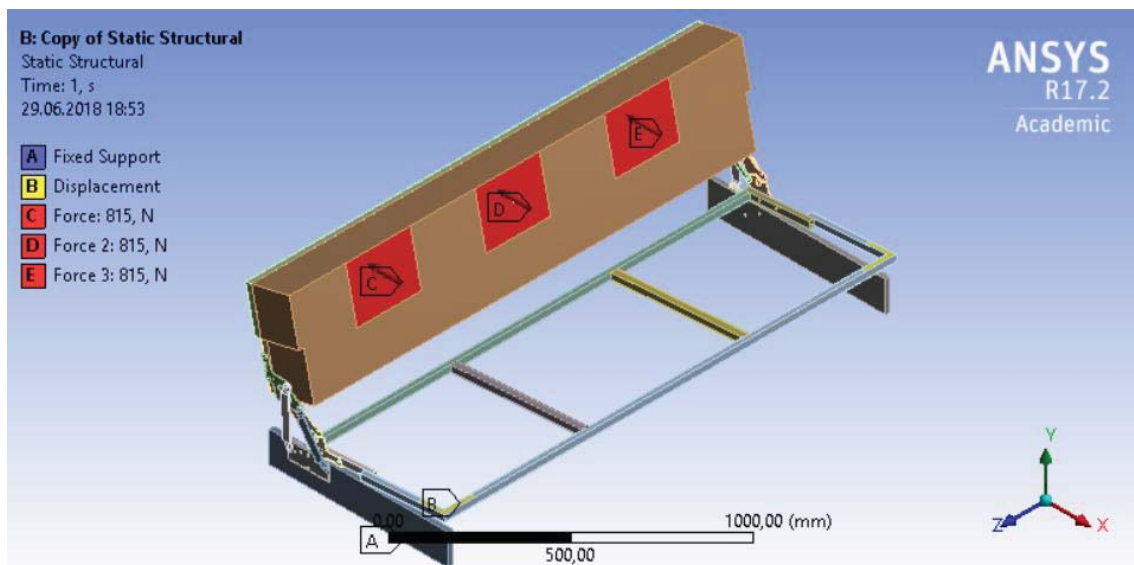


Figure 4: FEM type-II for Backrest test

The model was carried on to be improved. In FEM type-III, all boundary conditions, thickness of upholstery were taken as previous one (Fig. 5). The elastic behavior of the back upholster was defined better by inserting linear springs at A, B and C points, in the direction of the applied loads. Springs were defined between red areas, which are C, D and E points, and brown upholstery. By

this way, the upholster was modelled as it behaves as a hyperelastic material. The spring constants were provided from experiments. At the end of the analyses, FEM type-III gave better results on stress and displacement values than FEM type-I and II in the members of sofa. Results showed that FEM type-III can be used for the FEM analysis of upholstered sofas.

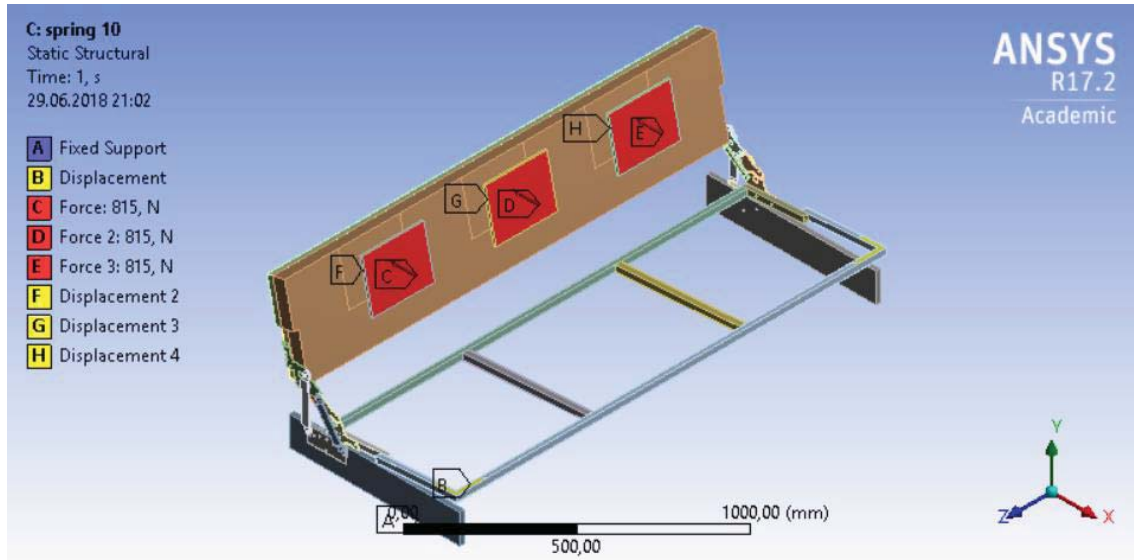


Figure 5: FEM type-II for Backrest test

RESULTS AND DISCUSSION

The FEM models were developed from FEM Type- I to Type – III to determine convenient values for some critical regions. The critical members and the regions were specifically chosen for this back rest frame test, as (i) the midpoint of the top of the backframe,

(ii) the sofa bed mechanism type of connection and (iii) short edges of the side rails. At each Type model, the mechanical properties of upholstered part were tried to be represented moderately, by making improvements for back upholstery.

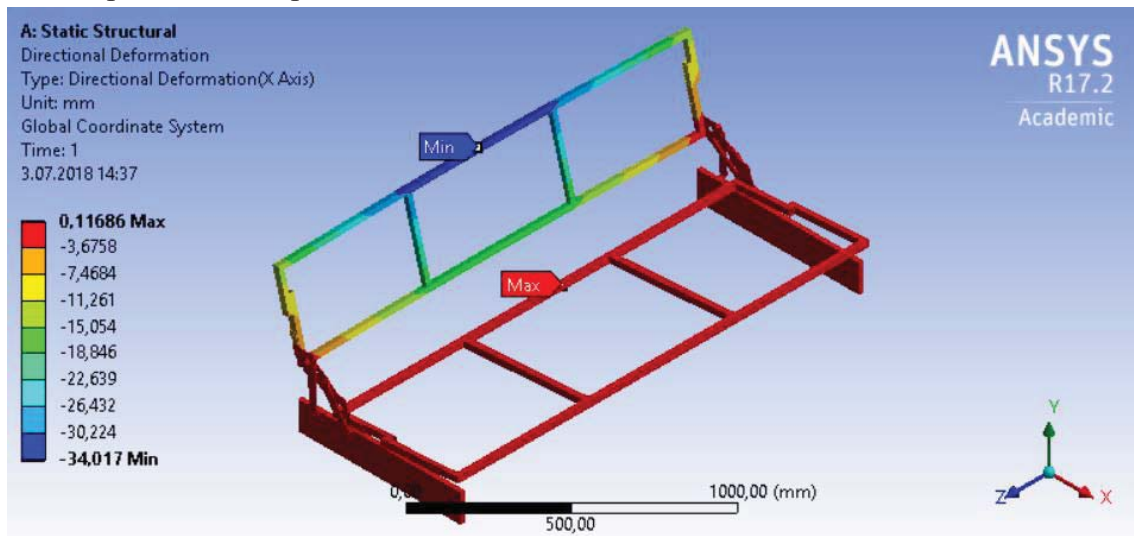


Figure 6: FEM type-I, displacement contour plot.

At all FEM types, the maximum deformation occurred at the midpoint of the top of the back frame. In addition to this, maximum

principle stress was developed at this point, in the sofa bed mechanism type of connection and the short edges of the seat frame. These values were tabulated in Table 1.

Table 1: Deformation in x direction and maximum principle stress values.

Critical Members	FEM Type-I		FEM Type-II		FEM Type-III		Experi- mental
	Δ_x (mm)	σ (MPa)	Δ_x (mm)	σ (MPa)	Δ_x (mm)	σ (MPa)	Δ_x (mm)
Midpoint of the top of the back frame(i)	34	357	18	60	26	232	35
Sofa bed mechanism type of connection (ii)	-	597	-	658	-	308	-
Short edge of the seat frame(iii)	-	320	-	336	-	286	-

In the FEM Type – I case, the deflection Δ_x was 34 mm (Fig. 6), which is close to the experimental value, on the other hand, the stress σ in the links (ii) was 597 MPa (Fig. 7-left), passing the yield value of the material. Contrarily, the stress value at the midpoint of the top of the back frame and the value (320MPa) at the short edge of the seat frame

were quite acceptable. In the product catalogue (Erdemir, 2017), the maximum value of yielding is given as 420 MPa, depending on the standard reference EN 10130 with DC01 quality. As it is known from the experiments, as the sofa is not failed at joints, then this value is decided to be lowered by simple modifications in the model.

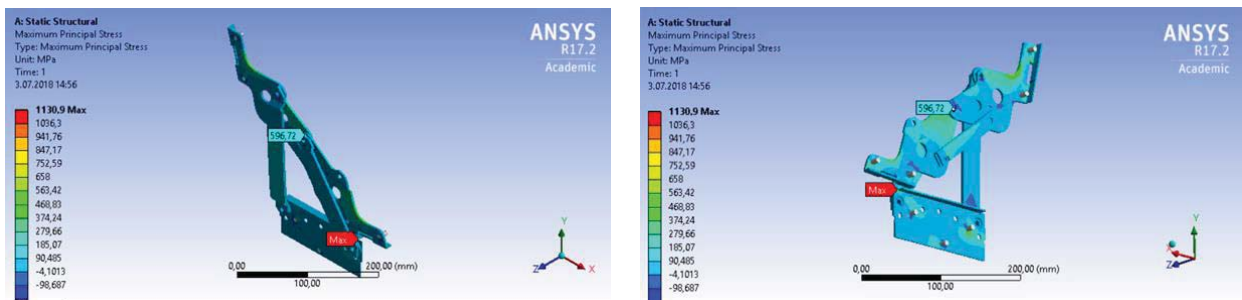


Figure 7: Stress state of scissors type of link, maximum principle stress, right view (left), left view(right)-stress concentration.

In the sofa bed mechanism type of connection, the stress was concentrated at the contacting region between the side rails. This concentrated value was occurred just because of the lack of model. In the real test models, this region had a rounded surface but, in contrast to this, in the computer model it had sharp edges (Fig. 7-right). This concentrated stress values were not taken into consideration.

The model was improved in FEM Type – II by increasing the thickness of the back upholster from 1 cm to 15 cm. In this case, the deflection at the top edge of the back frame comes out to be 18 mm utmost (Fig. 8), which does not reflect the reality. In addition to this, stress value at the link was 658 MPa (Table 1), that means it failed.

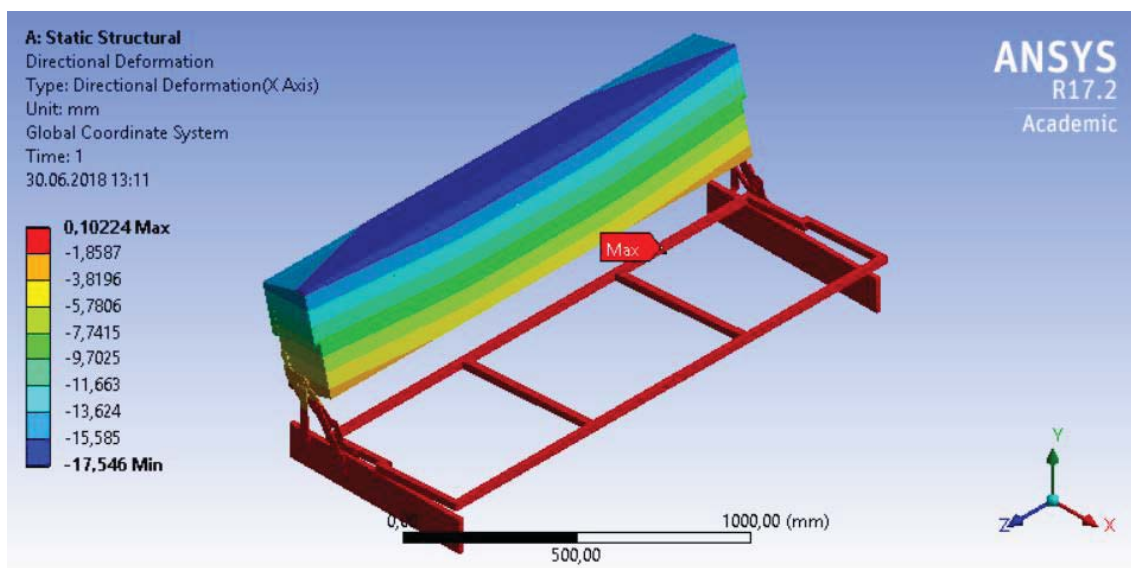


Figure 8: FEM type-II, displacement contour plot

As increasing the thickness of the upholstery was not a good approximation then, methodologically, another model, FEM Type III was generated by simply adding linear axial springs to the load application points C, D,

and E. In this case, the deflection of the mid-point of top edge was 26 mm which is close to the experimental result. A good agreement was almost achieved also for the stress values in all critical members such that none of the members are failed.

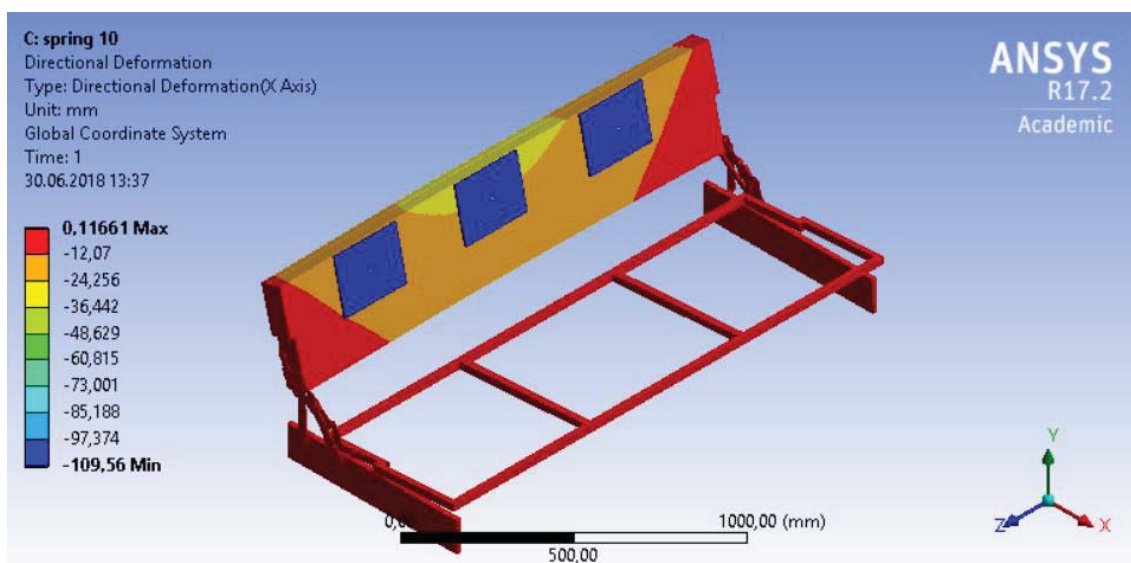


Figure 9: FEM type-III, displacement contour plot

CONCLUSION

In this study, an improvable methodological approach was developed which can be used to estimate deformation and stress values of upholstered furniture. It could be clearly seen from the results, when uphol-

stery system is approximated to be hyperelastic, results are approximate to actual performance tests. Numerical tests did not reflect the reality without including the upholstery as in the numerical test for FEM Type – I. The upholstery is made up of a kind of mate-

rial sponge like, a hyperelastic material. It affects the response of the furniture subjected to the cyclic loading. When it is taken as a whole, with its original thickness, the material properties of it, e.g. the MOE and shear modulus, should be well defined. In this study, MOE was taken as constant in the case of FEM Type –II, which is very rough approximation such that the results are not in a good agreement with the experimental results. However, as in the case of FEM Type – III, when the upholster was resembled with a plate, has a moderate thickness, and axial linear springs, all the critical values are close to these measured in the experiments. Here, one more step can be taken into account, by improving the performance of these springs. Theoretically, this kind of hyperelastic materials behaves in a nonlinear manner in the axial loading case, such that the spring constant can be taken as a function of displacement. In addition to this, a damping property of this sponge like material can be included in to the numerical tests.

As a result of this study, an improvable methodological approach was recommended to users who related with furniture design as in an engineering methodology, which is used to predict stress and deformation values on backrest tests results for upholstered furniture by FEM analysis. According to the principles of FNAE 80-214 General Services Administration Upholstered Furniture Test Method, other load cases could be studied by following this methodology as a future task.

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