International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

On the Use of a MATLAB for the Analysis of Some Deformations in Magnetic Shape Memory Materials

[1]Juan Manuel Hernández Calderón, [2]Luis Demetrio Herrera Cobos

[1]Universidad del Valle de México (UVM) Av. José López Portillo 346, Los Sabinos II, 55720 San Francisco Coacalco, México (Email: juan.hernandezc@uvmnet.edu)

[2]Universidad del Valle de México (UVM) Av. José López Portillo 346, Los Sabinos II, 55720 San Francisco Coacalco, México (Email: A660006094@my.uvm.edu.mx)

***Abstract* - The Analysis of the behavior of a Ni-Mn-Ga single crystal in cantilever is done using a MATLAB code based on the theoretical point of view of Landau´s elasticity theory [1]. The dislocation theories presented in [1–7] for crystalline materials are considered, and a set of field equations based on the decomposition of the strain tensor into a plastic and elastic behavior under the premise that in this sort of materials dislocations are geometrically organized causing a reversible elasto-plastic deformation. Some simulations are presented using experimental data from [24] where small samples of a Ni-Mn-Ga single crystal of three different geometries were subjected to bending by applying a rotating magnetic field in order to get information about the behavior of the sample in cantilever, as well as being able to get more information about the dynamic process experienced by the dislocations of the material and the deformation analysis when both the magnitude of the magnetic field and its orientation change. This information is used to establish the possible form of the strain tensor. For the purpose of the present investigation, both the slip system and the value of the Poisson ratio for Ni-Mn-Ga single crystal are proposed, since there is not enough experimental information about it. And taking into account that the highly anisotropic character of these materials does not allow to establish a constant value for the Poisson's ratio, however the proposed MATLAB code allows to consider in each iteration the possible variation of this information.**

Keywords: Magnetic shape memory, MATLAB code, Continuum mechanics, Beam bending, Elasto-plastic behavior.

I. INTRODUCTION

Magnetic shape memory materials have been extensively used throughout the last decade being the Ni2-Mn-Ga single crystal the most widely studied and the first magnetic material with shape memory properties reported [4]. Among its most important and widely studied features at present is the induction of a reversible plastic deformation under the action of a magnetic field.

Here reversible plastic deformation is a term used when the sample subjected to a magnetic field undergoes a deformation that is not fully recover once the action of the magnetic field has been removed, however, the deformation can be eliminated as long as a new field acts on the material in a certain suitable direction.

Its crystalline nature and the presence of localized dislocations make the study of these materials of wide interest for their possible applications, specifically in actuators, but these properties also impose a degree of significant difficulty in the study of the behavior of said alloys.

The plastic behavior on crystalline materials is presented essentially as a response to the motion of the internal dislocations of the material on the crystallographic planes and in the slip directions [5]. Given the crystalline nature of most of the material in engineering it is possible to attribute the plastic behavior of the material purely to the kinematics of the internal dislocations of the material during the deformation process. Considering a plastic behavior due to the propagation of the internal dislocations it is not feasible to use the theory of the continuum only since it does not consider the existence of dislocations. For this reason, it is necessary to extend the fundamental theoretical aspects of the continuum mechanics (mainly the corresponding to finite elasticity and small deformations). As it is known, the motion of the dislocations is accompanied, in addition to an elastic deformation, of a deformation of the crystal lattice that is not linked to the appearance of internal stresses, generating a plastic deformation [1].

Recent advances in image processing and analysis have allowed understand a little more about the behavior of these materials. Rothenbuhler et al [8] uses the Hough transformation to characterize the Ni2MnGa alloy finding information about the motion and location of the martensite twin boundaries. Müllner et al [9] uses a MATLAB code to

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

analyze about 30,000 images and extract information on the behavior of Ni2MnGa alloy samples into a variable rotating magnetic field.

In recent years, in addition to the study of the properties and benefits that magnetic shape memory alloys can offer to technological advances, scientists, researchers and engineers have proposed to develop some mathematical models to better understand the behavior of these materials. This type of models goes from the analysis of the relationship between temperatures and stresses under the action of an external field, to the study of the magnetic behavior of NiMnGa alloys and others. But also, the interest is changing horizons and they have begun to study the properties of Fe - Mn - Cr - Si - Tb - B type alloys [10].

There are two possible theories that can be used in modeling the behavior of magnetic shape memory materials [12]. The first, based on the microscopic properties and the physics of solids. Essentially used by physicists and theorists. Some relevant articles can be found in [13-16]. The second is based mainly on the analysis of macroscopic and thermodynamic properties. Focused on dynamical systems and develop and manufacture of actuators. These kinds of models are used mainly by engineers. Such models can be found in [17, 18]. Although several models have been proposed for the study of plastic behavior of materials based on crystallographic and thermodynamics properties [19], or related with the polar decomposition of the deformation gradient [20-22]. Few models focused on the analysis of the process of dislocations in magnetic shape memory materials can be found at present.

The aim of this paper is to properly establish the variation of the radius of curvature of some samples in cantilever subjected to the action of different magnetic field strengths and different directions, and use this information to find the form of the strain tensor with a MATLAB code, based on the decomposition of this tensor into an elastic and a plastic part using the displacements vector field proposed by Landau [1].

II. KINEMATICS OF FINITE DEFORMATIONS IN SINGLE CRYSTALS

Nonlinear continuum dislocation theory (NCDT) is based on the premise that plastic response is related to a dislocation process and it is feasible to use the decomposition of the deformation gradient as follows [6]:

$$\boldsymbol{F}(\boldsymbol{p},t) = \boldsymbol{F}(\boldsymbol{p},t)^{\boldsymbol{E}} \circ \boldsymbol{F}(\boldsymbol{p},t)^{\boldsymbol{P}} (1)$$

Where the term $\boldsymbol{F}(\boldsymbol{p},t)^{\boldsymbol{P}}$ is associated with the dislocation process which characterizes the kinematics of the crystal structure along the deformation, see Fig. 1. Expression (1) has the immediate consequence for the strain tensor field:

$$\boldsymbol{E}(\boldsymbol{p},t) = \boldsymbol{E}(\boldsymbol{p},t)^{\boldsymbol{E}} + \boldsymbol{E}(\boldsymbol{p},t)^{\boldsymbol{P}} \qquad (2)$$

This is:

$$\boldsymbol{E}(\boldsymbol{p},t) = \frac{1}{2}(\boldsymbol{\nabla u}(\boldsymbol{p},t) + \boldsymbol{\nabla u}(\boldsymbol{p},t)^{\boldsymbol{T}}) + \boldsymbol{E}(\boldsymbol{p},t)^{\boldsymbol{P}} (3)$$

Where:

$\boldsymbol{E}(\boldsymbol{p},t)^{\boldsymbol{E}}$Represents the elastic part of the strain tensor field. This part causes stresses in the material.

$\boldsymbol{E}(\boldsymbol{p},t)^{\boldsymbol{P}}$Represents the part of the strain tensor field related to the plastic behavior of the material. It is convenient to mention that this term can also be defined by changes of temperature or atomic slides, but for the moment and for our analysis we will only consider that it is completely defined by the dislocations the material undergoes.

With

$$det\ \boldsymbol{F}^{\boldsymbol{P}} > 0$$

$$det\ \boldsymbol{F}^{\boldsymbol{P}} = 1, for\ the\ elastic\ behavior\ only$$

The following representation for the plasticity gradient can be considered [7]:

$$\boldsymbol{E}^{\boldsymbol{P}}(\boldsymbol{p},t) = \boldsymbol{\gamma}(\boldsymbol{p},t)\mathbb{s}(\boldsymbol{p})\otimes\mathbb{m}(\boldsymbol{p})(4)$$

Where the vectors $\mathbb{s}$ and $\mathbb{m}$ constitute a slip system,$\mathbb{s}$ represents the slip direction and$\mathbb{m}$ represents the unit normal to the slip plane, and$\boldsymbol{\gamma}(\boldsymbol{p},\boldsymbol{t})$) is the scalar shear slip rate.

In the case of Magnetic shape memory alloys, the slip planes and directions in which the dislocations occur are represented by a transformation system well known [19]. The expression (4) represents the case for which is defined a single twin boundary and a single slip system. In general, if α (slip) systems are considered, where α = 1… n. The expression (4) can be written as follows:

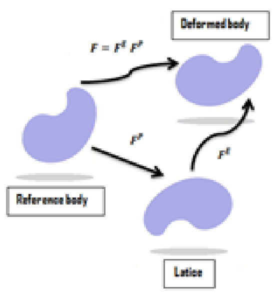

Figure 1: Kinematics of the plastic deformation

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

$$\boldsymbol{E}^{\boldsymbol{P}}(\boldsymbol{p},t) = \sum_{\alpha=1}^{n} \gamma^{\alpha}(\boldsymbol{p},t)\mathbb{s}^{\alpha}(\boldsymbol{p})\otimes\mathbb{m}^{\alpha}(\boldsymbol{p}) \qquad (5)$$

Thus, by combining expressions (3) and (5), we can obtain the form of the strain tensor (found it in most of the current literature):

$$\boldsymbol{E}(\boldsymbol{p},t)_{\boldsymbol{T}} = \frac{\mathbf{1}}{\mathbf{2}}(\nabla\boldsymbol{u}(\boldsymbol{p},t) + \nabla\boldsymbol{u}(\boldsymbol{p},t)^{\boldsymbol{T}}) + \sum_{\alpha=1}^{n} \gamma^{\alpha}(\boldsymbol{p},t)\mathbb{s}^{\alpha}(\boldsymbol{p})\otimes\mathbb{m}^{\alpha}(\boldsymbol{p})(6)$$

Since the behavior of magnetic shape memory alloys (MSMA) can be consider as elasto-plastic with reversible plastic response the above expression can be considered for their analysis. Expression (6) reveals the intimate relation between the phenomenological macro and the microcrystalline aspects in the material. Then the elasto-plastic problem can be understood as a scale problem.

The total elasto-plastic deformation gradient can be decomposed as follows:

$$\boldsymbol{F}(\boldsymbol{p},t) = \boldsymbol{F}(\boldsymbol{p},t)^{\boldsymbol{E}} \circ \boldsymbol{F}(\boldsymbol{p},t)^{\boldsymbol{P}} =$$

$$= \boldsymbol{F}(\boldsymbol{p},t)^{\boldsymbol{E}}\left[\boldsymbol{I} + \sum_{\boldsymbol{\alpha}=\mathbf{1}}^{\boldsymbol{n}} \boldsymbol{\gamma}(\boldsymbol{p},t)\mathbb{s}(\boldsymbol{p})\otimes\mathbb{m}(\boldsymbol{p})\right](7)$$

The main objective of this paper is to carry out a series of simulations using expressions 6 and 7 using a matlab code that allows to incorporate experimental data.

III. ANALYSIS OF BENDING DEFORMATION OF A SINGLE CRYSTAL BEAM

3.1 Introduction

The objective of this section is to analyze from a geometric point of view the possible motion and deformations the material with magnetic shape memory can present. The experimental data used for the analysis of the bending behavior is fully presented in [24]. Where Hernández et al used small beams of a single crystal grown with composition Ni51Mn27Ga22 and applied a magnetic force at constant angles of 45°, 90° and 135° increasing and decreasing magnitude, with measurements every 79.58kAm-1 (0.1T). Once the 955 kAm-1 [1.2T] magnetic field was reached, it was gradually reduced in such a way that a measurement could be made every 79.58kAm-1 (0.1T) in order to observe the material's recovery capacity. This series of tests was carried out for three different geometries see Table I. For this paper only sample 1 was considered. Some data is presented in appendix II.

TABLE 1: Samples dimensions

Sample	Cross section (mm^2)	Length (mm)
1	2x2	10
2	1x1	5
3	5x4	6

3.2 Problem Statement

Let Ω (Fig. 2) be the bounded regular region of the geometric space $\boldsymbol{E^i}$, where i = 1, 2, 3, with analytical boundaries ∂Ωi, so that ∂Ωi has a parametric representation. With the Dirichlet and Neumann boundary conditions that expresses the cantilever problem:

1) $\boldsymbol{u}(\boldsymbol{p},t) = \boldsymbol{p}, in\mathcal{s}_0, for\ all t > t_0$

$\nabla\boldsymbol{u}(\boldsymbol{p},t) = 0, in\mathcal{s}_0, for\ all t > t_0$

Where $\boldsymbol{u}(\boldsymbol{p},t) = \boldsymbol{p}$ is the function that describes the displacement of Ωfor all$t > t_0$. The vector field that describes the displacement is given by [1]:

$$\boldsymbol{u}(\boldsymbol{p},t) = \begin{bmatrix} -\dfrac{(P_3{}^2+\upsilon(P_1{}^2+P_2{}^2))}{2R} \\ -\dfrac{\upsilon P_1P_2}{R} \\ \dfrac{P_1P_3}{R} \end{bmatrix} \qquad (\mathbf{8})$$

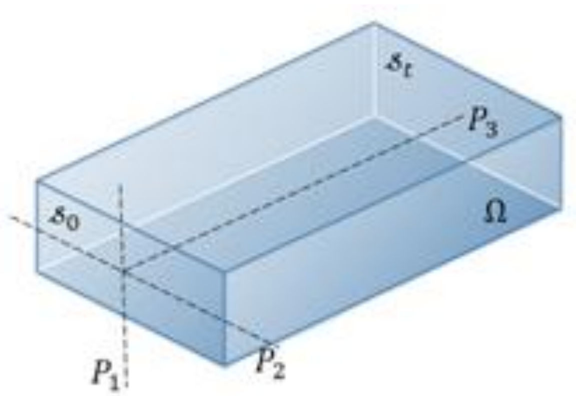

Figure 2: Regular region Ω

Where R represents the radius of curvature of the beam and υ is the Poisson's ratio. Using this vector field, the strain tensor is given by:

$$\boldsymbol{E}(\boldsymbol{p},t) = \frac{1}{2}[\nabla\boldsymbol{u}(\boldsymbol{p},t) + \nabla\boldsymbol{u}(\boldsymbol{p},t)^T] =$$

$$= \begin{bmatrix} -\dfrac{\upsilon P_1}{R} & -\dfrac{\upsilon P_2}{R} & 0 \\ -\dfrac{\upsilon P_2}{R} & -\dfrac{\upsilon P_1}{R} & 0 \\ 0 & 0 & \dfrac{P_1}{R} \end{bmatrix} \qquad (9)$$

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

This expression allows incorporate specific information on the planes and directions of slip system as well as experimental information like the radius of curvature of the beam and dimensions of the sample which is the main objective of this paper.

The use of the data obtained by Hernandez et al [24] and get a series of simulations that allow knowing about the possible movement of a cantilever beam of a magnetic shape memory material.

3.3 MATLAB Code

In this section some simulations were carry out and an analysis of the strain tensor and the variation of the radius of curvature was done. An analysis of the variables of the equations 9 and 10 was first done in order to create a graphical interface in MATLAB. First, the screen in MATLAB asks for the dimensional correction matrix (C) to be specified, only if it is different from the unit matrix. This is a base change matrix applied to the part that represents plastic behavior in expression 10, this is because this term is defined upon the lattice of the sample.

See [23] for a full justification and description of this process. It is obvious that this matrix requires information about the lattice orientation to be defined. Since this information is lacking, all simulations will be carried out considering C as the identity matrix.

It also asks for the number of iterations of the vector summation. From this it will enter a loop where for each iteration it will ask for the vectors $\mathbb{s}$ and $\mathbb{m}$, this is the slip system of interest as well as the *scalar shear slip rate gamma***.** Fig. 3.

Once the information is complete, the tensor product of s and m is calculated and multiplies by gamma. Once the number of iterations is over, plastic matrix is calculated using the following expression:

$$E^P(\boldsymbol{p},t)_{\boldsymbol{T}} = C^{-1}\left[\sum_{\alpha=1}^{n}\gamma^{\alpha}(\boldsymbol{p},t)\mathbb{s}^{\alpha}(\boldsymbol{p},t)\otimes\mathbb{m}^{\alpha}(\boldsymbol{p},t)\right]\mathrm{C} \qquad (11)$$

After this, the matrix that describes the elastic behavior of the body is calculated. This requires the vector equation 8, in terms of 'x = P_1', 'y = P_2' and 'z = P_3', this represent the dimension of the sample. With these data, the gradient of the vector equation obtained.

Figure 3: Interface. Plastic part

In the last part of the program, only the elastic and plastic matrices obtained previously are added, obtaining the final matrix of elasto-plastic behavior of the body, showing the three matrices. And at the end the option to graph the radius of curvature of the object was added. Fig. 4. This only requires that enter the radius of curvature and select whether you want to overlap several values or not. With this a graph in two dimensions is obtained.

Figure 4: Elasto-Plastic Behavior

3.4 Simulations and results

The generation of bending strain induces a variation in the radius of curvature as a result of the displacement of the martensite variants. In figure 5 a magnetic field with a

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

direction of 45°, 90° was applied to the sample from 0 to 1.2T at increments of 100mT, and finally decreased to 0T. Once the magnetic field is removed, the material recovers, that is, it has an elastic behavior that may include a "pseudoelastic" portion which is carried by twin boundary motion. See [26]

But the sample does not return to the initial position until a new field is applied, so this can be understood as a reversible elasto-plastic behavior.

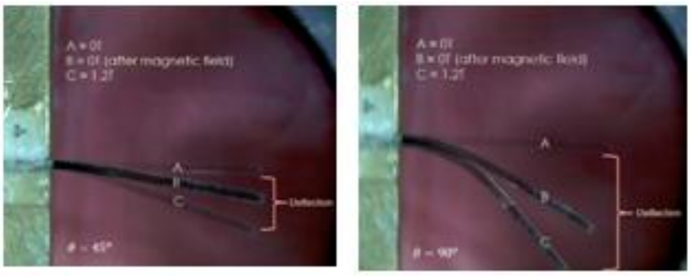

Figure 5: Deflection before and after a magnetic field is applied

Considering this, several simulations were carried out using the data of the radius of curvature presented in appendix II in equation 9. The variation was plot in order to observe the behavior of the radius of curvature as the magnetic field increases at the rate of 0.1T and up to 1.2T. In appendix III the results for the variation of the radius of curvature when increasing and reducing the magnetic field are presented.

3.5 Strain tensor and plastic behavior

The experimental information about the variation of the radius of curvature is used in expression 9 and the value of the strain tensor is obtained. In table 2, 3 and 4 the results of the simulations for each of the magnetic field directions are presented.

TABLE 2: Magnetic field at 45°

K	1/K	R	Strain tensor		
1	1.00000	1.00	-0.066 -0.066 0	-0.066 -0.066 0	0 0 0.2
2.68	0.37313	0.37	-0.177 -0.177 0	-0.177 -0.177 0	0 0 0.54
5.16	0.19380	0.19	-0.341 -0.341 0	-0.341 -0.341 0	0 0 1.03
5.96	0.16779	0.17	-0.393 -0.393 0	-0.393 -0.393 0	0 0 1.19
6.24	0.16026	0.16	-0.412 -0.412 0	-0.412 -0.412 0	0 0 1.25
7.48	0.13369	0.13	-0.494 -0.494 0	-0.494 -0.494 0	0 0 1.5
9.04	0.11062	0.11	-0.597 -0.597 0	-0.597 -0.597 0	0 0 1.81
9.96	0.10040	0.10	-0.657 -0.657 0	-0.657 -0.657 0	0 0 1.99
10.8	0.09259	0.09	-0.713 -0.713 0	-0.713 -0.713 0	0 0 2.16
11.7 2	0.08532	0.09	-0.774 -0.774 0	-0.774 -0.774 0	0 0 2.34
12.0 8	0.08278	0.08	-0.797 -0.797 0	-0.797 -0.797 0	0 0 2.42
12.8	0.07813	0.08	-0.845 -0.845 0	-0.845 -0.845 0	0 0 2.56

TABLE 3: Magnetic field at 90°

K	1/K	R	Strain tensor		
3.68	0.27174	0.27	-0.243 -0.243 0.000	-0.243 -0.243 0.000	0.000 0.000 0.736
15.84	0.06313	0.06	-1.045 -1.045 0.000	-1.045 -1.045 0.000	0.000 0.000 3.168
14.68	0.06812	0.07	-0.969 -0.969 0.000	-0.969 -0.969 0.000	0.000 0.000 2.936
14.8	0.06757	0.07	-0.977 -0.977 0.000	-0.977 -0.977 0.000	0.000 0.000 2.960
13.12	0.07622	0.08	-0.866 -0.866 0.000	-0.866 -0.866 0.000	0.000 0.000 2.624
13.96	0.07163	0.07	-0.921 -0.921 0.000	-0.921 -0.921 0.000	0.000 0.000 2.792
14.16	0.07062	0.07	-0.935 -0.935 0.000	-0.935 -0.935 0.000	0.000 0.000 2.832
13	0.07692	0.08	-0.858 -0.858 0.000	-0.858 -0.858 0.000	0.000 0.000 2.600
13.88	0.07205	0.07	-0.916 -0.916 0.000	-0.916 -0.916 0.000	0.000 0.000 2.776
11.28	0.08865	0.09	-0.744 -0.744 0.000	-0.744 -0.744 0.000	0.000 0.000 2.256
10.64	0.09398	0.09	-0.702 -0.702	-0.702 -0.702	0.000 0.000

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

			0.000	0.000	2.128
11.36	0.08803	0.09	-0.750	-0.750	0.000
			-0.750	-0.750	0.000
			0.000	0.000	2.272

TABLE 4: Magnetic field at 135°

K	1/K	R	Strain tensor		
1.48	0.67568	0.68	-0.098	-0.098	0
			-0.098	-0.098	0
			0	0	0.3
1.04	0.96154	0.96	-0.069	-0.069	0
			-0.069	-0.069	0
			0	0	0.21
1.52	0.65789	0.66	-0.1	-0.1	0
			-0.1	-0.1	0
			0	0	0.3
0.16	6.25000	6.25	-0.011	-0.011	0
			-0.011	-0.011	0
			0	0	0.03
0.4	2.50000	2.50	-0.026	-0.026	0
			-0.026	-0.026	0
			0	0	0.08
0.32	3.12500	3.13	-0.021	-0.021	0
			-0.021	-0.021	0
			0	0	0.06
0.8	1.25000	1.25	-0.053	-0.053	0
			-0.053	-0.053	0
			0	0	0.16
0.84	1.19048	1.19	-0.055	-0.055	0
			-0.055	-0.055	0
			0	0	0.17
0.84	1.19048	1.19	-0.055	-0.055	0
			-0.055	-0.055	0
			0	0	0.17
1.72	0.58140	0.58	-0.114	-0.114	0
			-0.114	-0.114	0
			0	0	0.34
2.68	0.37313	0.37	-0.177	-0.177	0
			-0.177	-0.177	0
			0	0	0.54
1.48	0.67568	0.68	-0.098	-0.098	0
			-0.098	-0.098	0
			0	0	0.3

In single crystals the plastic deformation takes place in certain planes and directions. Every plane and direction create a slip system. For the case of 10M Martensite the modulation of the crystal lattice can be expressed through periodic changes along the system of planes (110) and directions $[1\bar{1}0]$, see [25]. Under this consideration, simulation was performed considering 2 active slip systems Fig. 6.

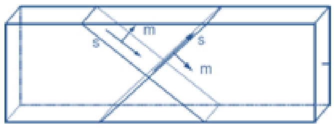

Figure 6: Two active slip systems

For the case of the plastic behavior, a total of twelve slip systems were analyzed (see table 5). Considering the existence of only two for each simulated sample. The main objective of this is to have more detailed information of the tensor field that represents the elastic behavior. Each simulation was carried out considering a variation in the γ^{α} value of 0.1.

For the elastic analysis the expression 9 was used, considering a value of 0.33 in the Poisson's ratio and the dimensions of the sample 1 mentioned in table 1.

TABLE 5: Slip systems

α	$\mathbb{s}^{\alpha}$	$\mathbb{m}^{\alpha}$
1	$[01\bar{1}]$	(111)
2	$[\bar{1}01]$	(111)
3	$[1\bar{1}0]$	(111)
4	$[01\bar{1}]$	$(\bar{1}11)$
5	$[101]$	$(\bar{1}11)$
6	$[\bar{1}\bar{1}1]$	$(\bar{1}11)$
7	$[011]$	$(\bar{1}1\bar{1})$
8	$[10\bar{1}]$	$(\bar{1}1\bar{1})$
9	$[\bar{1}\bar{1}0]$	$(\bar{1}1\bar{1})$
10	$[011]$	$(11\bar{1})$
11	$[1\bar{1}0]$	$(11\bar{1})$
12	$[101]$	$(11\bar{1})$

Finally, the simulations were carried out considering a variation of 45°, 90° and 135° between the axis of the sample and the direction of the magnetic field. In table 6 the results of the simulations for each system are presented. Equation 5 was used with a variation of the scalar shear slip rate$\boldsymbol{\gamma}(\boldsymbol{p},\boldsymbol{t})$ from 0.1 up to 0.9.

This in order to have a broader representation of the behavior of equation 5 when $\boldsymbol{\gamma}(\boldsymbol{p},\boldsymbol{t})$ varies. Equation 5 is related with plastic behavior.

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

Table 6: Simulation of the slip systems

	System 1			*System 2*			*System 3*			*System 4*			*System 5*			*System 6*			*System 7*			*System 8*			*System 9*			*System 10*			*System 11*			*System 12*		
S⊗M	0	0	0	-1	-1	-1	1	1	1	0	0	0	-1	1	1	1	-1	-1	0	0	0	-1	1	-1	1	-1	1	0	0	0	1	1	-1	1	1	-1
	1	1	1	0	0	0	-1	-1	-1	-1	1	1	0	0	0	1	-1	-1	-1	1	-1	0	0	0	1	-1	1	1	1	-1	-1	-1	1	0	0	0
	-1	-1	-1	1	1	1	0	0	0	1	-1	-1	-1	1	1	-1	1	1	-1	1	-1	1	-1	1	0	0	0	1	1	-1	0	0	0	1	1	-1
0.1	0	0	0	-0.1	-0.1	-0.1	0.1	0.1	0.1	0	0	0	-0.1	0.1	0.1	0.1	-0.1	-0.1	0	0	0	-0.1	0.1	-0.1	0.1	-0.1	0.1	0	0	0	0.1	0.1	-0.1	0.1	0.1	-0.1
	0.1	0.1	0.1	0	0	0	-0.1	-0.1	-0.1	-0.1	0.1	0.1	0	0	0	0.1	-0.1	-0.1	-0.1	0.1	-0.1	0	0	0	0.1	-0.1	0.1	0.1	0.1	-0.1	-0.1	-0.1	0.1	0	0	0
	-0.1	-0.1	-0.1	0.1	0.1	0.1	0	0	0	0.1	-0.1	-0.1	-0.1	0.1	0.1	-0.1	0.1	0.1	-0.1	0.1	-0.1	0.1	-0.1	0.1	0	0	0	0.1	0.1	-0.1	0	0	0	0.1	0.1	-0.1
0.2	0	0	0	-0.2	-0.2	-0.2	0.2	0.2	0.2	0	0	0	-0.2	0.2	0.2	0.2	-0.2	-0.2	0	0	0	-0.2	0.2	-0.2	0.2	-0.2	0.2	0	0	0	0.2	0.2	-0.2	0.2	0.2	-0.2
	0.2	0.2	0.2	0	0	0	-0.2	-0.2	-0.2	-0.2	0.2	0.2	0	0	0	0.2	-0.2	-0.2	-0.2	0.2	-0.2	0	0	0	0.2	-0.2	0.2	0.2	0.2	-0.2	-0.2	-0.2	0.2	0	0	0
	-0.2	-0.2	-0.2	0.2	0.2	0.2	0	0	0	0.2	-0.2	-0.2	-0.2	0.2	0.2	-0.2	0.2	0.2	-0.2	0.2	-0.2	0.2	-0.2	0.2	0	0	0	0.2	0.2	-0.2	0	0	0	0.2	0.2	-0.2
0.3	0	0	0	-0.3	-0.3	-0.3	0.3	0.3	0.3	0	0	0	-0.3	0.3	0.3	0.3	-0.3	-0.3	0	0	0	-0.3	0.3	-0.3	0.3	-0.3	0.3	0	0	0	0.3	0.3	-0.3	0.3	0.3	-0.3
	0.3	0.3	0.3	0	0	0	-0.3	-0.3	-0.3	-0.3	0.3	0.3	0	0	0	0.3	-0.3	-0.3	-0.3	0.3	-0.3	0	0	0	0.3	-0.3	0.3	0.3	0.3	-0.3	-0.3	-0.3	0.3	0	0	0
	-0.3	-0.3	-0.3	0.3	0.3	0.3	0	0	0	0.3	-0.3	-0.3	-0.3	0.3	0.3	-0.3	0.3	0.3	-0.3	0.3	-0.3	0.3	-0.3	0.3	0	0	0	0.3	0.3	-0.3	0	0	0	0.3	0.3	-0.3
0.4	0	0	0	-0.4	-0.4	-0.4	0.4	0.4	0.4	0	0	0	-0.4	0.4	0.4	0.4	-0.4	-0.4	0	0	0	-0.4	0.4	-0.4	0.4	-0.4	0.4	0	0	0	0.4	0.4	-0.4	0.4	0.4	-0.4
	0.4	0.4	0.4	0	0	0	-0.4	-0.4	-0.4	-0.4	0.4	0.4	0	0	0	0.4	-0.4	-0.4	-0.4	0.4	-0.4	0	0	0	0.4	-0.4	0.4	0.4	0.4	-0.4	-0.4	-0.4	0.4	0	0	0
	-0.4	-0.4	-0.4	0.4	0.4	0.4	0	0	0	0.4	-0.4	-0.4	-0.4	0.4	0.4	-0.4	0.4	0.4	-0.4	0.4	-0.4	0.4	-0.4	0.4	0	0	0	0.4	0.4	-0.4	0	0	0	0.4	0.4	-0.4
0.5	0	0	0	-0.5	-0.5	-0.5	0.5	0.5	0.5	0	0	0	-0.5	0.5	0.5	0.5	-0.5	-0.5	0	0	0	-0.5	0.5	-0.5	0.5	-0.5	0.5	0	0	0	0.5	0.5	-0.5	0.5	0.5	-0.5
	0.5	0.5	0.5	0	0	0	-0.5	-0.5	-0.5	-0.5	0.5	0.5	0	0	0	0.5	-0.5	-0.5	-0.5	0.5	-0.5	0	0	0	0.5	-0.5	0.5	0.5	0.5	-0.5	-0.5	-0.5	0.5	0	0	0
	-0.5	-0.5	-0.5	0.5	0.5	0.5	0	0	0	0.5	-0.5	-0.5	-0.5	0.5	0.5	-0.5	0.5	0.5	-0.5	0.5	-0.5	0.5	-0.5	0.5	0	0	0	0.5	0.5	-0.5	0	0	0	0.5	0.5	-0.5
0.6	0	0	0	-0.6	-0.6	-0.6	0.6	0.6	0.6	0	0	0	-0.6	0.6	0.6	0.6	-0.6	-0.6	0	0	0	-0.6	0.6	-0.6	0.6	-0.6	0.6	0	0	0	0.6	0.6	-0.6	0.6	0.6	-0.6
	0.6	0.6	0.6	0	0	0	-0.6	-0.6	-0.6	-0.6	0.6	0.6	0	0	0	0.6	-0.6	-0.6	-0.6	0.6	-0.6	0	0	0	0.6	-0.6	0.6	0.6	0.6	-0.6	-0.6	-0.6	0.6	0	0	0
	-0.6	-0.6	-0.6	0.6	0.6	0.6	0	0	0	0.6	-0.6	-0.6	-0.6	0.6	0.6	-0.6	0.6	0.6	-0.6	0.6	-0.6	0.6	-0.6	0.6	0	0	0	0.6	0.6	-0.6	0	0	0	0.6	0.6	-0.6
0.7	0	0	0	-0.7	-0.7	-0.7	0.7	0.7	0.7	0	0	0	-0.7	0.7	0.7	0.7	-0.7	-0.7	0	0	0	-0.7	0.7	-0.7	0.7	-0.7	0.7	0	0	0	0.7	0.7	-0.7	0.7	0.7	-0.7
	0.7	0.7	0.7	0	0	0	-0.7	-0.7	-0.7	-0.7	0.7	0.7	0	0	0	0.7	-0.7	-0.7	-0.7	0.7	-0.7	0	0	0	0.7	-0.7	0.7	0.7	0.7	-0.7	-0.7	-0.7	0.7	0	0	0
	-0.7	-0.7	-0.7	0.7	0.7	0.7	0	0	0	0.7	-0.7	-0.7	-0.7	0.7	0.7	-0.7	0.7	0.7	-0.7	0.7	-0.7	0.7	-0.7	0.7	0	0	0	0.7	0.7	-0.7	0	0	0	0.7	0.7	-0.7
0.8	0	0	0	-0.8	-0.8	-0.8	0.8	0.8	0.8	0	0	0	-0.8	0.8	0.8	0.8	-0.8	-0.8	0	0	0	-0.8	0.8	-0.8	0.8	-0.8	0.8	0	0	0	0.8	0.8	-0.8	0.8	0.8	-0.8
	0.8	0.8	0.8	0	0	0	-0.8	-0.8	-0.8	-0.8	0.8	0.8	0	0	0	0.8	-0.8	-0.8	-0.8	0.8	-0.8	0	0	0	0.8	-0.8	0.8	0.8	0.8	-0.8	-0.8	-0.8	0.8	0	0	0
	-0.8	-0.8	-0.8	0.8	0.8	0.8	0	0	0	0.8	-0.8	-0.8	-0.8	0.8	0.8	-0.8	0.8	0.8	-0.8	0.8	-0.8	0.8	-0.8	0.8	0	0	0	0.8	0.8	-0.8	0	0	0	0.8	0.8	-0.8
0.9	0	0	0	-0.9	-0.9	-0.9	0.9	0.9	0.9	0	0	0	-0.9	0.9	0.9	0.9	-0.9	-0.9	0	0	0	-0.9	0.9	-0.9	0.9	-0.9	0.9	0	0	0	0.9	0.9	-0.9	0.9	0.9	-0.9
	0.9	0.9	0.9	0	0	0	-0.9	-0.9	-0.9	-0.9	0.9	0.9	0	0	0	0.9	-0.9	-0.9	-0.9	0.9	-0.9	0	0	0	0.9	-0.9	0.9	0.9	0.9	-0.9	-0.9	-0.9	0.9	0	0	0
	-0.9	-0.9	-0.9	0.9	0.9	0.9	0	0	0	0.9	-0.9	-0.9	-0.9	0.9	0.9	-0.9	0.9	0.9	-0.9	0.9	-0.9	0.9	-0.9	0.9	0	0	0	0.9	0.9	-0.9	0	0	0	0.9	0.9	-0.9
Σ	0	0	0	-4.5	-4.5	-4.5	4.5	4.5	4.5	0	0	0	-4.5	4.5	4.5	4.5	-4.5	-4.5	0	0	0	-4.5	4.5	-4.5	4.5	-4.5	4.5	0	0	0	4.5	4.5	-4.5	4.5	4.5	-4.5
	4.5	4.5	4.5	0	0	0	-4.5	-4.5	-4.5	-4.5	4.5	4.5	0	0	0	4.5	-4.5	-4.5	-4.5	4.5	-4.5	0	0	0	4.5	-4.5	4.5	4.5	4.5	-4.5	-4.5	-4.5	4.5	0	0	0
	-4.5	-4.5	-4.5	4.5	4.5	4.5	0	0	0	4.5	-4.5	-4.5	-4.5	4.5	4.5	-4.5	4.5	4.5	-4.5	4.5	-4.5	4.5	-4.5	4.5	0	0	0	4.5	4.5	-4.5	0	0	0	4.5	4.5	-4.5

ISSN (online): 2581-3048
Volume 5, Issue 1, pp 20-39, January-2021
https://doi.org/10.47001/IRJIET/2021.501004

IV. CONCLUSION

In this paper a MATLAB code was developed for the analysis of some deformations that magnetic shape memory materials can suffer when they are in cantilever conditions and to visualize the components of the strain tensor as the deformation is presented and above all to be able to speculate on its possible behavior as various parameters change such as the radius of curvature, direction of the magnetic field, the Poisson's ratio and dimensions of the sample. The code developed and presented in Appendix I achieves the above.

It is worth mentioning that the high anisotropy of shape memory materials involves a variation in their behavior depending on the direction of analysis, as well as the variation in certain properties such as Poisson's ratio, which obviously cannot be considered constant, but which in the present work was considered a value equal to 0.33 since it is a value that appears frequently in some alloys with magnetic shape memory, see [19].

The incorporation of experimental information in the code, such as the dimensions of the sample or the radius of curvature measured directly and presented in Appendix II, allows data generation for the development of semi-empirical models that can increasingly approximate the behavior of these materials. This can be corroborated in Tables 2, 3 and 4, the data on the variation of the strain tensor allows us to see that in the case of 90º this tensor has components with values greater than those of the other two directions. This initially assumes that the sample will experience greater deflection and possibly greater recovery once the magnetic field is removed, and this is verified in image 5.

Table 6 has the objective of generating the widest amount of data on the variation of the tensor that represents the plastic part, for different slip systems. The slip systems used in the simulation correspond to the most studied for these alloys. Once the information on the elastic behavior (strain tensor) and the plastic part has been obtained, expression 10 can be used to be able to have a global representation of the tensor field that is generated with the total deformation of the material. In this first work, the need to generate as much data as possible about the shape of these two tensors has been prioritized. In later work, priority will be given to finding both the maximum and minimum forms of these tensors, as well as the possible slip systems and magnetic field directions that generate them.

Finally, from the images obtained in Appendix III, it is possible to verify the elasto-plastic character of the deformation suffered by the Ni-Mn-Ga alloy once it has been subjected to the magnetic field and it has been removed. The empirical evidence and the results of the simulation allow to raise, at least hypothetically, the assumption that the behavior of these materials can be analyzed as a composition of two processes, one elastic (or pseudoelastic) in which experimental information such as radius of curvature and dimensions of the samples can be used and one purely plastic (reversible), which considers relevant information of the crystalline structure such as planes, directions and lattice parameters.

REFERENCES

[1] L.D. Landau & E.M. Lifshitz. Theory of Elasticity (Volume 7 of A Course of Theoretical Physics) Pergamon Press (1963).

[2] Charles A. Wert. Physics of solids. International Student Edition (1964).

[3] Morton E. Gurtin. An introduction to continuum mechanics. Mathematics in science and engineering, vol 158. (1981).

[4] K. Ullakko, J.K Huang, C. Kantner, R.C. O`Handley, and V.V. Kokorin “Large magnetic-field-induce strains in Ni2MnGa single crystals” in applied Physics letters, vol. 69, no. 13, (1996)

[5] M. E. Gurtin. The Mechanics and Thermodynamics of Continua (pages 583-640). Carnegie Mellon University, Pennsylvania (2010).

[6] M. E. Gurtin. & B. D. Reddy. Some issues associated with the intermediate space in single crystal plasticity. Journal of the mechanics and physiscs of solids 95 (2015).

[7] R. J. Asaro. Crystalplasticity. Journal of applied Mechanics. Vol 50. (921-934). (1983)

[8] A. Rothenbuhler, E. Barney, P. Müllner. “Application of image processing to track twin boundary motion in magnetic shape memory alloys” SPIE-IS&T, (2012).

[9] J. K. Nikole, C. L. Patrick & P. Mullner. Magnetic field induced bending and straining of NiMnGa single crystals beams with high aspect ratios. Acta Materialia 95 (284-290). (2015).

[10] YoshiakiTani, TakashiTodaka, Masato. E. “Development of an engineering model for ferromagnetic shape memory alloys” Journal of Magnetism and magnetic Materials (2008).

[11] Dimitris C. Lagoudas, Bjoern Kiefer “Constitutive modeling of magnetic shape memory alloys with magneto-mechanical coupling” 6th International Symposium on Advanced Composites. Cortu, Greece. (2007).

[12] A. Hubert, N. Calchond, Y. Le Gorrec, J-Y. Gauthier “Magnetic shape memory alloys as smart materials for micro-positioning devices” Advances Electromagnetics Symposium, Telecom Paristech, Paris, France (2012).

ISSN (online): 2581-3048
Volume 5, Issue 1, pp 20-39, January-2021
https://doi.org/10.47001/IRJIET/2021.501004

[13] R. Tickle and R.D. James "Magnetic and magnetomechanical properties of Ni2MnGa" Journal of the Magnetism and Magnetics Materials, vol, 195, (1999).
[14] A. DeSimone and R.D. James "A constrained theory of magneto-elasticity" Journal of the Mechanics and Physics of solids, vol, 50, no.2. (2002).
[15] P. Mûllner, V. Chernenko, and G. Kostorz "A microscopi approach to the magnetic-field-induced deformation of martensite (magneto plasticity)" Journal of the Magnetism and Magnetics Materials, vol. 267, (2003).
[16] R. Ahluwalia, T. Lookman, and A. Saxena "Dynamic strain loading of cubic to tetragonal martensites" Actamateralia, vol. 54 (2006).
[17] N.N. Sarawate and M.J. Dapino "A continuum thermodynamics model for the sensing affect in ferromagnetic shape memory NiMnGa" Journal of applied physics, (2007).
[18] J.Y. Gauthier, C. Lexcellent, A. Hubert, J. Abadie, and N. Chaillet "Modeling rearrangement process of martensite platelets in a magnetic shape memory alloy Ni2MnGa single crystal under magnetic field and (or) stress action" Journal of intelligent Material Systems and structures, vol. 18, (2007).
[19] S. Rajasekhara, P. J. Ferreira. "A dislocation model for the magnetic field induced shape memory effect in Ni2MnGa" Scriptamaterialia, (2005)
[20] S. Bohua. "On plastic dislocation density tensor" ResearchGate, (2018).
[21] S. Kweon, D. Raja. "Investigation of the mechanical response of single crystal magnesium considering slip and twin" International Journal of Plasticity, (2018).
[22] K. C. Le, "Three dimensional continuum dislocation theory" Intenational Journal Of Plasticity, (2015).
[23] J. Hernández Calderón. Caracterización experimental del movimiento de una barra de material con memoria de forma magnética en campos magnéticos variables y consecuentes desarrollos teóricos. PhD thesis. (2019). UNAM.
[24] J. Hernández, P. Mullner, P. Linquist, and J. Carrera, Experimental Characterization of Geometric Aspects of the Behavior of Magnetic Shape Memory Materials and Theoretical Interpretation, European Journal of Engineering Research and Science, Vol. 4 (2019) No. 3.
[25] L. Straka et al, Highly mobile twinned interface in 10 M modulated Ni–Mn–Ga martensite: Analysis beyond the tetragonal approximation of lattice, 2011 acta materialia 59
[26] L. Straka et al, Twin interaction and large magnetoelasticity

Appendix I: MATLAB code and Simulations

```
classdefElasto_Plastic<matlab.apps.AppBase

    % Properties that correspond to app components
    properties (Access = public)

    %Properties that correspond to app variables
    properties (Access = private)
        Property % Description
        PlasticMatrix=zeros(3);    %Platic Matrix
        ElasticMatrix=zeros(3);    %Elastic Matrix
        Iterations=0;              %Iteration Value
        it=1;                      %Iteration Label value
        DCF=zeros(3);              %Dimensional Correction
        Factor
        U=sym(['0','0' ,'0']);     %Vector U
        GU=sym(zeros(3));          %Gradient of U
        GLV=0;
    End

    % Callbacks that handle component events
    methods (Access = private)

        % Code that executes after component creation
        function startupFcn(app)
            %Stablish de Identity Matrix for the Dimensional
            Correction
            %Factor
            app.tblCB.Data =  eye(3);
        end

        % Value changed function: cbxCB
        function cbxCBValueChanged(app, event)
            %Allows to enable the change of the Dimensional
            Correction
            %Factor
            if app.cbxCB.Value==true
                app.tblCB.Enable = 'on';
            else
                app.tblCB.Enable = 'off';
            end
        end

        % Button pushed function: btnIteration
        function btnIterationButtonPushed(app, event)
            %Change the current selected tab
            app.tbdPlastic.SelectedTab=app.SummationTab;
            %Set the number of iterations
            app.Iterations=app.txtIIteration.Value;
            app.lblnumber.Text=num2str(app.it);
```

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

```
    %Set the dimensional correctio factor Matrix
    app.DCF=app.tblCB.Data;
    %Change the enable status of the buttons
    app.btnIteration.Enable=false;
    app.btnSumCal.Enable=true;
end

% Button pushed function: btnSumCal
function btnSumCalPushed(app, event)
    %Create the variables
    TensorialProduct=zeros(3);  %Tensorial Matrix
    R=zeros(3);             %Result Matrix
    gamma=app.Gamma.Value;      %Gamma
    %Vector M & S
    VectorM=[app.Mx.Valueapp.My.Valueapp.Mz.Val
    ue];
    VectorS=[app.Sx.Valueapp.Sy.Valueapp.Sz.Value];
    %Calculate the Tensorial product of M & S,
    Gamma times
    %Tensorial Produt, and save add it to the plastic
    matrix
    for i=1:3
        for j=1:3
            TensorialProduct(i,j)=VectorS(i)*VectorM(j
            );
            R(i,j)=TensorialProduct(i,j)*gamma;
            app.PlasticMatrix(i,j) =
            app.PlasticMatrix(i,j)+R(i,j);
        end
    end

    %Show the obtain values
    app.tblTensorialProduct.Data=TensorialProduct;
    app.tblTPTimesGamma.Data=R;
    app.tblSummation.Data=app.PlasticMatrix;
    %Check the remaining number of iteration
    if app.Iterations==1
        %The iteration loop has finished then:
        %Change the enable status in all the
        components of the
        %window
        app.btnSumCal.Enable=false;
        app.btnSumNext.Enable=true;
        app.Sx.Enable=false;
        app.Sy.Enable=false;
        app.Sz.Enable=false;
        app.Mx.Enable=false;
        app.My.Enable=false;
        app.Mz.Enable=false;
        app.Gamma.Enable=false;
    else
        %Update the iteration values
        app.Iterations = app.Iterations-1;
        app.it=app.it+1;
        app.lblnumber.Text=num2str(app.it);%Iteration
        Label Value
        %The iteration loop remains
        %Reset the values of gamma , vector S & M.
        app.Sx.Value=0;
        app.Sy.Value=0;
        app.Sz.Value=0;
        app.Mx.Value=0;
        app.My.Value=0;
        app.Mz.Value=0;
        app.Gamma.Value=0;
    end
end

% Button pushed function: btnSumNext
function btnSumNextButtonPushed(app, event)
    %Change the current selected tab
    app.tbdPlastic.SelectedTab=app.IterationTab;
    %Change the enable status of the window items
    app.btnSumNext.Enable=false;
    app.btnNext_It.Enable=true;
    app.tblCB.Enable='off';
    app.cbxCB.Enable=false;
    app.txtIIteration.Enable=false;
    %Calculate the plastic matrix
    app.PlasticMatrix = ((app.DCF^-
    1)*app.PlasticMatrix)*app.DCF;
    %Show the plastic matrix
    app.tblPlastic.Data=app.PlasticMatrix;
end

% Button pushed function: Elastic_Cal
function Elastic_CalButtonPushed(app, event)
    try
        %Store the values for the Vector U, entered by
        the user
        app.U =
        [str2sym(app.Ux.Value);str2sym(app.Uy.Value)
        ;
        str2sym(app.Uz.Value)];
        syms x y z;%Create the variables for the
        symbolic calculus
        %Calculate the gradiant for Vector U
        for i=1:3
            var=['x' 'y' 'z'];
            for j=1:3
                app.GU(i,j)=diff(app.U(i),var(j));
            end
        end

        %Evaluate the gradient, with user-entered
        values.
```

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

```
        app.GU=subs(app.GU,{x,y,z},{app.Xval.Value,
        app.Yval.Value, ...
        app.Zval.Value});
        app.GU=double(app.GU);
        %Sum the gradiant matrix and its transposed
        FinalU=app.GU+app.GU';
        %Obtain the elastic Matrix
        app.ElasticMatrix=0.5.*FinalU;
        %Show the calculated matrixes
        app.tblGu.Data=app.GU;
        app.tblGu_Eval.Data=FinalU;
        app.tblElastic.Data=app.ElasticMatrix;
        %Change the enable status of the buttons of the
        window
        %app.Elastic_Cal.Enable=false;
        app.Elastic_Next.Enable=true;
    catch ME
        %The program enter's here if there's an error
        if
        strcmp(ME.identifier,'symbolic:kernel:Division
        ByZero')
            %Division by zero error
            warndlg('Division by zero','Error');
        elseif
        strcmp(ME.identifier,'MATLAB:badsubscript')
            %Empty Vector U error
            warndlg('Please, fill all the parameters for
            vector U','Error');
        elseif
        strcmp(ME.identifier,'MATLAB:UnableToCon
        vert')||strcmp( ...
            ME.identifier,'symbolic:str2sym:UnableToC
            onvert')
            %Syntax Error
            warndlg('Syntax Error. Please check the
            function','Error');
        end
    end
end

% Button pushed function: btnNext_It
function btnNext_ItButtonPushed(app, event)
    %Change the current tab
    app.TabGroup.SelectedTab=app.ElasticTab;
    %Change the enable status of the buttons
    app.btnNext_It.Enable=false;
    app.Elastic_Cal.Enable=true;
end

% Button pushed function: Elastic_Next
function Elastic_NextButtonPushed(app, event)
    %Change the current tab
    app.TabGroup.SelectedTab=app.ResultTab;
    %change the enable status ob the elastic tab
    components
    app.Elastic_Next.Enable=false;
    app.Ux.Enable=false;
    app.Uy.Enable=false;
    app.Uz.Enable=false;
    app.Xval.Enable=false;
    app.Yval.Enable=false;
    app.Zval.Enable=false;
    %Enable the graph button
    app.btnGraph.Enable=true;
    %Show in the final tab the elastic and plastic
    matrixes, and
    %the sum of this two
    app.tblFinalPlasticValue.Data=app.PlasticMatrix;
    app.tblFinalElasticValue.Data=app.ElasticMatrix;
    app.tblFinalMatrix.Data=app.ElasticMatrix+app.Pla
    sticMatrix;
end

% Button pushed function: PlotButton
function PlotButtonPushed(app, event)
    x=0:0.1:1; %Create Vector X & Z
    z=0:0.1:1;
    R=app.REditField.Value; %Get the ratio value
    for i=1:1:11 %Calculate the new X values
        z(i)=-(x(i)^2/(2*R));
    end
    %Plot the ratio
    plot(app.CurvatureAxes,x,z,'DisplayName',strcat('R
    =',num2str(R)));
    %Show th legend
    legend(app.CurvatureAxes,'show','Location','south
    west');
    %Re-size the plot if required
    if(z(11)<app.GLV)
    %If the new graph's lower value its lower than the
    previous one
        app.GLV=z(11); %Update de value.
    end
    axis(app.CurvatureAxes,[0 1 app.GLV 0.20]);
end

% Value changed function: HoldPlotSwitch
function HoldPlotSwitchValueChanged(app, event)
%Hold the ratio Plot
value = app.HoldPlotSwitch.Value;
hold(app.CurvatureAxes,lower(value));
end
end
```


International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

```
    % Component initialization
    methods (Access = private)
    % App creation and deletion
    methods (Access = public)
end
```

Appendix II. Experimental bending strain data

Bending strain can be calculated by relating some parameters of the dimensions of the specimen and the radius of curvature observed. The bending strain can be calculated as follows:

$$\varepsilon_B = \frac{d * k}{2}$$

Where:

d = width of the sample
k = 1/R, where R represents the radius of curvature

The image analysis of about 3000 photos with a MATLAB code provided by **Boise State University**, Idaho, was done, the variation of bending strain was analyzed throughout the experiment and the degree of recovery of the material after reaching the maximum deformation and remove the magnetic field gradually. The following experimental data was obtained.

Table 7: Bending strain (ε_B) vs Magnetic Field (T), Θ = 45°

Bending strain (ε_B)	Magnetic Field (T)	K (mm)
-0.25	0.1	1
-0.67	0.2	2.68
-1.29	0.3	5.16
-1.49	0.4	5.96
-1.56	0.5	6.24
-1.87	0.6	7.48
-2.26	0.7	9.04
-2.49	0.8	9.96
-2.7	0.9	10.8
-2.93	1	11.72
-3.02	1.1	12.08
-3.2	1.2	12.8

Table 8: Bending strain (ε_B) vs Magnetic Field (T), Θ = 45°(removing the field)

Bending strain (ε_B) Back	Magnetic Field (T)	K (mm)
-2.18	0.1	8.72
-2.41	0.2	9.64
-2.6	0.3	10.4
-2.72	0.4	10.88
-2.69	0.5	10.76
-2.83	0.6	11.32
-2.93	0.7	11.72
-3.05	0.8	12.2
-3.19	0.9	12.76
-3.14	1	12.56
-3.23	1.1	12.92
-3.2	1.2	12.8

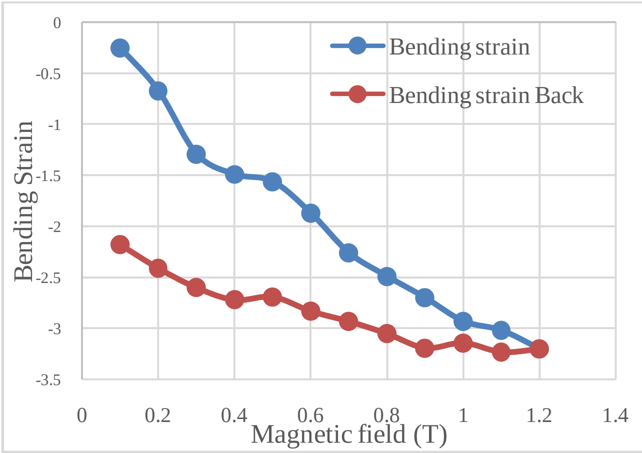

Figure 7: Bending strain and bending strain back, Θ = 45o

Table 9: Bending strain (ε_B) vs Magnetic Field (T), Θ = 90°

Bending strain (ε_B)	Magnetic Field (T)	K (mm)
-0.92	0.1	3.68
-3.96	0.2	15.84
-3.67	0.3	14.68
-3.7	0.4	14.8
-3.28	0.5	13.12
-3.49	0.6	13.96
-3.54	0.7	14.16
-3.25	0.8	13
-3.47	0.9	13.88
-2.82	1	11.28
-2.66	1.1	10.64
-2.84	1.2	11.36

ISSN (online): 2581-3048
Volume 5, Issue 1, pp 20-39, January-2021
https://doi.org/10.47001/IRJIET/2021.501004

Table 10: Bending strain (ε_B) vs Magnetic Field (T), Θ = 90°(removing the field)

Bending strain (ε_B) Back	Magnetic Field (T)	K (mm)
-2.7	0.1	10.8
-2.72	0.2	10.88
-2.92	0.3	11.68
-2.85	0.4	11.4
-2.86	0.5	11.44
-2.61	0.6	10.44
-2.79	0.7	11.16
-2.7	0.8	10.8
-2.73	0.9	10.92
-2.85	1	11.4
-2.85	1.1	11.4
-2.84	1.2	11.36

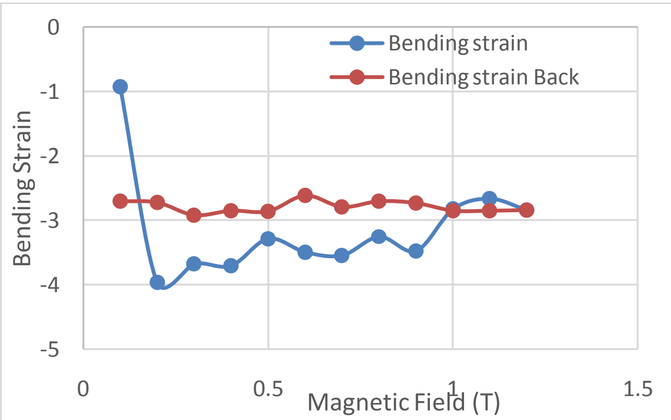

Figure 8: Bending strain and bending strain back, Θ = 90°

Table 11: Bending strain (ε_B) vs Magnetic Field (T), Θ = 135°

Bending strain (ε_B)	Magnetic Field (T)	K (mm)
-0.25	0.1	1
-0.19	0.2	0.76
-0.16	0.3	0.64
-0.04	0.4	0.4
0.19	0.5	0.76
1.19	0.6	4.76
1.96	0.7	7.84
2.29	0.8	9.16
2.47	0.9	9.88
2.67	1	10.68
2.7	1.1	10.8
2.82	1.2	11.28

Table 12: Bending strain (ε_B) vs Magnetic Field (T), Θ = 135° (removing the field)

Bending strain (ε_B) Back	Magnetic Field (T)	K (mm)
1.8	0.1	7.2
2.06	0.2	8.24
2.32	0.3	9.28
2.35	0.4	9.4
2.6	0.5	10.4
2.68	0.6	10.72
2.69	0.7	10.76
2.86	0.8	11.44
2.85	0.9	11.4
2.67	1	10.68
2.88	1.1	11.52
2.82	1.2	11.28

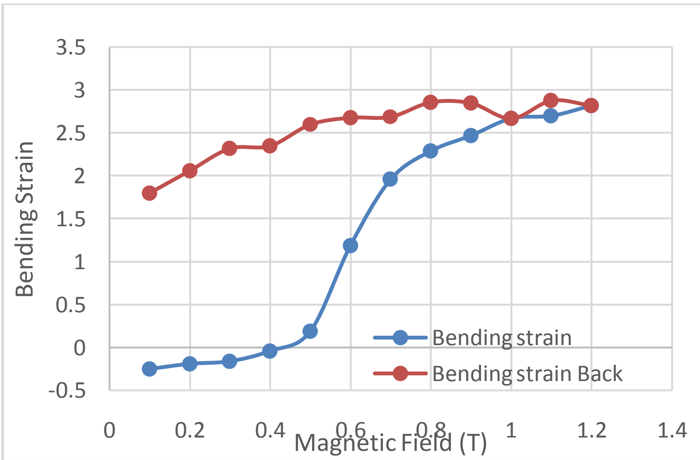

Figure 9: Bending strain and bending strain back, Θ = 135°

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

Appendix III a: Simulations for the variation of radius of curvature. Increasing magnetic field

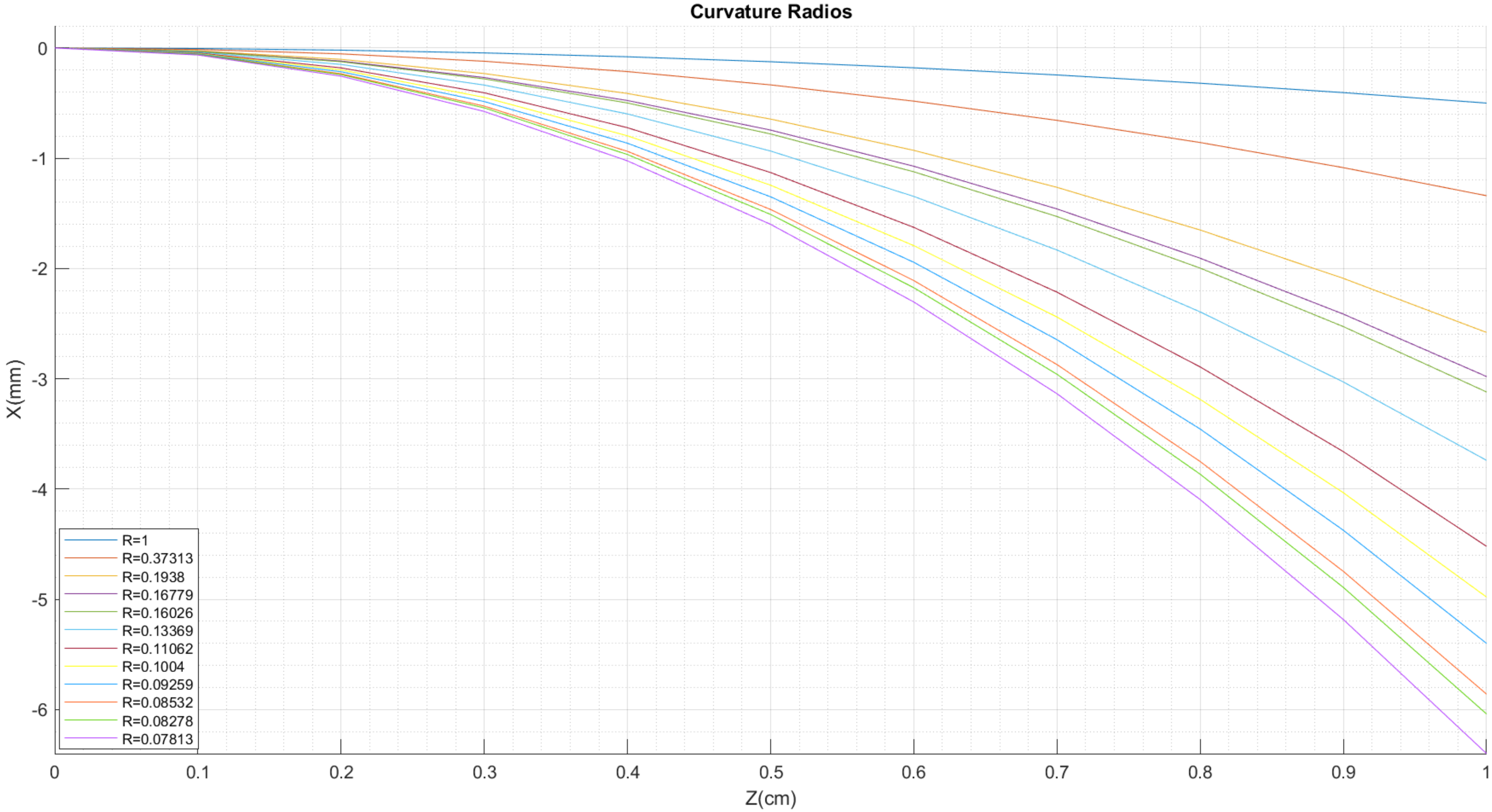

Figure 10: Variation of radius of curvature at 45°

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

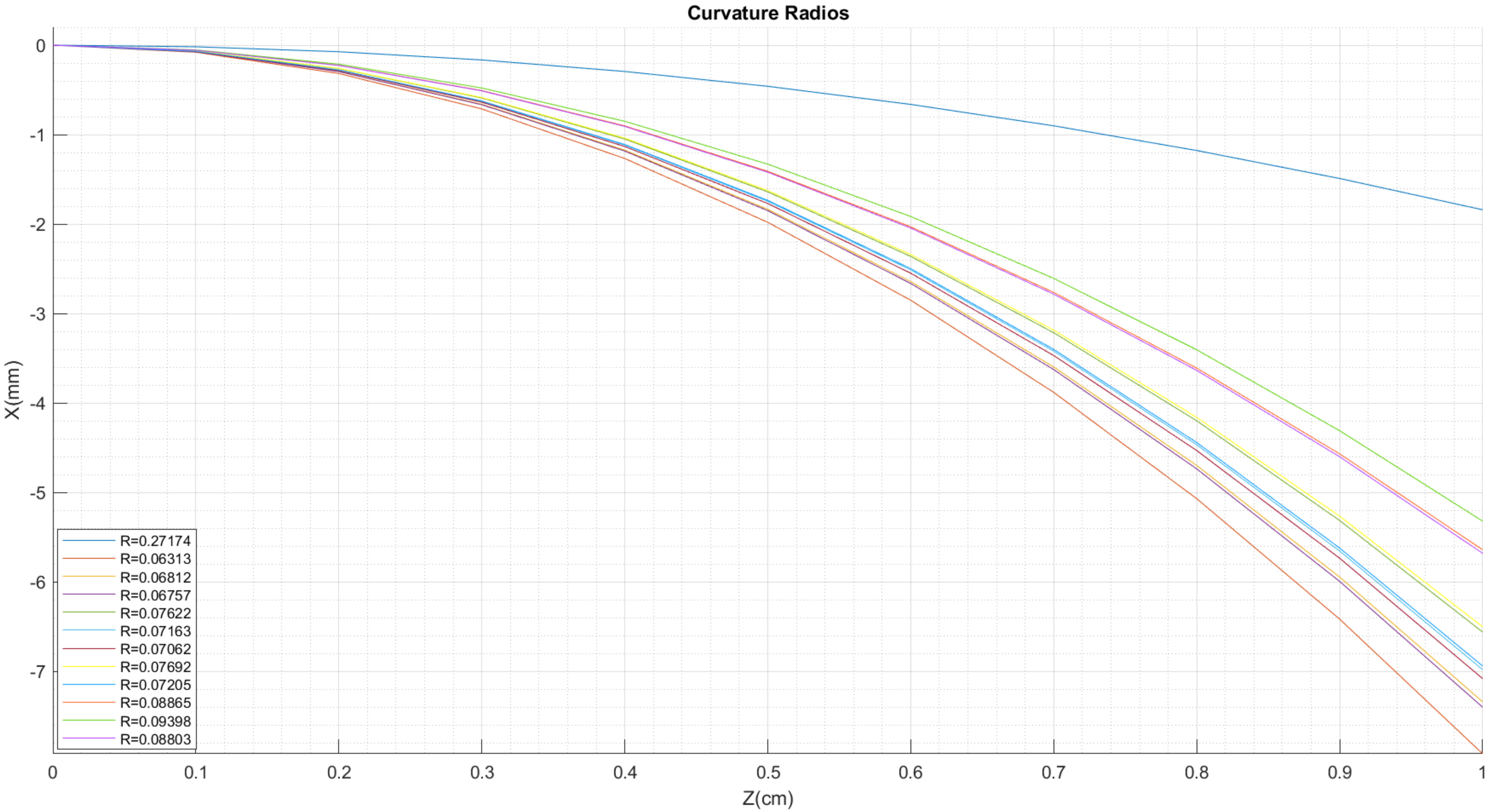

Figure 11: Variation of radius of curvature at 90°

International Research Journal of Innovations in Engineering and Technology (IRJIET)
ISSN (online): 2581-3048
Volume 5, Issue 1, pp 20-39, January-2021
https://doi.org/10.47001/IRJIET/2021.501004

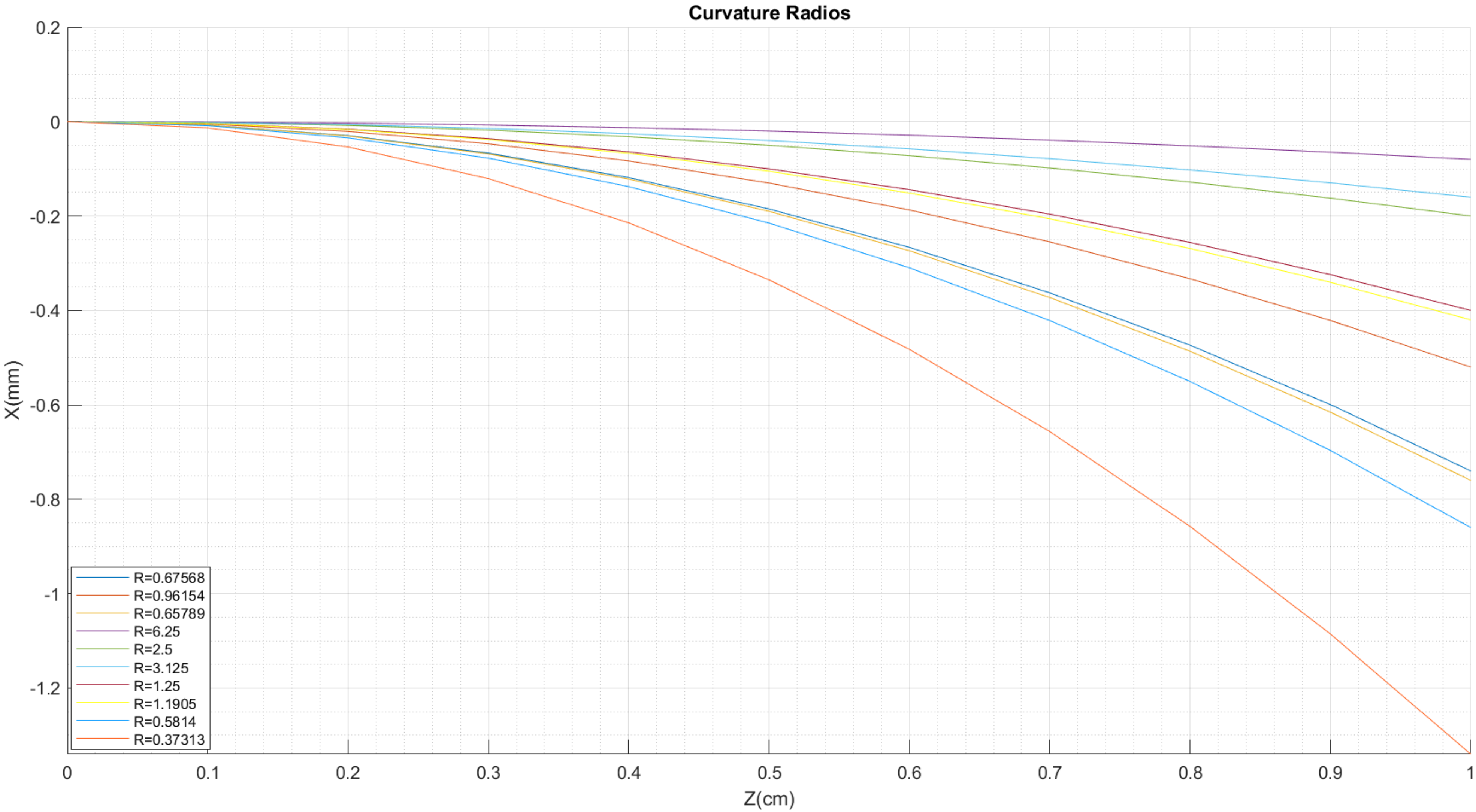

Figure 12: Variation of radius of curvature at 135º

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

Appendix III b: Simulations for the variation of radius of curvature. Decreasing magnetic field

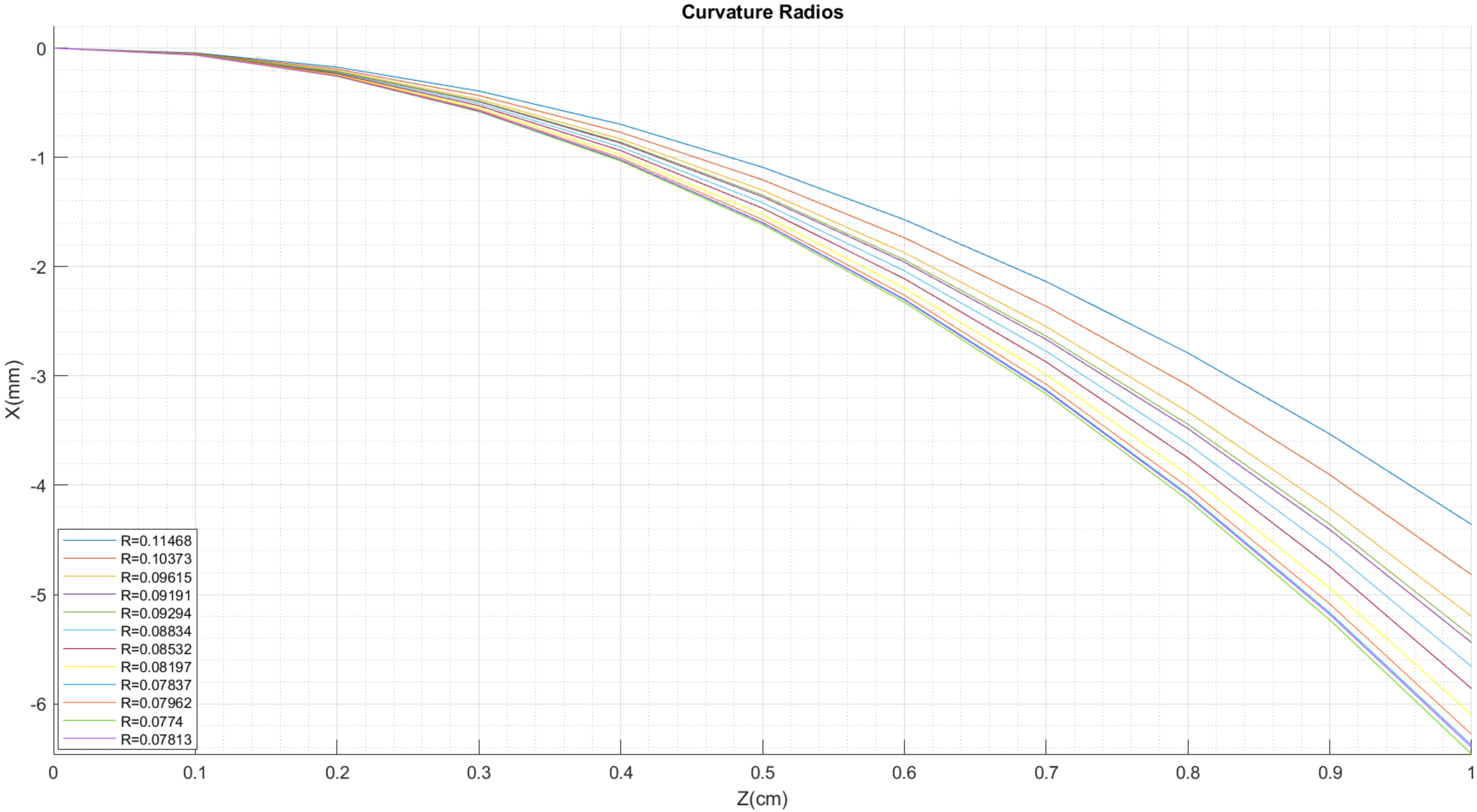

Figure 13: Variation of radius of curvature at 45°

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

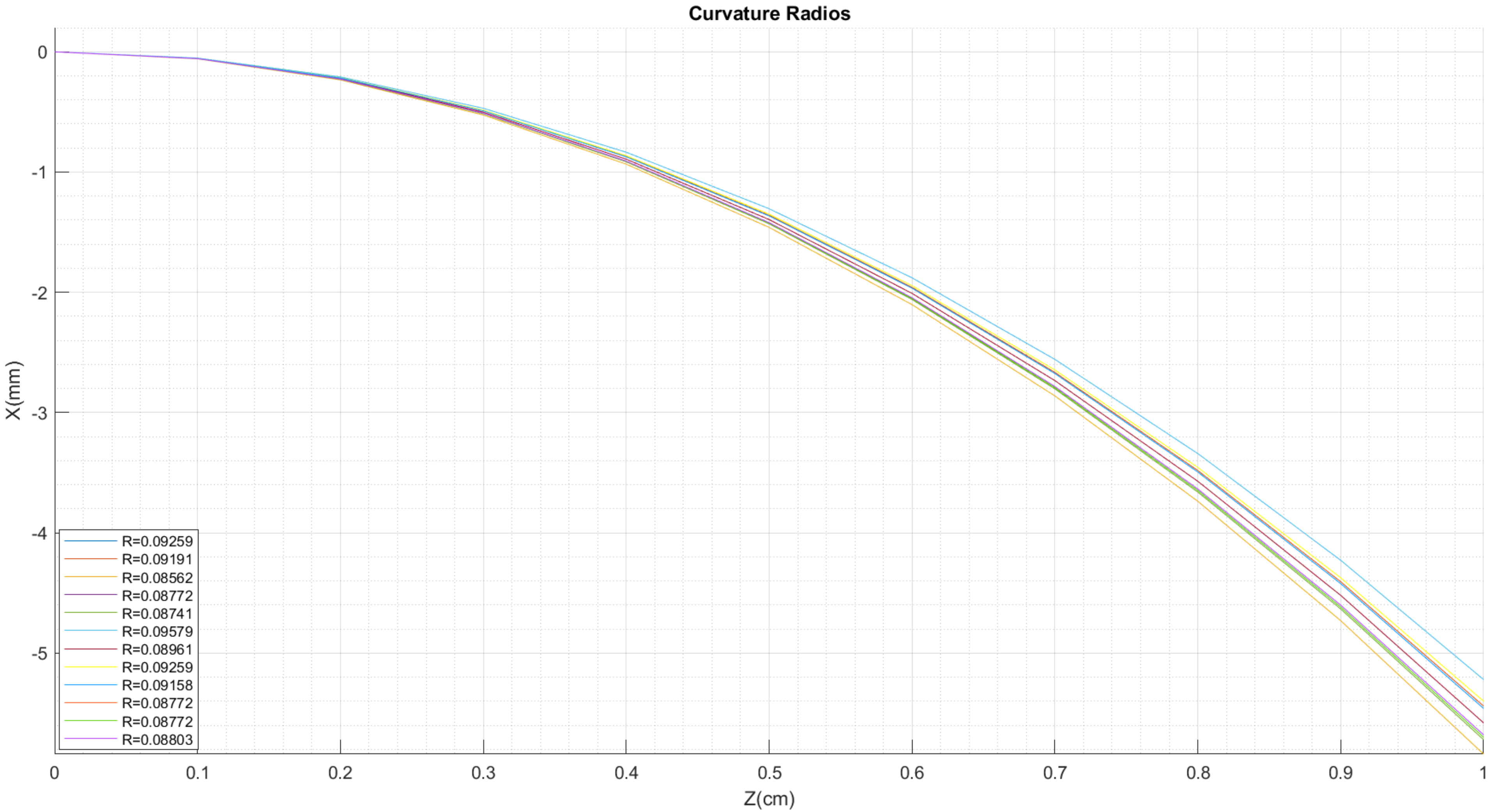

Figure 14: Variation of radius of curvature at 90°

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 5, Issue 1, pp 20-39, January-2021

https://doi.org/10.47001/IRJIET/2021.501004

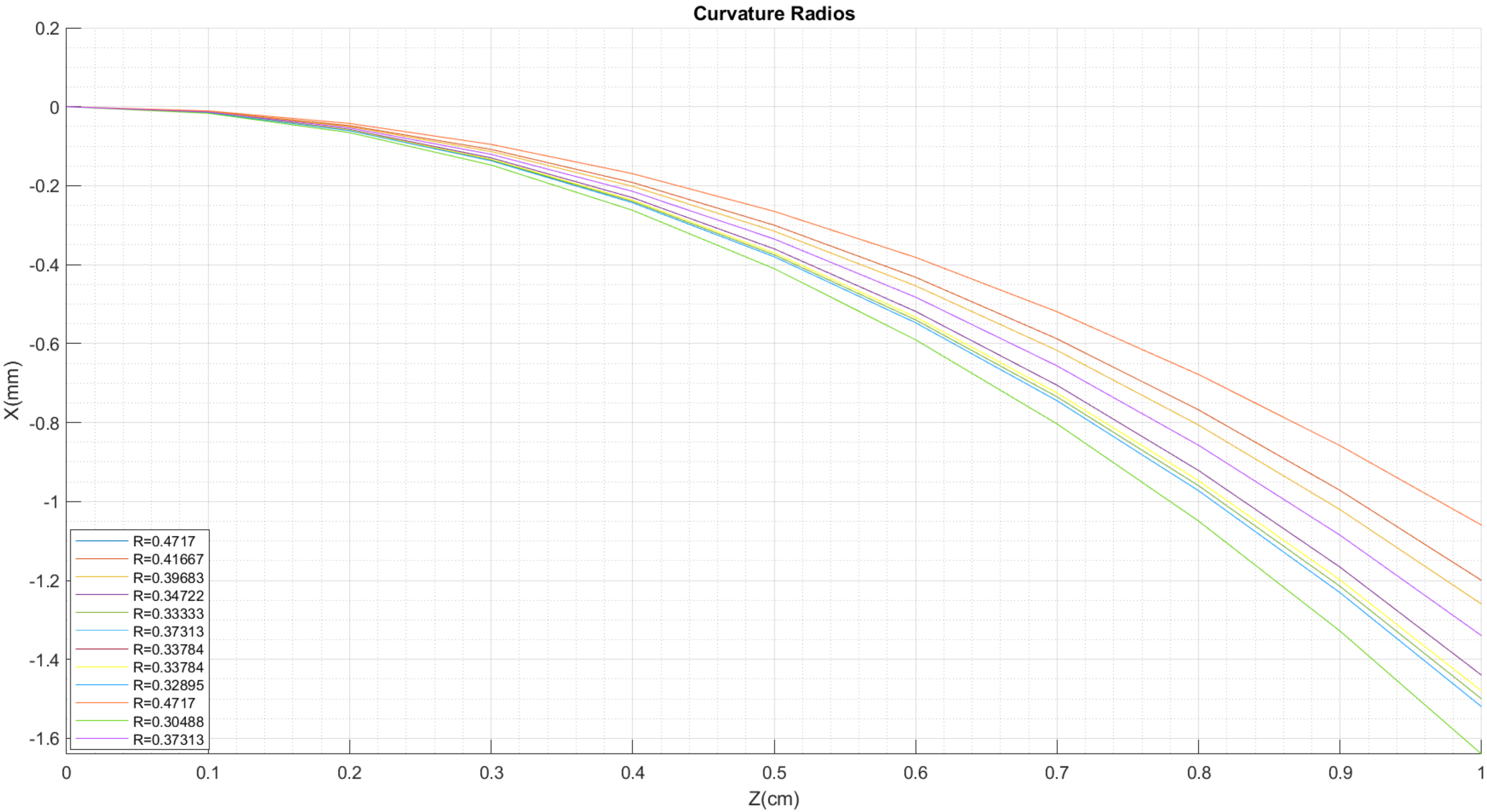

Figure 15: Variation of radius of curvature at 135º

ISSN (online): 2581-3048
Volume 5, Issue 1, pp 20-39, January-2021
https://doi.org/10.47001/IRJIET/2021.501004

AUTHOR'S BIOGRAPHIES

1st Author Photo	**Dr. Juan Hernandez Calderon** is a full-time professor focused on the study of materials with elastic properties and the mathematical modeling of stresses.
2nd Author Photo	**Luis Demetrio Herrera Cobos** is a mechatronics engineering student about to obtain his engineering degree.

Citation of this Article:

Juan Manuel Hernández Calderón, Luis Demetrio Herrera Cobos, "On the Use of a MATLAB for the Analysis of Some Deformations in Magnetic Shape Memory Materials" Published in *International Research Journal of Innovations in Engineering and Technology - IRJIET*, Volume 5, Issue 1, pp 20-39, January 2021. Article DOI https://doi.org/10.47001/IRJIET/2021.501004

****