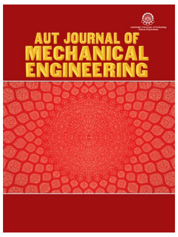

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Optimum design and comparison of four soft reinforced actuators by Taguchi experimental design method

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ABSTRACT: In this paper, four soft reinforced actuators are studied and their performance is compared. The soft actuators, because of their ability to match their shape with unknown environment, could be utilized in medical instruments such as rehabilitation devices, grippers, manipulators and bio-mimic hand. Here, the considered actuators are included a single elastomer channel wrapped with fiber reinforcements and an inextensible layer. Four actuators with half-circular and rectangular geometry are discussed. Two actuators have constant cross section and others have variable cross section. To study their performance they are modeled in Abaqus software. Also, a prototype of the soft actuator is manufactured and the numerical results are validated by the experiment results. Moreover, for studying the effect of each parameter and their interactions and finding the optimum design of the actuators the Taguchi method is used with a set of experiments. To this end, L27 array experiments are designed and each experiment is performed by finite element analysis in Abaqus. Then, the performance of each actuator is discussed and compared with each other and the optimum values of the parameters are determined. Results show the rectangular actuator has a more range of motion in comparison to half-circular one.

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1- Introduction

Nowadays the soft actuators are well known among the robotic communities. Soft robotic is a subfield of robotic that the main structure of the robots consists of flexible silicon materials and hyperelastics [1]. Soft actuators such as soft pneumatic actuators (SPAs) are kind of soft robots with two general types of Pneunets [2, 3] and Pneuflex [4, 5]. Pneunets actuators are included a multi elastomer channel and an inextensible layer and pneuflex actuators are included a single elastomer channel reinforced with fibers that have been wrapped around it and also, there is an inextensible layer in the actuators that produce a bending motion. Due to their simplicity, low cost and easy control, the pneumatic actuators are suitable to use in various applications to produce the linear [6] and complex motions like bending [2, 4, 7]. The usage of them as a gripper is an interesting idea, because of their ability to match their shape with unknown environment [1,8]. The soft actuators like SPAs are capable to be used in a wide range of applications. They could be utilized in medical instruments such as rehabilitation devices [9-12], grippers, manipulators [8, 13], bio-mimic hand [5].

There are some research teams that proceed to study the soft actuators by experimental, numerical and analytical modeling [2, 4, 5]. In previous works, the researchers obtained valuable information about the effect of the soft actuator parameters on its performance, but their studies are limited to one or two parameters of the soft robot [2, 4]. So, still all aspects of this matter are not completely specified. For example, it is not clear that the width or height has more or less effect on inflation than wall thickness or thickness of the inextensible layer. Also, the interaction effect of the parameters on each other is not clear. The previous method used in [4] is one factor at a time (OFAT) [14] and this method could not estimate the interaction of the factors. In an experimental approach, the combination of the parameters for designing a set of experiments is important and it is more difficult when we have a lot of parameters with multi levels. For example, in full factorial designs, all the observations are used to estimate the effect of each factor and each interaction and it would be time and money-consuming when the factors have more than two levels. As it is mentioned above OFAT method has its drawbacks. Therefore, in this work, the main effect, the interaction of the parameters and the optimum parameters are studied by Taguchi method which uses special orthogonal arrays to study all the design factors with minimum of experiments.

In this paper, four actuators with different half-circular and rectangular geometry are discussed. Two actuators have constant cross section and others have variable cross section. The actuators are modeled in Abaqus software and their performances are compared. Also, a prototype of the soft actuator is manufactured and the numerical results are

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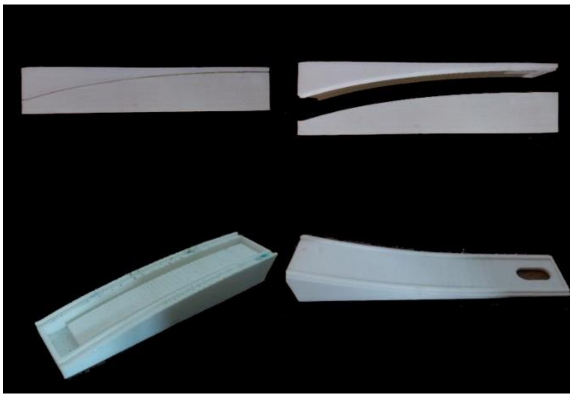


Fig. 1. Rectangular soft actuator mold with variable cross-section created by 3D printer

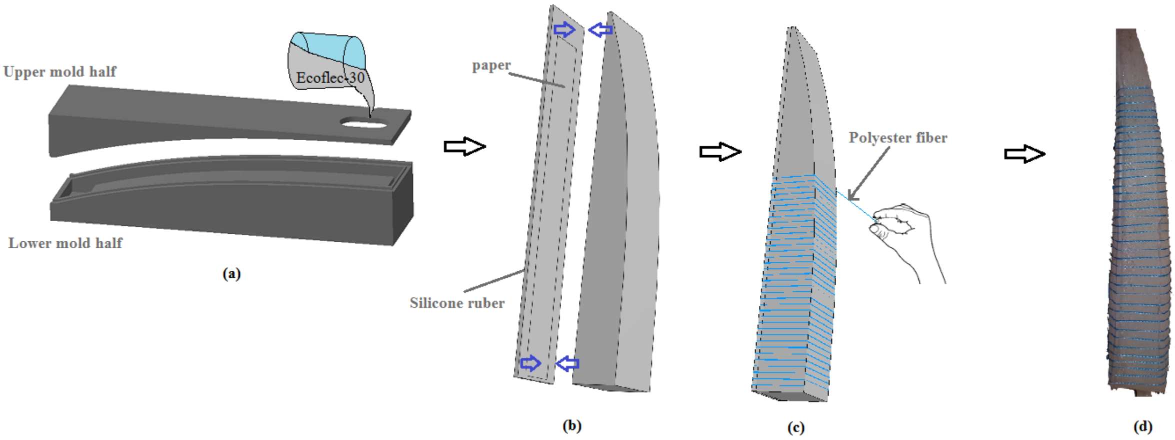


Fig. 2. Fabrication procedure: (a) Molding step by using 3D printed mold, (b) Attaching the inextensible layer to the actuator, (c) Twisting the polyester fiber around the actuator, (d) Fabricated soft reinforced actuator.

validated by the experiment results. Taguchi experimental design is used for studying the effect of each parameter and optimum design of the actuators. To study the main effects and the interaction effects of each design parameter on the actuators performance, L27 array experiments are designed. The simulation results of each experiment are obtained in Abaqus. Then, the performance of each actuator is discussed and compared with each other and the optimum values of the parameters are determined. The Taguchi experimental design is used for studying the effect of each parameters and optimum design of the soft robots.

The remaining of this paper is organized as follows. Fabrication method is presented in Section 2. In Section 3, the finite elements method (FEM) for analyses the actuators is shown and verification of the FEM model is discussed in Section 4. The performance of all actuators is compared in Section 5. For experimental design, the experiments and methods are presented in Section 6. In Section 7, the principle of the Taguchi method for experiment planning is presented and the results are discussed in Section 8. Optimization and its results are presented in Section 9. Finally, conclusions and remarks are presented.

2- Fabrication of actuator

There is some method to fabricate a fiber reinforced actuator. In the simplest method, the pieces of wood or plastic parts are used to make a mold to produce a part with simple geometry but it's not practical for all actuators with complex shape. Here, the mold of actuator with rectangular variable cross section is designed similar to Fig.1 and made by 3D printer with accuracy of 0.1 mm by Poly Lactic Acid (PLA). In the soft reinforced actuators the bending motion is produced by inextensible layer. Here, paper is used as an inextensible layer. In Fig.2, the fabrication process is shown briefly. In this research, a layer of paper covered with a thin layer of silicon is attached to the molded part using silicone glue as the inextensible layer. In this type of soft actuator, the lateral strains are limited by fibers that are wrapped around the actuators. Here, due to the tensile strength of the polyester fibers, the lateral strains are limited with fibers that they have been fastened in ring shape separately around the actuator. A thin layer of silicon is used to cover the rings to justify their position. To complete the actuator, a silicone pipe is used at the root of the actuator to provide inner pressure. Also, silicone glue is used for sealing it.

Table 1. Material properties.

Part	Parameter		Density (kg/m^3)
Ecoflex-30	C_1=0.012 MPa	D_1=0	1020
Inextensible layer(paper+ silicone)	C_1=7.9 MPa	D_1=0	1920
Polyester fiber	E=31.076 MPa	υ=0.36	1520

Table 2. Number of nodes and elements for soft actuator in the FEM

Wall thickness=2mm height=20mm width=20mm length=130mm inextensible layer thickness=1.5mm

Mesh size	Number of elements	Number of nodes
2mm	33750	108962

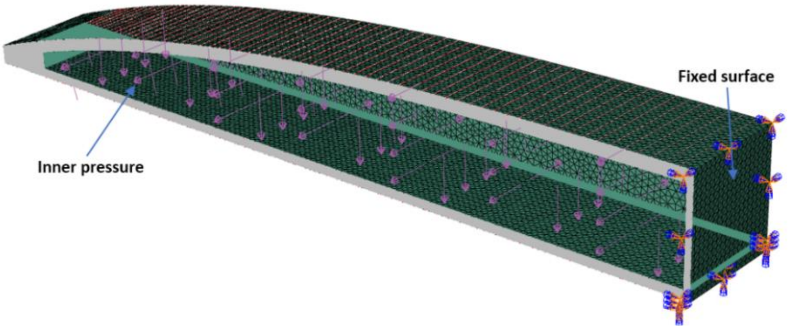


Fig. 3. Longitudinal cross section of the soft actuator with loading condition & constraint. The actuator has been modeled with 10 node-tetrahedral hybrid elements (C3D10H).

3- Finite element model of actuator

In this study, the displacement analysis of four types of actuators is modeled in Abaqus. Each actuator has been modeled with python scripting technique in Abaqus. This procedure could help to investigate a series of analysis and compare the results quickly. As mentioned in the previous section, the actuators with variable cross section are considered to compare with constant cross section ones. The cross section along the actuator with variable cross section is produced by a polynomial function given in Eq. (1).

$$y = ax^2 + bx^3 \qquad -130 \le x \le 0 \quad a = 29*10^{-6} \quad b = 7*10^{-6} \tag{1}$$

To describe the rubbery behavior of the materials, they were modeled as a hyperplastic by using the nearly incompressible hyperelastic model that the strain energy density is given as [15]:

$$w = \sum_{i=1} C_{i0}\left(I_1 - 3\right)^i + \sum_{k=1} \frac{1}{D_k}\left(j-1\right)^{2k} \tag{2}$$

where C_{i0} and D_i are material constants obtained by tensile test. In this work, according to the previous research [4], the material behavior of the ecoflex-30 is defined by hyperelastic model with specified coefficients in Table 1. Due to the fact that the inextensible layer is made from two layers of silicone and paper, to increase the convergence of the simulations the inextensible layer is modeled as an elastomer with material coefficient of C_{10} which is combination of the silicone and paper coefficients (C_c=7.9MPa). The polyester fibers are modeled with linear elastic model with defined coefficients in Table 1. To study the displacement of the actuator's tip, the actuator is constrained like a cantilever beam. In the real model, the fibers are separated with equal space from each other and are fastened to actuator's surfaces. Also, a hydrostatic pressure is applied on the inner surfaces of the actuator, see Fig.3.

Because the soft actuators are light weight, the static analysis is suitable for analyzing them. But, in high strain conditions, the static analysis could not fully converge. So, in this state, the quasi static analysis will help to converge the simulations [2]. Considering the incompressible material used in actuator's body, the three dimensional 10 nodes tetrahedral element (C3D10H) which is benefit from a hybrid formulation is used for the soft robot model and the quadratic beam element with radius of 0.08 mm is used for the fibers (B32). The number of nodes and elements was summarized in Table 2.

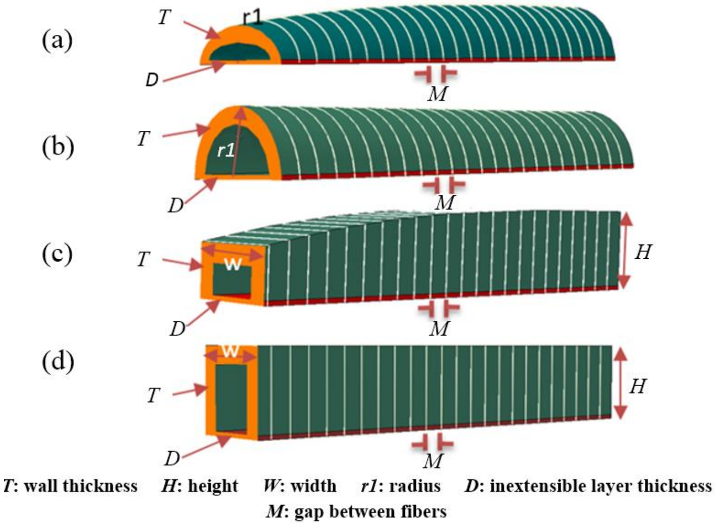


Fig. 4. Soft fiber-reinforced actuator with four different geometry: (a) Half-circular variable cross section(HVC), (b) Half-circular constant cross section(HCC), (c) Rectangular variable cross section(RVC), (d) Rectangular constant cross section(RCC)

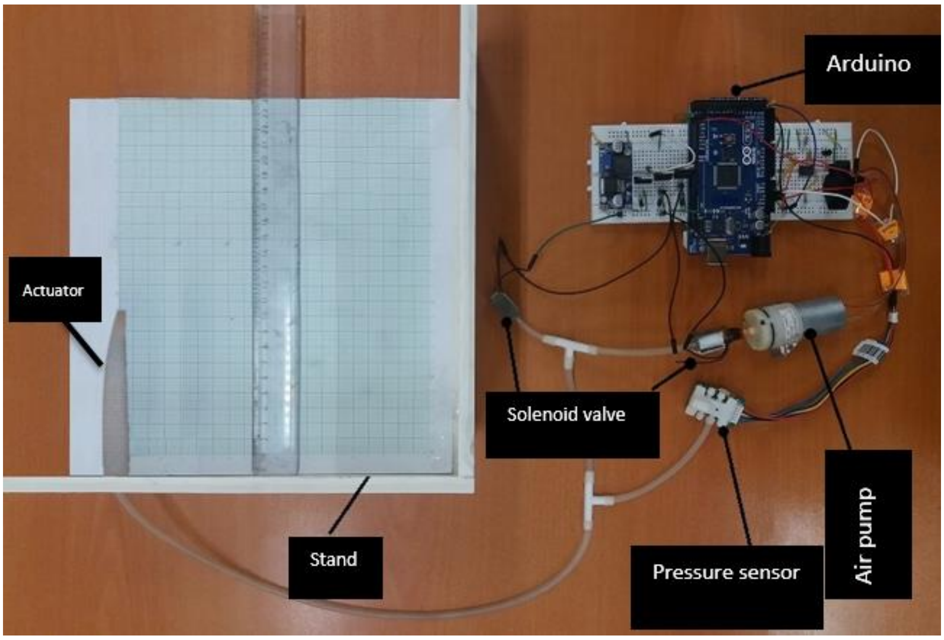
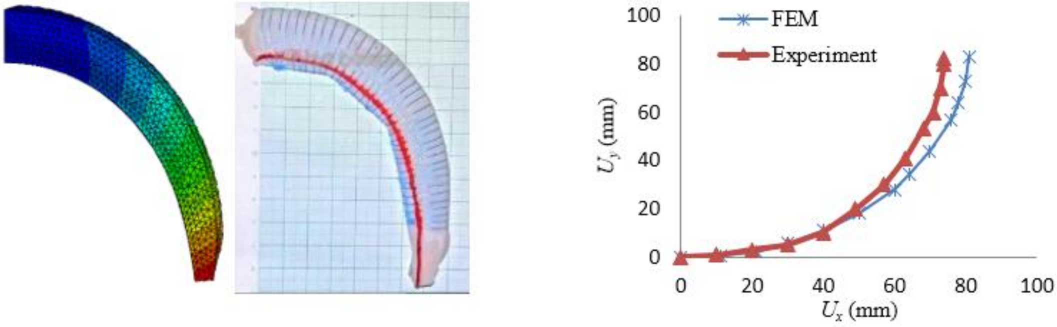


Fig. 5. Experimental setup: the setup is for a variable rectangular cross section actuator.

Here, in addition to the rectangular constant cross section (RCC) and the half-circular constant cross section (HCC), the rectangular variable cross section (RVC) and half-circular variable cross section (HVC) are considered to study. To this end, four geometry of the soft bending actuator, as illustrated in Fig.4, are investigated and compared. Changing the area along the actuator is assumed as a factor that could affect performance.

4- Validation of finite element model

To validate the numerical analysis, an experimental test, which is illustrated in Fig.5, is carried out on the fabricated prototype. To this end, the actuator is tightly connected from root end to a Teflon stand. To minimize the effect of gravity, the stand and the actuator are placed horizontally. To observe and record the amount of displacement of the tip of the actuator, graph paper is placed on the back of the



(b) (a)

Fig. 6. (a) The experimental and numerical results of variable rectangular cross-section at pressure 10 kPa. (b) Displacement of actuator in FEM and experimental test.

stand. Once the compressor is switched on, the actuator is bent rapidly and the situation of the actuator's tip is recorded. The experimental test is performed at the same pressure as the FEM results (10kPa) and it is repeated three times. In Fig.6, the numerical and experimental results have been compared. This figure shows the numerical results have a good agreement with the experimental results (less than 10% error).

5- Comparison of actuators response

The response of the four types of soft actuators with identical length (130mm) are studied at three pressures 10, 15 and 20 kPa. In Fig.7(a), the results show that the actuator motion with constant rectangular cross section follows a circular trajectory which has a constant radius along the actuator. Fig.7(b) shows reduction of the cross section along the actuator is caused to increase the radius of curvature along the actuator. So that, the radius is increased from the root to the tip of the actuator. As it is clear, in Fig. 7(c), the half-circular cross section compared to the rectangular cross section has a poor performance and needs more pressure for bending. However, changing the ratio of the sides of the rectangle can change this conclusion and rectangle one could have more bending resistance compared to half-circular one. Displacement in the longitudinal direction is far less than in altitude direction and the actuator directly going down with slight curvature. Furthermore, the variable cross section highlights this behavior, see Fig.7(d).

6- Design of experiment

In general, experiments are used to study the performance of a process or a system. The process and system could be a method, machine, operation, people and other sources that have some inputs and some outputs. There are some controllable variables and uncontrollable parameters. The first step in the experiment design is collecting the variables that could have an effect on the response of the process. In the soft actuator, the thickness, height, width, fiber's gap, inextensible layer thickness, length and material properties are parameters that could have a potential effect on output response of the robot. To plan the experiments, some strategies like best guess approach, OFAT, factorial and Taguchi which are well-known strategies for the design of the experiments are used [16]. For example, in OFAT method a starting point of each factor level is chosen then continuously factor level changes over its range while the other factors are held constant at the first point of the level. Usually, a series of the graph will be prepared that shows the effect of changing a factor while the other is kept constant. The major disadvantage of this method is that it's unable to consider the interaction between the factors and produces poor results when there is an interaction between them [16]. In this paper, a set of experiments is designed by Taguchi method for studying the effect of the actuator parameters on the displacement of the actuator tip and finding the effective parameters and their interactions on displacement of the actuators. Also, the optimum value of the parameters is determined for reaching the highest displacement of the actuator's tip. In this method, the combination of all factors and their levels are constructed with minimum number of experiments by orthogonal array design. According to the number of factors and their levels, the specific orthogonal array is suggested by Minitab software.

7- Experimental Design

Now, the experiment planning with Taguchi method is explained step by step.

7- 1- Selection of Factors and levels:

Factors are the independent variables that will have an effect on the response, those factors that could have the greatest impact on the response will be selected. It is important that it be practical, feasible, and cost-effective.

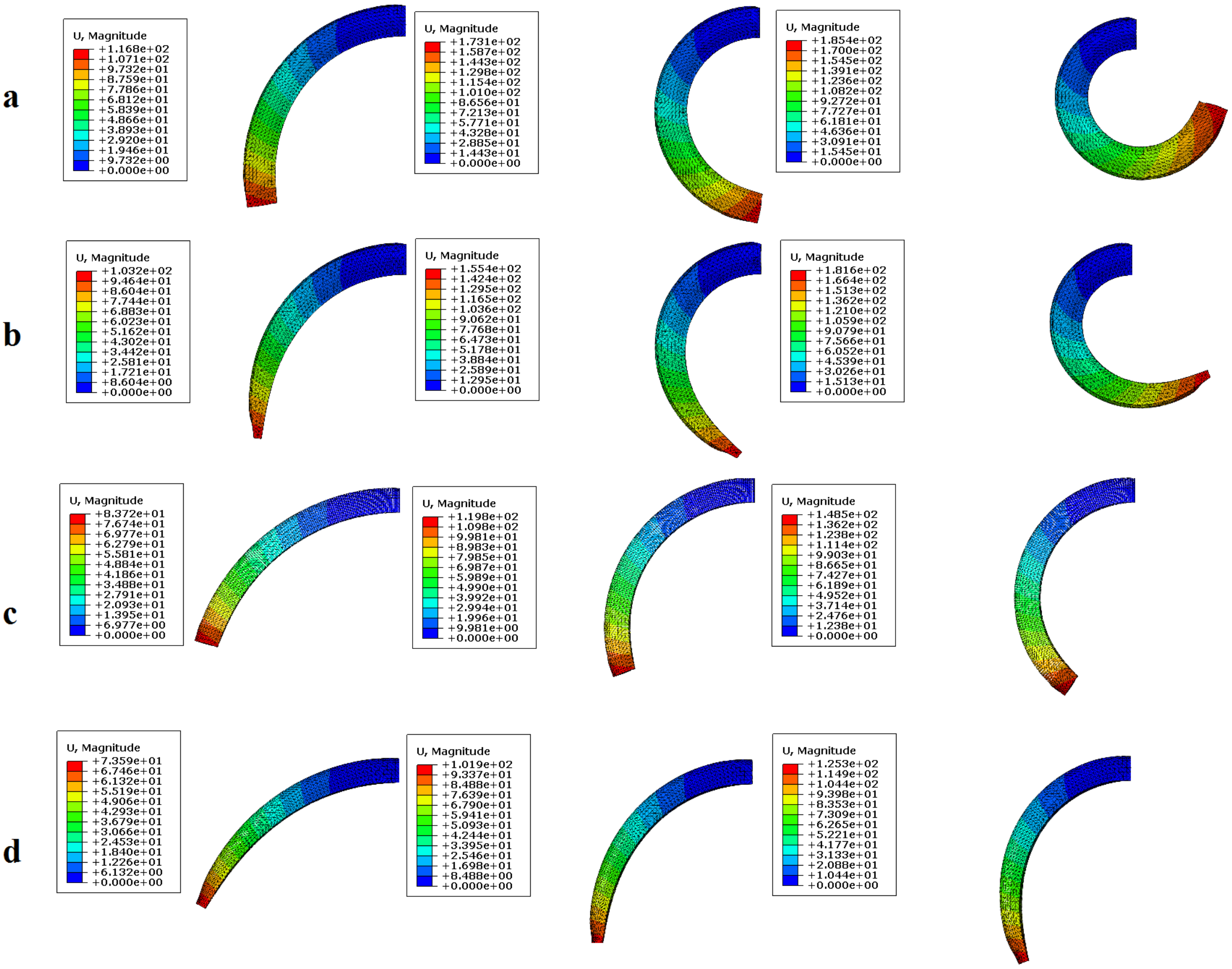


Fig. 7. Comparison of response of different actuators with constant and variable cross section. (a) Actuator with rectangular constant cross section. (b) Actuator with rectangular variable cross section. (c) Actuator with half-circular constant cross section. (d) Actuator with half-circular variable cross section.

In this paper, because of utilization of commercial package Abaqus and python scripting, it's possible to select all actuator parameters and changing their level in appropriate ranges. Each soft actuator with rectangular and half circular cross-section consists of five and four-factor, respectively, which could be effective for the actuator performance. Here, wall thickness, height, width, outer radius, fiber gap and inextensible layer thickness are considered as a factor. Three levels are considered for factors.

7- 2- Selection of output:

The outputs are the dependent variables of the process. In experiment design, some measurable outputs can be used. Here, the magnitude of the total displacement of the soft actuator tip is considered as the output.

7- 3- Design of experiments:

Taguchi matrices are divided from classical full factorial arrays. A series of Taguchi designs are available for studying factors with two, three, four, five and mixed levels in [17]. The type of design is highly dependent on the number of factors. L27 are suggested in the Taguchi method that can be used for up to 13 factors at 3 levels [17]. In this work, 5 and 4 factors at 3 levels are studied. Here, L27 is selected to study the main effect of factors and their interaction . So, the interaction of the factors is reported such that in the past works [2, 4] are not considered. To this end, four L27 array in Table 3 are studied to investigate the interaction between the factors, all factors have been changed in three levels like Table 4.

8- Simulations results

Using the analysis of variance on the results of simulations, the main effect of each parameter on the displacement of the actuators' tip is studied. As shown in Fig.8 and Fig.9, the effect of the parameters is similar to each other in both models, RCC and RVC. Thickness of the walls and inextensible layers has a high slope, which means they are the most effective parameters. So that, by increasing T and D, the bending resistance is increased and the tip displacement

Table 3. Experiments design for considering the interactions of each factor.

EXP. DESIGNS	Interactions			
L27	*T-H*	*T-W*	*T-M*	*T-D*
L27	*H-W*	*H-M*	*H-D*	___
L27	*W-M*	*W-D*	___	___
L27	*D-M*	___	___	___

Table 4. L27 Taguchi matrix by five factors at three levels.

Experiment Number	*T* (mm)	*H* (mm)	*W* (mm)	*M* (mm)	*D* (mm)
1	2	16	16	1	1
2	2	16	18	3	2
3	2	16	20	5	3
4	2	18	16	3	3
5	2	18	18	5	1
6	2	18	20	1	2
7	2	20	16	5	2
8	2	20	18	1	3
9	2	20	20	3	1
10	3	16	16	1	1
11	3	16	18	3	2
12	3	16	20	5	3
13	3	18	16	3	3
14	3	18	18	5	1
15	3	18	20	1	2
16	3	20	16	5	2
17	3	20	18	1	3
18	3	20	20	3	1
19	4	16	16	1	1
20	4	16	18	3	2
21	4	16	20	5	3
22	4	18	16	3	3
23	4	18	18	5	1
24	4	18	20	1	2
25	4	20	16	5	2
26	4	20	18	1	3
27	4	20	20	3	1

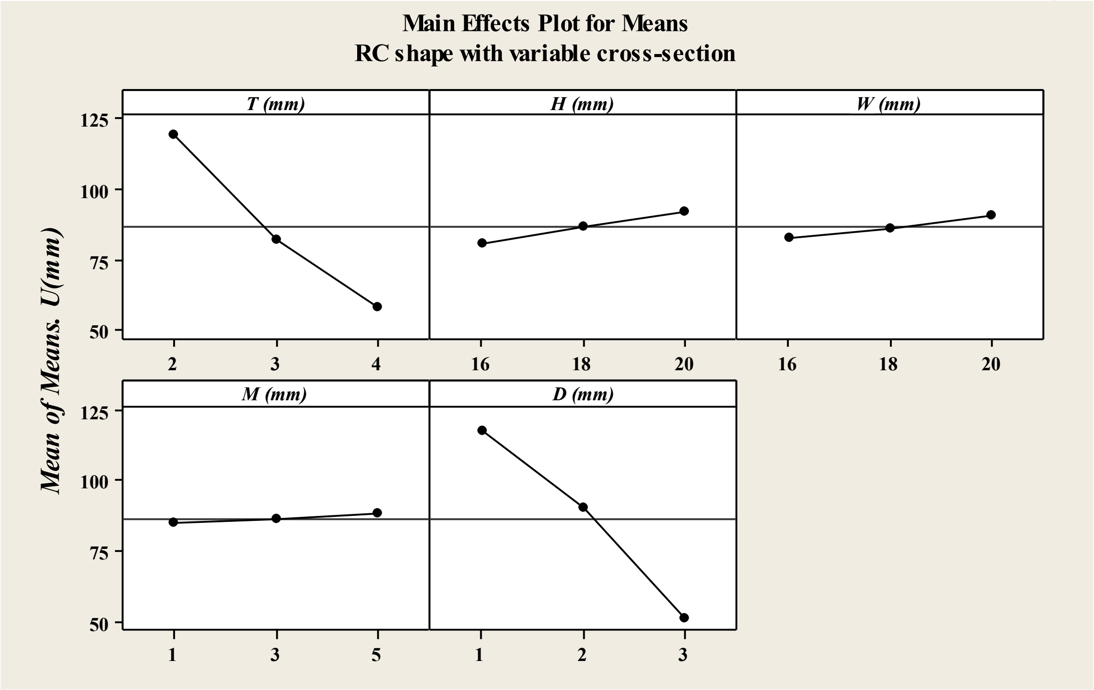


Fig. 8. The main effect of parameters on the displacement of the RVC model.

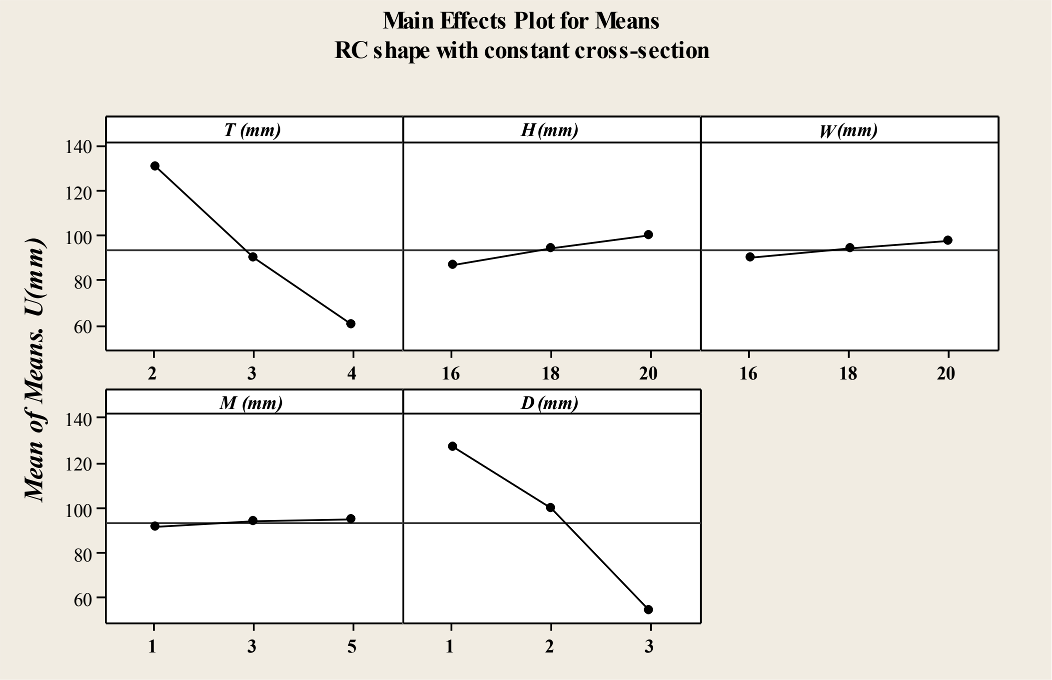


Fig. 9. The main effect of parameters on the displacement of the RCC model.

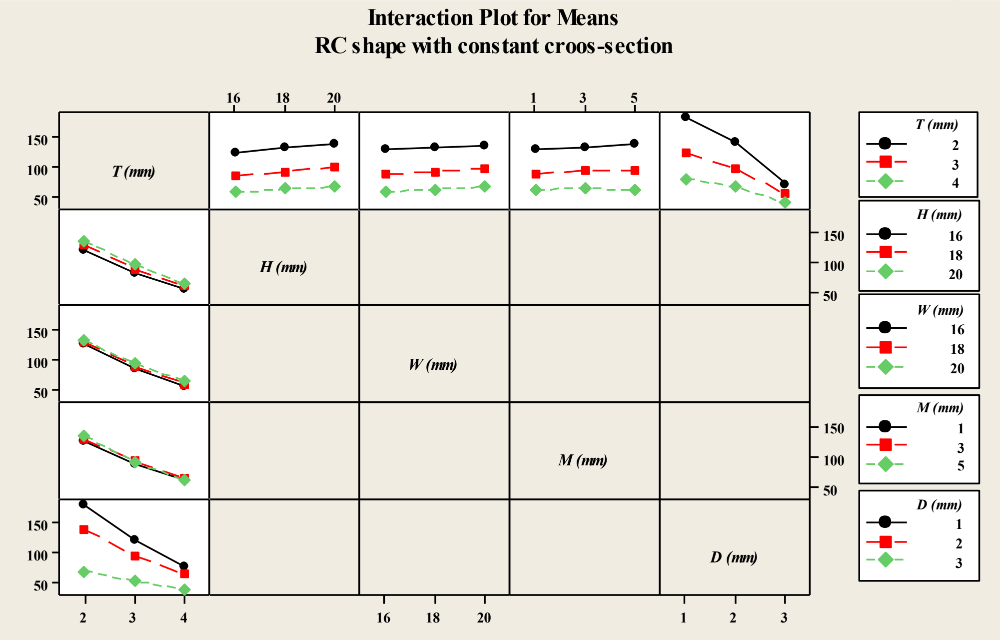


Fig. 10. Interaction plot for the RCC soft robot.

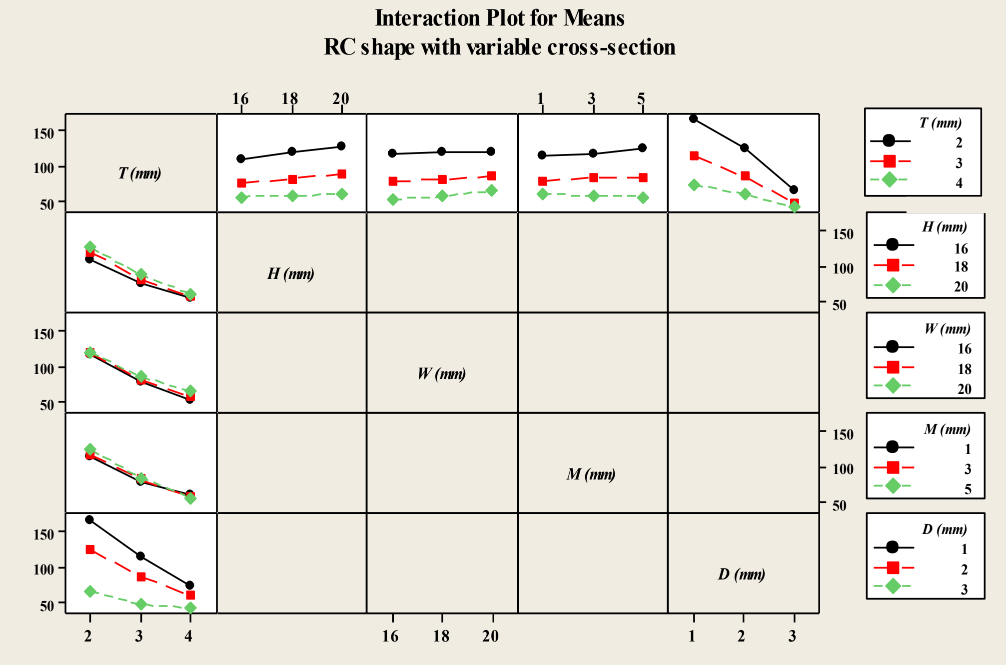


Fig. 11. Interaction plot for the RVC soft robot.

of the actuator is decreased. The height, width and rings with slight slope have the least effect on the actuator deformation. These results point to the fact that small variations in thickness make big changes in the displacement. In contrast, the height, width and gap between the rings have no significant effect on the mean of displacement.

Fig.10 and Fig.11 show all interactions of the wall thickness specified in Table 3. There is an interaction when the graphs are crossover or do not have the same slope. The plots on the top show the effect of the thickness of the wall on efficacy of the width, height, gap of the rings and the thickness of the inextensible layer. The plots on the left side

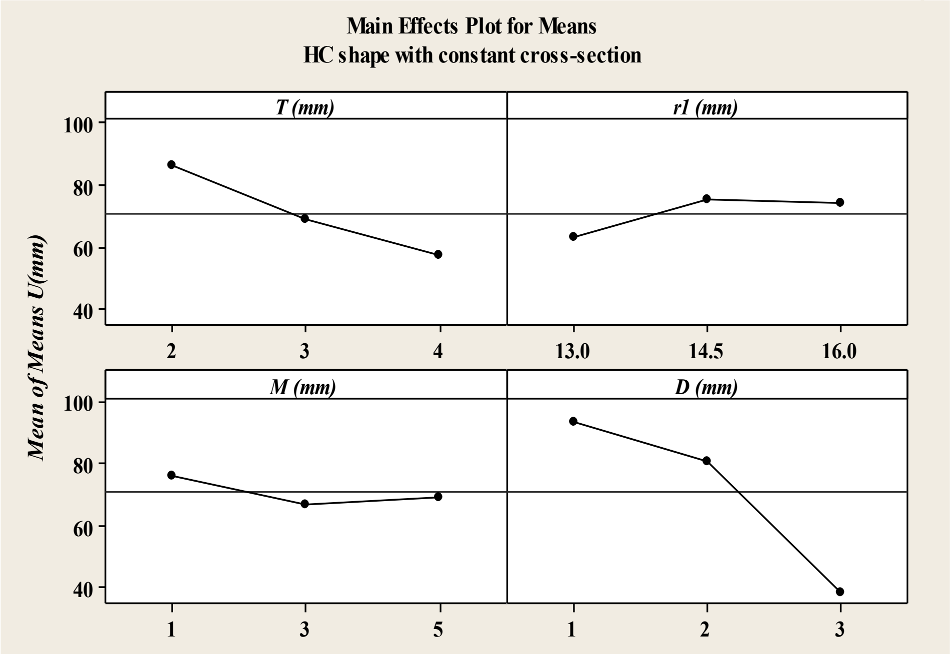


Fig. 12. Main effect of parameters on the displacement of the HCC model.

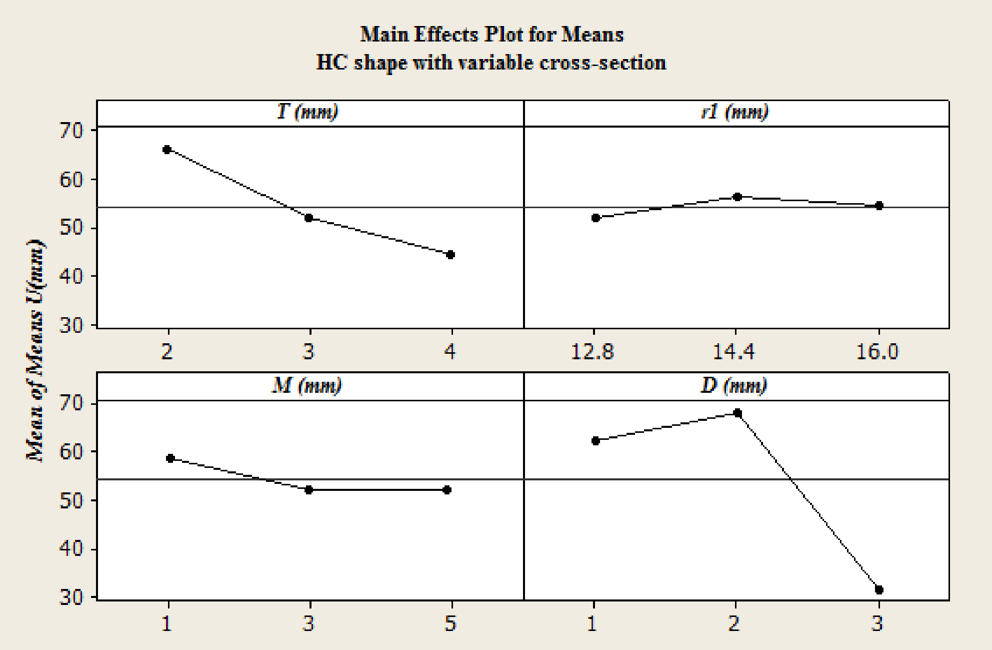


Fig. 13. Main effect of parameters on the displacement of the HVC model.

of the figures show the interaction of the parameters with the wall thickness. It is clear that the thickness of the wall and the inextensible layer have a significant interaction and the rest of the parameters have parallel lines and there is no significant interaction between them.

The main effect of the parameters on the deformation of the half-circular model with constant and variable cross-section is shown in Figs.12 and 13. Fig.12 shows that the inextensible layer thickness is the most effective parameter in the half-circular model and the radius of the cross-section and the gap of the rings have a minimal impact on the displacement of the actuator tip. Fig.13 shows that in the half-circular model

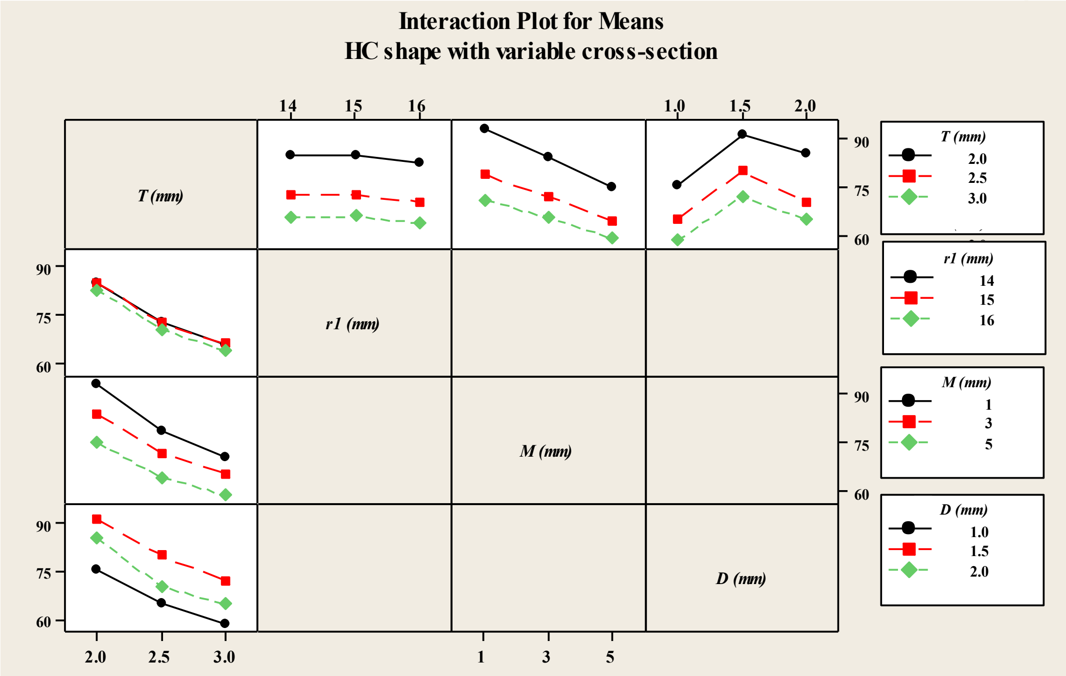


Fig. 14. Interaction plot for the HVC soft robot.

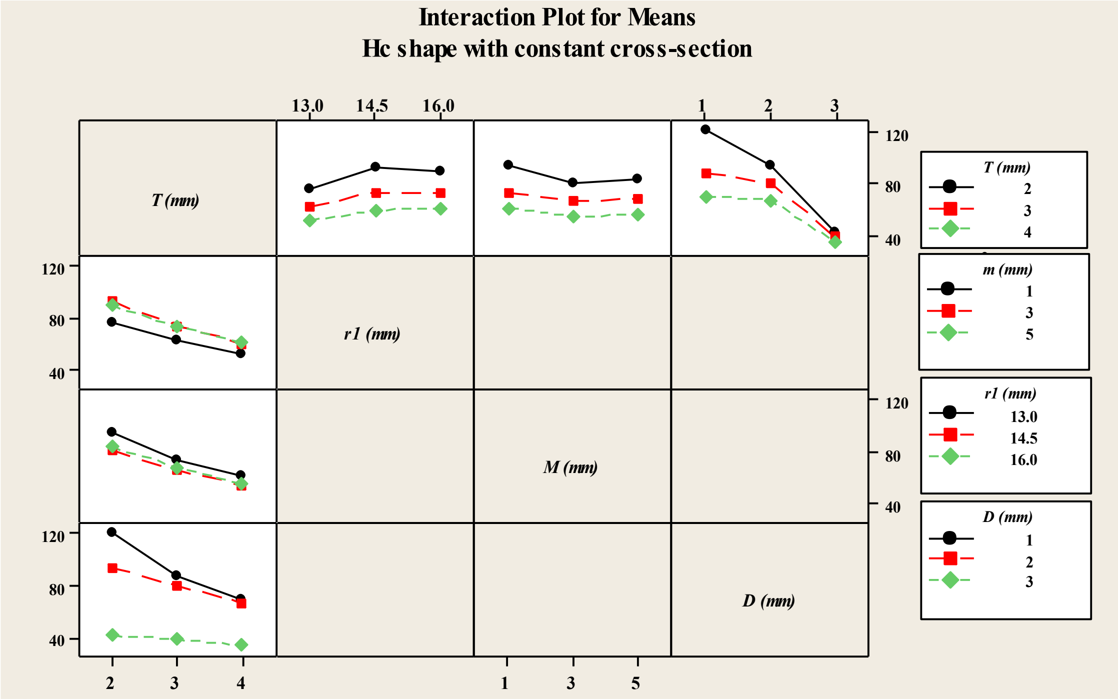


Fig. 15. Interaction plot for the HCC soft robot.

with variable cross-section, the inextensible layer thickness between the first and second levels has a positive effect on the deflection and the gap between the rings has the same impact on the displacement of the actuator tip in the half-circular model with constant cross-section.

The effect of the interaction of the parameters on the displacement of the actuators' tip in the constant and variable half-circular models is shown in Fig.14 and Fig.15, respectively. As shown in Fig.14, there is no significant interaction between the parameters of the half-circular model with variable cross section, and the coordinated effect between them is observed. The results in Fig.15 show that the

Table 5. Optimum value of parameters and optimum response of the soft actuators. (Uf is the displacement of the actuator's tip obtained with FEM. Ut is the displacement of the actuator's tip predicted with Taguchi method.)

Parameters	T(mm)	R_1(mm)	H(mm)	W(mm)	M(mm)	D(mm)	U_f (mm)	U_t (mm)	error %
Optimum value RCC	2	-	20	20	5	1	189	194.8	3
Optimum value RVC	2	-	20	20	5	1	176.5	181.5	2.8
Optimum value HCC	2	16	-	-	1	1	141.5	133.9	5.3
Optimum value HVC	2	16	-	-	1	1.5	102	99.2	2.7

interaction of the parameters in the half-circular model with constant cross-section is similar to the rectangular model, and only a significant effect is observed between the wall thickness and the inextensible layer thickness.

9- Optimum Design

In this study, it is important to know the optimum value of the parameters for maximizing the displacement of the actuator tip. In Taguchi method, the optimum value of each parameter is obtained by the means graphs. For maximizing the displacement of the tip of the actuator, the value of the parameters are obtained in Table 5. In more cases, the optimal conditions will not be one of the experiments that carried out, because the Taguchi test is only a small set of full factorial experiments, the optimum is always one of the experiments defined by the full factorial. To this end, Taguchi formula [18] is used to estimate the optimal response and given as:

$$y_{opt} = \frac{T}{N} + \left(\bar{A}_i - \frac{T}{N} \right) + \left(\bar{B}_i - \frac{T}{N} \right) + \left(\bar{C}_i - \frac{T}{N} \right) \qquad (3)$$

where T is the sum of the results of the experiments, N is the number of experiments, and are the average of the experiments result with parameters A, B, C at their optimal levels. The soft actuators performance in the optimal condition are obtained from Figs. 8, 9, 12, 13 and results is shown in Table 5 and compared with the numerical analysis.

10- Conclusions

In this paper, the performance of four soft reinforced actuators was compared. To this end, the Taguchi approach was used to design experiments and determine the optimum parameters of the fiber reinforced actuators. The results showed that the rectangular actuator has a more range of motion compare to half-circular one. Also, the results illustrated that the behavior and performance of all soft fiber-reinforced actuators depend more on the thickness of the walls and the inextensible layer. Moreover, the gap of the fibers has the least effect on the behavior among the design parameters of the soft actuators. But, the rings make the actuator more resistant to pressure. Also, studies on the interaction of the parameters showed that there is a significant interaction between the inextensible layer and wall thickness in all models so that by increasing the thickness of the inextensible layer, the effect of the wall thickness on the displacement of the actuator tip is reduced, but in the other parameters, there is no significant interaction.

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