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Influence of External Mechanical Stimulus on Response of Linked Structures Made from Lightweight Metals

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Authors' contributions

This work was carried out in collaboration between all authors. Author SS designed the study based on the desired objective, and the plan of approach to accomplish the objective. Author PPG managed the literature search and analyses of the study by performing numerical analysis. Author TSS examined the published literature, wrote and typed the first and revised drafts of the manuscript. All authors did read and approved the final manuscript.

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ABSTRACT

A progressive increase in interest in the use of linked metal structures has become increasingly evident in the time spanning the last three decades. These structures are gaining increasing attention and use in a spectrum of performance-related applications. This has certainly necessitated the need to study their mechanical response when subject to the influence of an external mechanical stimulus.Use of the finite element approach for purpose of analyzing the deformation response of linked structures when subject to loading, both in the elastic regime and plastic regime, was chosen for purpose of analysis. Simulation of the deformation behavior and/or response of structures containing a network of thin links and thick links were carefully studied. The approach was applied to two light-weight metals.The two light-weight metals chosen were an aluminum alloy and pure copper. For various levels of loading, as fractions of the yield load of the chosen metal, the analysis was computationally conducted using the finite element method.Results were carried out to

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study the variation of stress with strain under conditions of plane stress. The mechanical response quantified by displacement experienced by the centroidal nodes was recorded and compared using 3-D bar graphs for the chosen five load levels. The load levels chosen represent both the elastic regime and inelastic regime of the stress versus strain response of the chosen metal. This formulation is useful for purpose of studying the mechanical response of linked metal structures under the influence of an external mechanical stimulus.

Keywords: Linked structure; thick links; thin links; aluminum alloy; copper; finite element analysis; numerical computation; stress, deformation; displacements.

1. INTRODUCTION

Linked structures are an emerging configuration that is fast gaining the attention and approval of researchers for use in both performance-related and non-performance related structures that often find use in a spectrum of applications. The primary purpose of this study is to present the results of analyzing the behavior of linked structures when subjected to an external mechanical stimulus, such as, load and resultant mechanical deformation. This study provides the results obtained, with the aid of a numerical technique, when the linked structure is subjected to an external mechanical stimulus by way of tensile load or stress. In recent years, in a sizeable number of instances preferential use of linked structures in comparison to solid metal plates has gained increased attention due to their innate ability to offer light weight in conjunction with increased flexibility coupled with maneuverability. The existence and several benefits offered by linked metal structures has gained increased attention in their selection and preferential use for a wide spectrum of engineering applications. A linked structure consists of square perforations incorporated in a solid plate of the chosen metal.In combination with durability and ease of fabrication, that is characteristic of the family of lightweight metals belonging to the non-ferrous family, they do offer a combination of superior mechanical properties.With noticeable strides in the domain of design arising because of the emergence and use of computer aided design (CAD) in concurrence with the emergence of novel manufacturing techniques, linked metal structures, due to their superior combination of properties, are being widely chosen for use in a range of applications in the industries spanning, automotive, electrical and architecture. This has necessitated both the need and purpose of examining their response when under the influence of loading or external mechanical stimulus.The resultant response characteristics under the influence of an external stimulus will concurrently establish possible and potential failure modes and locations while also providing viable alternatives and situations for alteration in design of the structure for purpose of its selection and use in weight-critical applications.

In fact, adaptation of existing techniques coupled with concurrent improvement in strength and overall properties of the metals being developed and chosen for use in industries specific to mechanical engineering have led to both an emergence and incorporation of a wide variety of metal perforations that offer an interesting combination of geometry and physical appearance while concurrently ensuring performance that is commensurate with requirements.

Contemporary materials spanning the domain of metals have often been characterized by their complex structures at the fine microscopic kevel.One other viable alternatives to choosing linked metal structures is that in addition to both ease and accuracy in design, they are essentially light in weight, coupled with the innate capability to offer multi-functional properties to include the following: (a) high specific strength (σ_{UTS}/ρ), (b) high specific stiffness (E/ρ), (c) good load bearing capability, and (d) an acceptable level of heat dissipation in applications requiringheat transfer capability.Few research studies have been carried out and reported in the published literature on modeling of metal plates having differentdesignsas perforations.Few researchers [1,2] have put forth analytical results for both stresses and resultant displacements in perforated metal plates, which are being increasingly chosen for use in emerging practical applications. Results of these studies were made possible using the well-developed field equations for classical theory of elasticity.In an independent study, slot and co-workers [3], examined perforated metal plates and provided a viable solution for a perforated metal plate upon being subject to different types of loading, such as (i) edge loading, (ii) loading due to internal pressure, and (iii) uniform shear loading. These loading conditions were studied under conditions of plane stress.Yettram and coworkers [4] investigated use of the matrix stability method for purpose of analyzing elastic stability of metal plates. Also, the matrix stability method helped in predicting the buckling load, which was found to be helpful. A comprehensive review of the published literature revealed only few attempts to have been made to both examine and characterize the behavior of perforated metal plates and perforated metal sheets, or linked structures, by proposing methods to study both the stress and resultant deflection or deformation response [5-15]. Chen [16] derived and presented a theoretical model under conditions of yielding for studying and documenting both the deformation behavior and flow behavior of perforated metal sheets using finite element analysis.Their study provided a good agreement with experimental results for a structure that was assumed to be essentially isotropic and under conditions of plane stress. Through the years, several other researchers [17-26] have conducted both analytical and experimental research studies using the approach of conventional mechanical modeling for the purpose of investigating the behavior of perforated metal plates and perforated metal sheets, under conditions of uniaxial loading, for both the two-dimensional and three-dimensional cases using the finite element methodA yield criteria for perforated metal sheets having a triangular pattern with circular perforations coupled with a low ligament ratio was proposed by Lee and Chen [20]. In the decade of the 1990s Webb, Kormi and Co-workers [27] suggested a method for computing the effective elastic constants for a pattern of perforations by replacing a unit module with an overall module having the same dimension. Response of the replaced material must be identical to the overall module. Loading using a concentrated force at a specific node did generate a uniform distribution of pressure. Also, the stress that was developed both in and around the perforated area was visualized to be the case of stress intensification. Dobrzanski and co-workers [28] performed finite element simulation on cylindrical bars of aluminum when subject to tension and concluded that the tensile test could be safely used to both determine and study the stress and displacement field with the aid of finite element simulation. They made the conclusion since the results obtained from numerical simulation were in good agreement with experimental results obtained by other researchers.

In more recent tears, during the ongoing decade, use of the finite element analysis, as a powerful engineering tool, for designing and solving problems specific to structures and components and comprising of both linear-elastic analysis and elastic-plastic analysis gained increased attention and use.Dobrzanski and co-workers [28] provided an overview on the existence and preferential use of the finite element method (FEM) for purpose of analysis to have gained a strong base in a spectrum of industries pertinent and /or specific to mechanical engineering. Using advanced computational techniques, the arena of FEM has progressively developed and gradually been extended for use in a spectrum of emerging engineering applications. Thus, use of numerical techniques as a viable substitute to classical experimental testing has become both essential and prevalent. Further, it helps to lower the overall cost of analysis by eliminating the need for understanding the behavior, namely deformation-induced in linked metal structures having a network of links of different size, by way of experimental testing, using powerful finite element methods. Notable advantages of the finite element method are the following:

(i) It can be easily accessed and put to effective use even by small companies for studying and analyzing design parameters, and
(ii) Response of the different configurations when subject to either the influence of load or stress can be induced with relative ease.

To examine the role of stress and resultant deformation or strain gradients on material behavior, an attempt has been made to simplify the two-dimensional problem to ensure the prevalence of plane stress condition while concurrently investigating the influence of external mechanical stimulus such as loading on response of the structure. Furthermore, under condition if plastic flow the problem is treated numerically using the finite element method (FEM).

The primary purpose of this manuscript is to present and discuss the results of an investigation aimed at understanding the deformation that is induced in linked metal structures having a network of links of different thicknesses under conditions of both symmetric and asymmetric loading in uniaxial direction.

2. THE MATERIALS CHOSEN

Selection of a material is both an important and critical step in the prevailing era of modern technology, which is largely dependent on our innate capability of putting these materials to effective and efficient use.Materials chosen for both existing and emerging engineering applications was the focal point of this research study. Accordingly, two non-ferrous metals, namely an aluminum alloy and pure copper were two materials chosen for this study. The aluminum alloy chosen was 6061 in the T6 temper. The chemical composition of the two chosen metals is provided in Table 1 (above). These two light weight metals were chosen for studying the influence of an external mechanical stimulus, such as loading in the tensile direction, in inducing deformation in a structure that was essentially held together by a network of fine interconnected links.

The uniaxial tensile properties of the two chosen metals are summarized in in Table 2 [30].

3. BACKGROUND

3.1 Model Development

A 3-D model of the linked metals structure is shown in Fig. 1 and Fig. 2. In Fig. 1 is shown a pictorial view of the metal structure that is held together by a network of thin links while in Fig. 2 is shown a pictorial view of the metal structure that is held together by a network of thick links. The dimensions of the links in the appropriate structure are summarized in Table 3.

Finite element analysis (FEA) is a powerful tool, which is being increasingly used to both study and understand the basic aspects pertinent to modeling and numerical analysis of elements having a range of sizes. Currently, the analysis technique has grown significantly in the domains spanning complexity, flexibility and speed for use by design engineers located through a broad spectrum of industries. This analysis technique is now being considered as a novel method for the analysis of an unknown quantity, or quantities, by initially choosing a continuum, which is initially discretized into simple geometric shapes that are essentially finite in size. Hence, the technique was coined the name finite elements [FE]. Using material properties and governing relationships, which are considered for the chosen analysis elements, using a known set of loading and boundary conditions, results in a set of equations, which when solved does provide a comprehensive overview pertinent to behavior of the structure when under the influence of an external mechanical stimulus. Through the years, more so recently, the technique has gradually evolved to have proven itself to be effective in providing accurate results when the model is properly formulated.

Table 1. Nominal chemical composition of the two non-ferrous alloys chosen for this study (in weight percent)

Material	Si	Fe	Mn	Mg	Cr	Zn	Ti	Al	Cu
6061	0-4-0.8	0.7	0.15	0.8-1.2	0.04-0.35	0.25	0.15	Balance	0.15-0.4
Copper C-10100	-	-	-	-	-	-	-		99.95

Table 2. Uniaxial tensile properties of the two non-ferrous metal alloys chosen for this study

Material	Density	Elastic modulus		Tensile strength		Yield strength		Elongation in 50 mm	Poisson's Ratio
	g/cm^3	GPa	Psi	MPa	Ksi	MPa	Ksi	(%)	
C-10100	8.94	115	17E6	221-455	32-66	70-365	10-53	5-55	0.33
6061-T6	2.70	69	10E6	310	45	275	40	12-17	0.30

Table 3. Dimensions of the structure containing thin links and thick links

	Thin structure (mm)	Thick structure (mm)
Length	113.67	127.00
Breadth	76.84	86.36
Thickness	3.18	3.18

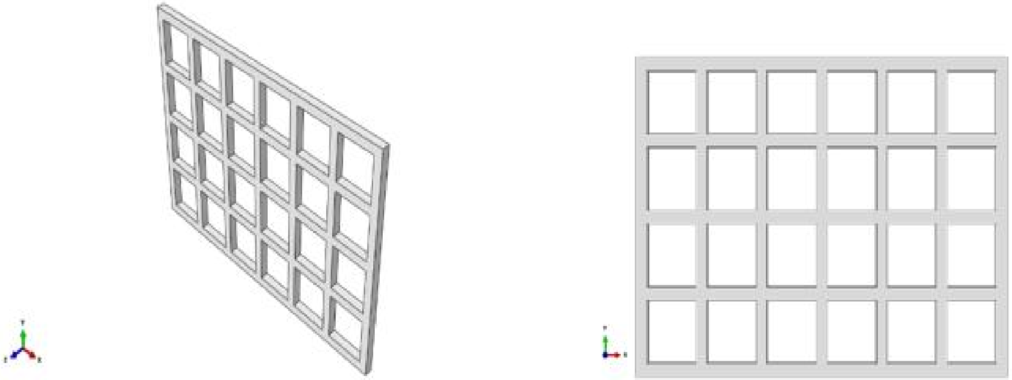

Fig. 1. Iso parametric view and top view of thin linked structure

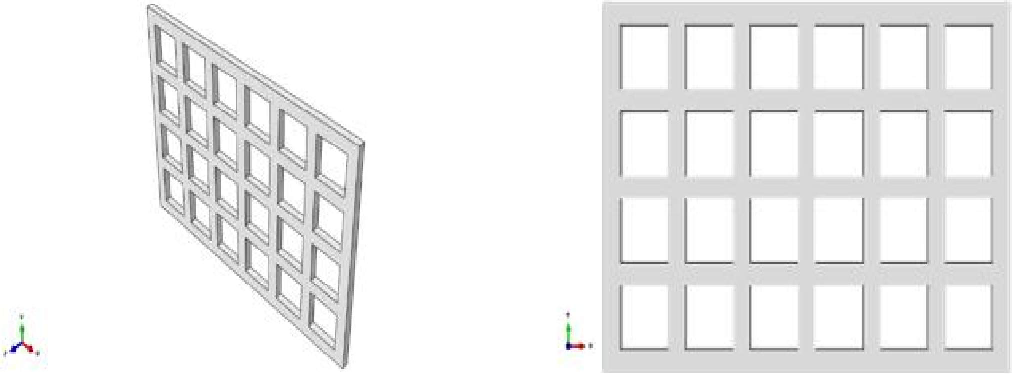

Fig. 2. Iso parametric view and top view of thick linked structure

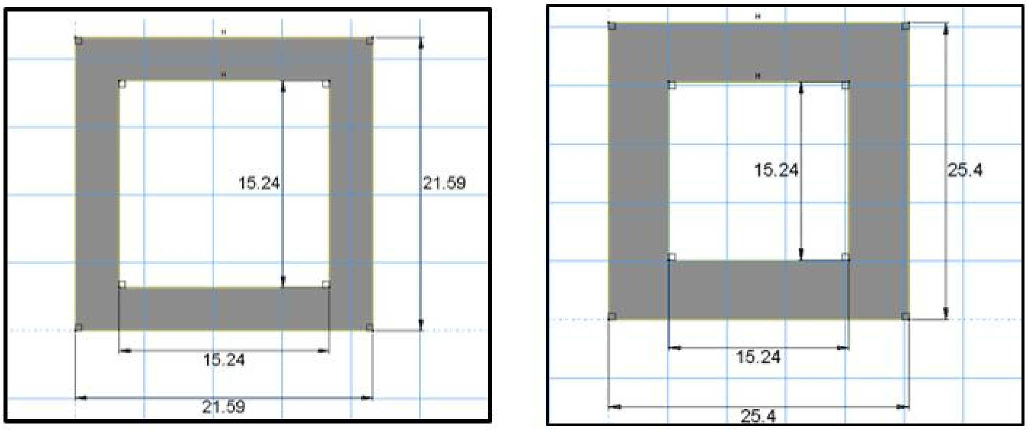

Fig. 3. Thin link and thick link perforated square with dimensions in mm

The finite element analysis software [ABAQUS 6.13.2 version] was used in this study for investigating the behavior of linked metal structures having links of two different thicknesses that were obtained from rectangular perforations made in a solid metal plate. The perforated metal plate now comprising of a fine network of links is subject to uniaxial tension loading in both the symmetric condition and asymmetric condition. The deformation behavior of links in the linked metal structure has only been studied and documented in the published literature by few researchers.Furthermore, during the early years, due on account to computational difficulties, or limitations, several of these independent studies the links were modeled using solid elements [29].

A dependence of both elastic modulus (E) and poison's ratio (υ) of a metal on the direction of loading is well established. The presence of a high concentration of stress at an intersection of the elements in a linked metal structure does make the overall structure complex. This makes it both interesting and necessary to study the complicated model. Due to inherent complexity of the model upon application of a load, it became both essential and critical to observe the behavior of a linked metal structure in the elastic regime, since presence of high level of "local" stress concentration causes a non-uniform state of stress to exist through the structure. Presence of high 'local' stress concentration, which makes testing not only difficult but also complex and often promotes failure of the linked metal structure by rupture.

The finite element analysis involved the following steps:

(i) Creating and meshing both the 2-D geometry and 3-D geometry of the linked structure,
(ii) Specifying suitable material properties,
(iii) Applying the desired load, and
(iv) Specifying the appropriate boundary conditions.

This analysis essentially deals with an understanding of the deformation kinetics from an application of load, i.e., tensile load, using the finite element analysis software [ABAQUS]. Both the 2-D model and 3-D model were created for purpose of analysis using ABAQUS and 2D-CPS4 solid elements having 4-node brick elements for the 2-D structure, and (b) ABAQUS and 3-D solid elements C3D8 having 8-node brick elements for the 3-D structure.

Purpose of the current investigation was to simulate stress distribution in the linked structure of the two chosen metals, i.e., aluminum alloy 6061-T6 and pure copper, upon application of a tensile load at two different intersections, or nodal points, in the linked structure.In this simulation, five different load levels spanning varying percentage of the yield strength of the metal were chosen, i.e., 10 pct. of yield strength, 25 pct., of yield strength, 50 pct., of yield strength, 100 pct., of yield strength and 105 pct. of yield strength.This was done for purpose of the following:

(i) Characterizing stress distribution in the linked metal structure and thereby recording the variation of stress with strain for the overall linked metal structure, and
(ii) Displacement experienced by each of the centroid nodes upon application of load or External mechanical stimulus.

The numerical results include the following: (a) stresses and strain in each zone, (b) displacements experienced by each node for the different load levels applied to the linked metal structure comprising of a network of thin links and structure comprising of a network of thicker links.

3.2 Material Properties

For the no-linear material model, the stress versus strain relationship for the materials chosen for this study is assumed. For purpose of analysis the two metals chosen for this study were homogeneous, isotropic and linear elastic.Both the 2-Dimensional finite element and 3-dimensionsl finite element processing program [ABAQUS version 6.13.2] was used for performing the analyses at each level of the applied load and the chosen loading conditions [symmetric versus asymmetric]. The equivalent Von-Mises stresses were obtained numerically and for purpose of ease in interpretation they were color coded. Properties of the chosen metal, such as Young's modulus and Poisson's ratio, were assigned specific to the metal chosen. For mechanical behavior in the plastic regime, both the yield stress and corresponding values of plastic strain were taken from the stress versus strain curves for the chosen metal. Under conditions of non-linear behavior of the chosen metal, the total strain comprises of the elastic strain component plus the plastic strain component. The values of plastic strain component were obtained using the following relationships:

$$\varepsilon_{total} = \varepsilon_{elastic} + \varepsilon_{plastic}$$
$$\varepsilon_{plastic} = \varepsilon_{total} – \sigma_{stress} / E$$

In this research study, the values of plastic strain were obtained using a plot digitizer.

3.3 Meshing

The mesh was made up of four-node plane stress elements resulting in:

(a) A sum of 1292 elements and 1869 nodes for the thin structure, and
(b) A sum of 836 elements and 1185 nodes for the thick structure.

The structure comprising of a network of fine interconnected links was pulled in uniaxial tension, at an angle of 45 degrees with respect to the horizontal axis, and at a constant speed. The meshing was done for conditions of plane stress since the linked metal structure satisfies the plane stress condition.

3.4 Boundary condition and Nature of Loading

This part of the study is essential since it provides both an efficient and systematic method for purpose of calculating behavior of the chosen linked metal structure when subject to an external mechanical stimulus or loading in the tensile direction. In Table 4 is provided a summary of the boundary conditions applied on both the thin link structure and the thick link structure. The boundary conditions were chosen and applied to restrict rigid body rotation, since the linked metal structure during finite element analysis is assumed to be free in 3D space. The chosen linked metal structure is meshed into nodes and elements such that each node in the linked structure comprises of three degrees of freedom [i.e., 2 transitional displacements and one rotational] along both the X and Y axis. For the structure to be stable in space, two sets were created for the boundary conditions and the end nodes. These boundary conditions are named as BC1 and BC2. For boundary condition BC1, movement or displacement of the nodes was fixed along the coordinate axis, such that the displacement was essentially zero and rotation was restricted along the axis of rotation. For boundary condition BC2, vertical displacement of the nodes was condensed along the Y and Z axis. The structure was if the matrix form, such that it was easy to both identify and locate the centroid node of a specific element. In Fig. 4 is shown a linked metal structure in the matrix form for both the thin-link structure and the thick-link structure.

The loading was essentially in uniaxial tension, such that the overall linked metal structure was symmetric along both the X- and Y- axis. Each chosen linked metal structure, i.e., structure containing a network of thin links and structure containing a network of thick links, was meticulously analyzed for two cases of loading, i.e., (i) Symmetric loading, and (ii) Asymmetric loading.

(i) Symmetric loading

For this type of loading the load was applied at Node (2,6) and Node (4.2); such that they follow the same line of action, so as to essentially induce a pull in the tensile direction for the thin-link structure and the thick-link structure.

(ii) Asymmetric loading

In this type of loading the load was applied on Node (2,6) and Node (4,1), such pull in tension is slightly offset. Furthermore, the loading was chosen to be of the ramp type, implying that the load could increase uniformly at a certain rate. Each chosen linked metal structure was assumed to be in a state of uniaxial tensile stress. Also, the following are assumed:

(a) That the applied load is equally distributed between the two nodes on which it was applied, and
(b) During deformation, the cross-sectional area remained constant, i.e., the analysis was essentially restricted to small displacements.

4. RESULTS AND DISCUSSION

For purpose of this study, two commonly vision chosen used metals in a spectrum of industry relevant applications with specific emphasis on light weight were chosen to study their behavior, or response, upon application of a tensile load. Few studies have been reported in the

Table 4. The chosen boundary conditions for the 2-D FEM under uniaxial tension

BC	U_x	U_y	UR3
BC1	$U_x = 0$	$U_y = 0$	$UR_3 = 0$
BC2	$U_x = 10$	$U_y = 0$	$UR_3 = 0$

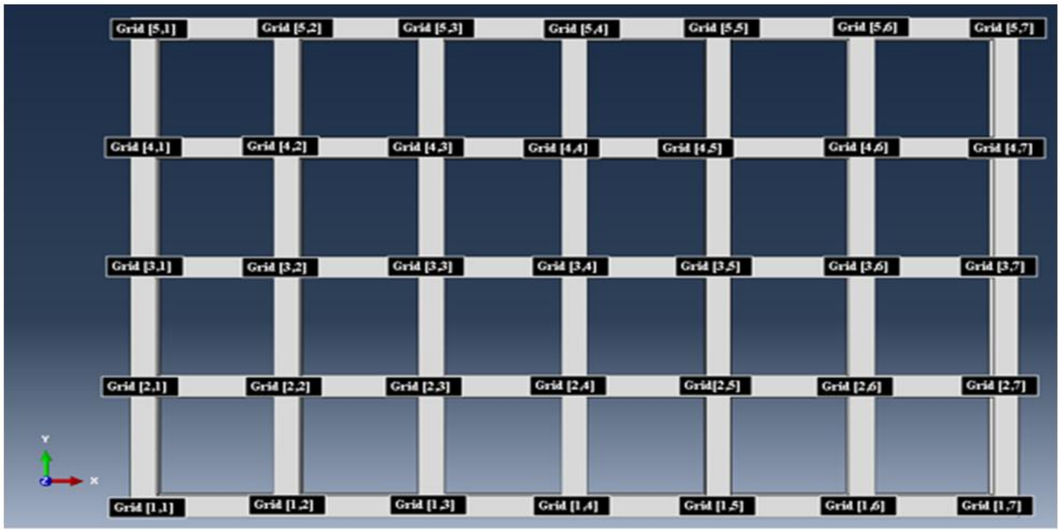

Fig. 4. Methodology used for the location of the grid points in the linked structure (Thin and Thick Structure)

published literature on the mechanical behavior of perforated sheets of metal under the influence of an external mechanical stimulus. For understanding the tensile behavior of linked metal structures the classic deformation theories quite like a solid plate element are applicable. However, the presence of perforations in a solid metal resulting essentially in a structure that is held together by a network of links does tend to develop shearing stresses at the “local” level. The presence of shearing stresses does tend to influence the overall stress distribution and resultant deformation behavior of the linked metal structure.

The results are shown in Fig. 5 and Fig. 6 showing the variation of stress with strain for four different linked structures of varying thickness. For plane stress condition of the linked metal structure, under conditions of uniaxial tension, a comparative study between a full 3-D and simplified 2-D i.e., with $\sigma_{xz} = \sigma_{yz} = \sigma_{zz} = 0$, simulation was carried out. In Fig. 5 and Fig. 6 is shown the engineering stress versus engineering strain curves for the two chosen metals under conditions of both symmetric loading and asymmetric loading. The overall deformation behavior of the linked structure was studied under conditions of plane stress. An observation of the data resulting from numerical computation revealed the test results from the three-dimensional (3-D) model did not significantly differ from those of the two-dimensional (2-D) model.Henceforth, the numerical results reported in this paper are for the 2-D plane stress condition.

In Fig. 5 is shown the variation of stress with strain for the chosen aluminum alloy 6061-T6 and copper C-10100 upon application of a load [i.e., both symmetric and asymmetric] at the appropriate grids shown in Fig. 4. The behavior can be easily studied from the stress versus strain curves upon application of a load. The analysis was done using the basic mechanical properties of the two chosen metals, as provided or summarized in Table 2.

In Fig. 6 is shown the stress versus strain curve for structures containing a network of thick links of the two chosen lightweight metals, i.e., 6061-T6 and C-10100 and upon uniform application of a load, i.e., endurance of the structure for the case of both symmetric loading and asymmetric loading, The stress versus strain curve shows a dissimilar behavior upon application of a symmetric load to a structure essentially containing a network of thick links, and the overall structure lasts just a little longer when compared one-on-one with asymmetric loading. For the case of asymmetric loading presence of stress concentration as a direct consequence of perforations in the chosen metal plate does play a crucial role in governing failure of the structure.

The distribution of strain computed for the chosen linked metal structure, upon application of a tensile load, was studied for two different designs of the structure. The distribution pattern was studied when the loading was applied uniformly at two different grids in the structure resulting in symmetric loading and asymmetric loading. Five different load levels, corresponding to percentage of the yield stress of the chosen metal, were chosen to study the deformation induced in the links of the structure containing a network of thin links and structure essentially containing a network of thick links.

To verify the proposed criterion for the different loads levels [10 pct. of yield stress, 25 pct. of yield stress, 50 pct. of yield stress, 100 pct. of yield stress and 105 pct. of yield stress] applied to the linked metal structure, a finite element analysis was done to study the distribution of stresses in the links and resultant displacements experienced by the centroid of the links or the nodes. For a chosen linked metal structure, the displacement was systematically recorded for the five different load levels. For each chosen linked structure the Von-Mises yield criterion and equivalent plastic strain (PEEQ) were obtained from the analysis.

In this analysis, for linked structures, i, e., two structures containing a network of thin links and

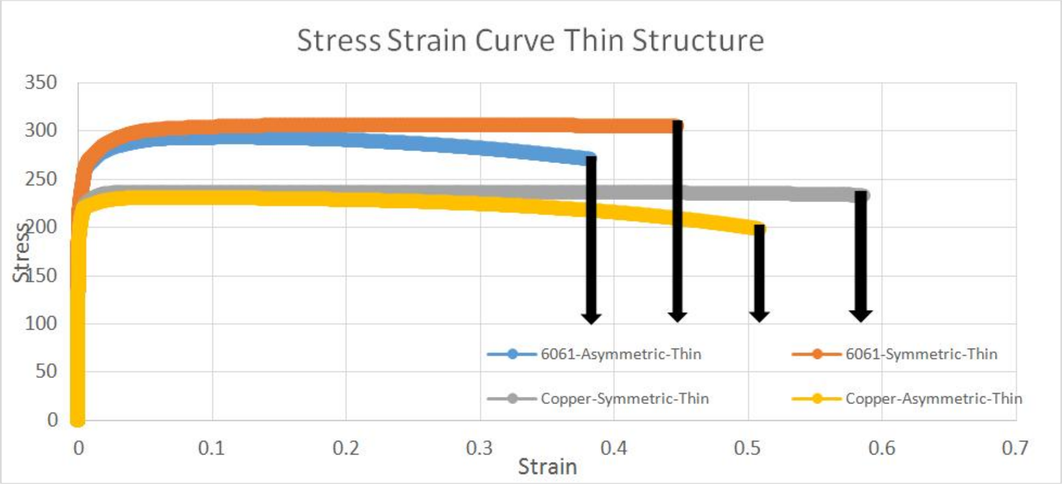

Fig. 5. Stress Strain Curve for 6061-T6 and C-10100 for thin linked structure

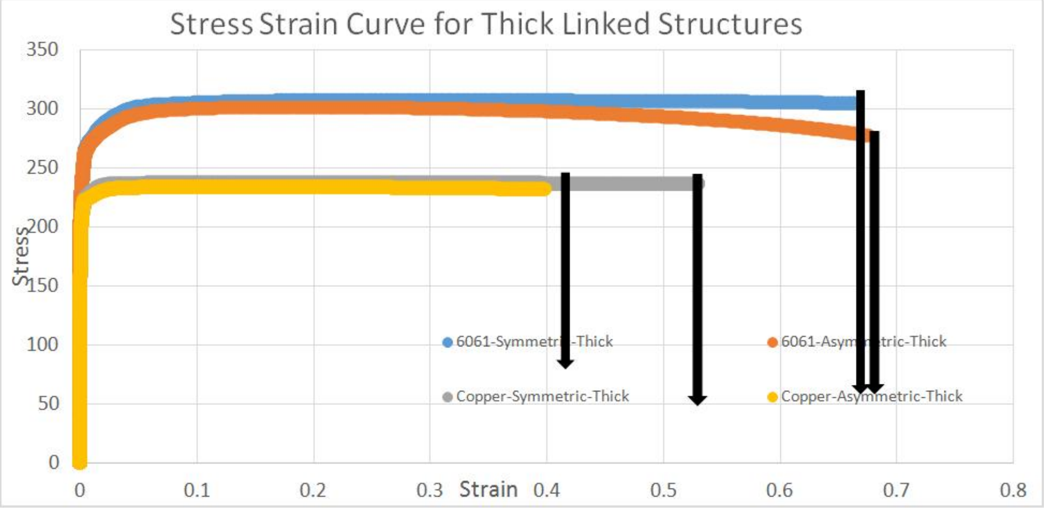

Fig. 6. Stress Strain Curve for 6061-T6 and C-10100 for thick linked structure

two structures containing a network of thick links were examined upon application of load at the two chosen grid positions, i.e., Node (2,6) and Node (4,2) for the case of symmetric loading, and (b) Node (2,6) and Node (4.1) for the case of asymmetric loading. The corresponding values of displacement experienced by the nodes was recorded to both study and concurrently analyze the overall pattern shown by the linked metal structure.

4.1 Structure Containing Thin Links in Aluminum Alloy 6061 and Copper

4.1.1 Symmetric loading

The deformation experienced by the centroid nodes is shown in Fig. 7 and Fig. 9 for the case of symmetric loading when subject to a tensile load that was applied at Node (2,6) and Node (4.2) of the two chosen metals, i.e., aluminum alloy 6061-T6 and cooper.The deformation behavior is represented on 3-D bar graphs indicating that a comparison can be made from the displacements experienced by the nodal points in aluminum alloy AA6061, which is relatively higher when compared one-on-one with displacements experienced by the nodes in pure copper.For different levels of the load used, i.e., 10 pct. of yield stress, 25 pct. of yield stress, 50 pct. of yield stress, 100 pct. of yield stress and 105 pct. of the yield stress, for the case of symmetric loading, maximum displacement was observed to occur at Node (4,2) and the region in the immediate vicinity. From Fig. 7 it is observed that maximum displacement was occurring towards upper region of the linked metal structure.The upper region of the linked metal structure also experienced a larger displacement when compared to the links that are positioned towards the lower region.Also, for the case of pure copper, the deformation experienced by the linked metal structure was quite like the observations made for aluminum alloy 6061. However, the overall values of deformation experienced by the link elements was relatively low. The nodes in copper experienced observably lower displacement when compared one-on-one with the nodes in the linked metal structure of aluminum alloy 6061-T6.

4.1.2 Asymmetric loading

When loading is from symmetric to asymmetric, we observe the presence of both elastic strain and plastic strain to change the deformation behavior of the structure at the ‘local’ or fine microscopic level. The deformation response was plotted and reveals that when the point of load application is shifted to the next adjacent grid, to ensure asymmetric loading, does result in a noticeable decrease in the magnitude of displacement experienced by the nodes when compared to the magnitude of displacement for the case of symmetric loading. Also, the links located at the upper right region of the metal structure containing a network of thin links experienced a higher level of deformation. When the material begins to yield, maximum deflection was observed to occur at the lower grid point where actual load is applied. For the case of linked metal structure of copper, we observe deformation of the link elements to be non-uniformly distributed at the center while the region both at and near the load area experienced maximum deflection. When the values of displacement are compared for the two chosen metals, aluminum alloy 6061-T6 revealed a higher “local” value of strain or displacement while pure copper experienced a lower value of strain or displacement experienced by the link elements for all the five values of the load chosen and applied. In Table 5 is summarized values of maximum displacement observed at the grid locations for different values of the applied load, as a function of yield stress of the chosen metal. To provide an insight on the extent of displacement experienced at the node or grid, in Table 5 is provided the value of maximum displacement at the respective location of the grid.

4.2 Structure Containing Thick Links in Aluminum Alloy 6061 and Copper C10100

Dimensions of the metal structure containing a fine network of thick links is provided in Table 3.The metal structure containing a network of thick links was subject to simple uniaxial tension applied at Node (2,6) and Node (4,2) resulting essentially symmetric loading and analyzed methodically using the technique of finite element simulation. From the data obtained at the five-chosen load levels the corresponding displacement values were represented on a 3-D bar graph, for purpose of ease in comparison between the load levels chosen for a given material and even between the two chosen materials for a given level of load. The data collected for the linked structures focused primarily on the elastic regime and one load was chosen in the non-linear or plastic region with the prime objective of examining and documenting response of the structure in the inelastic region.

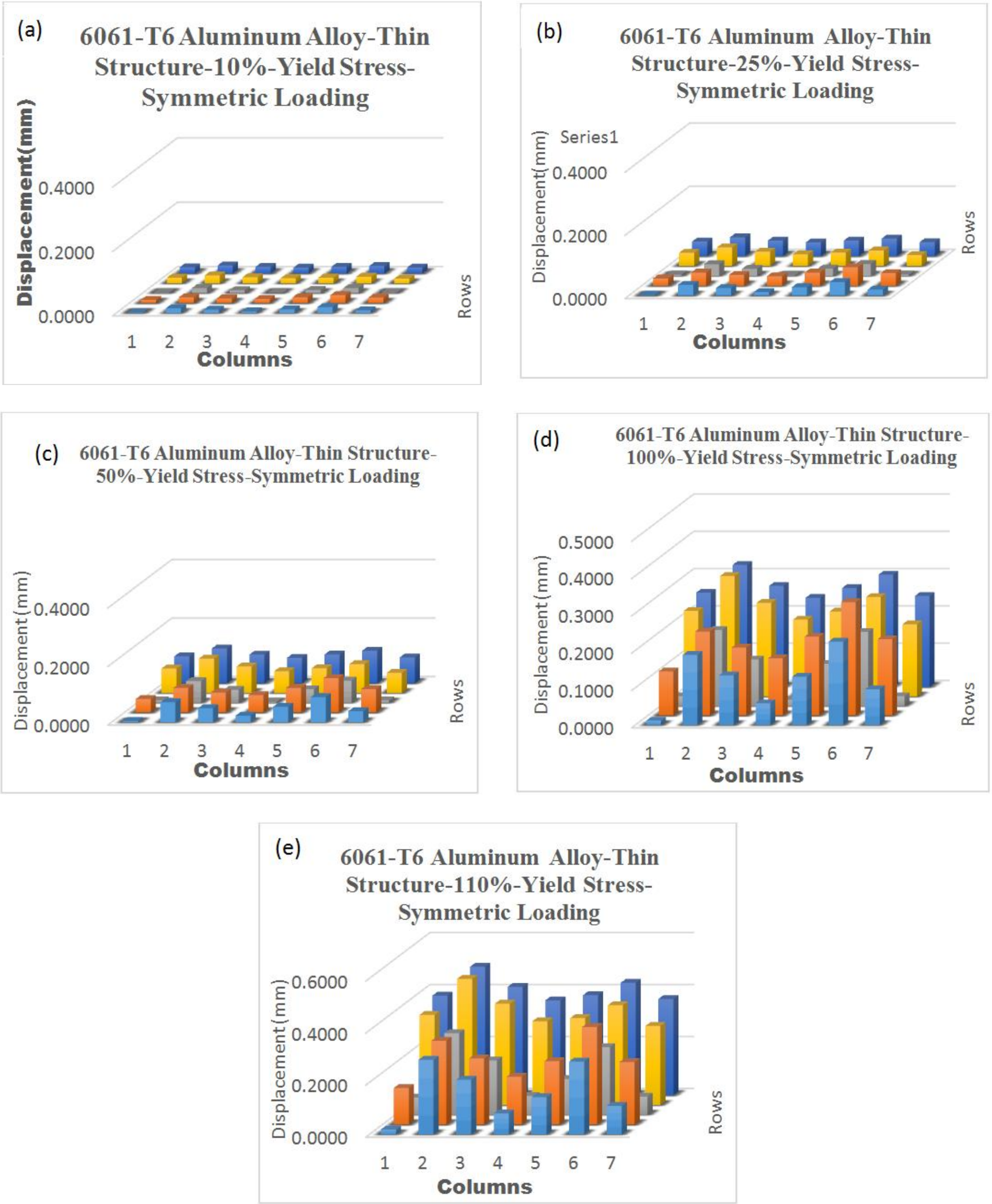

Fig. 7. Profile showing the displacement experienced by the different links of the "thin" linked structure of aluminum alloy 6061-T651 (referred to as symmetric loading) when subjected to load (percentage of the elastic limit) applied at nodes (2,6) and (4,2). i.e. (a) 10%, (b) 25%, (c) 50%, (d) 100% and (e) 110%

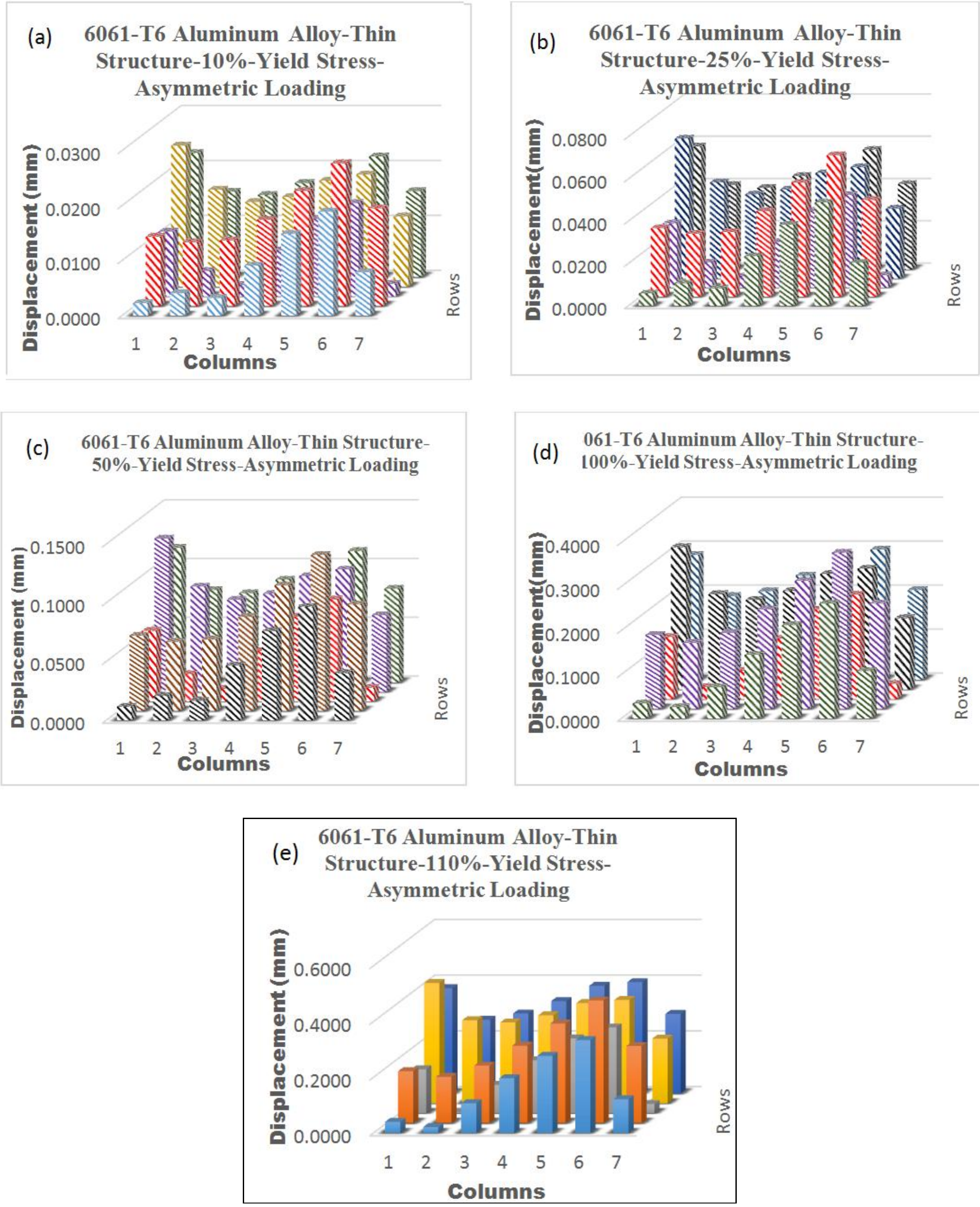

Fig. 8. Profile showing the displacement experienced by the different links of the "thin" linked structure of aluminum alloy 6061-T651 (referred to as asymmetric loading) when subjected to load (as percentage of the elastic limit) at Node (2,6) and Node (4,1). i.e. (a) 10%, (b) 25%, (c) 50%, (d) 100% and (e) 110%

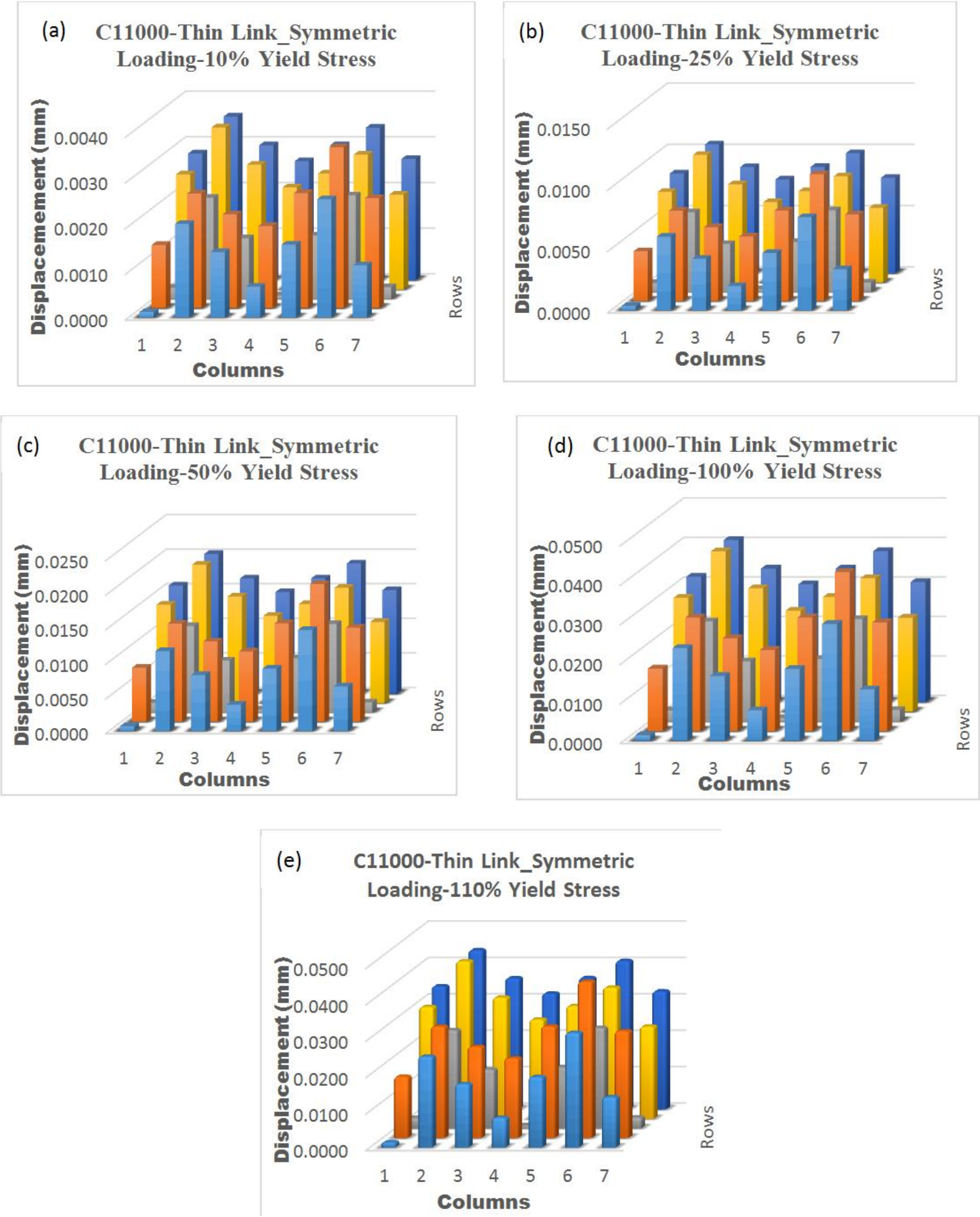

Fig. 9. Profile showing the displacement experienced by the different links of the "thin" linked structure of commercial copper alloy C11000 (referred to as symmetric loading) when subjected to load, as percentage of the elastic limit, applied at Node (2,6) and Node (4,2). i.e. (a) 10%, (b) 25%, (c) 50%, (d) 100% and (e) 110%

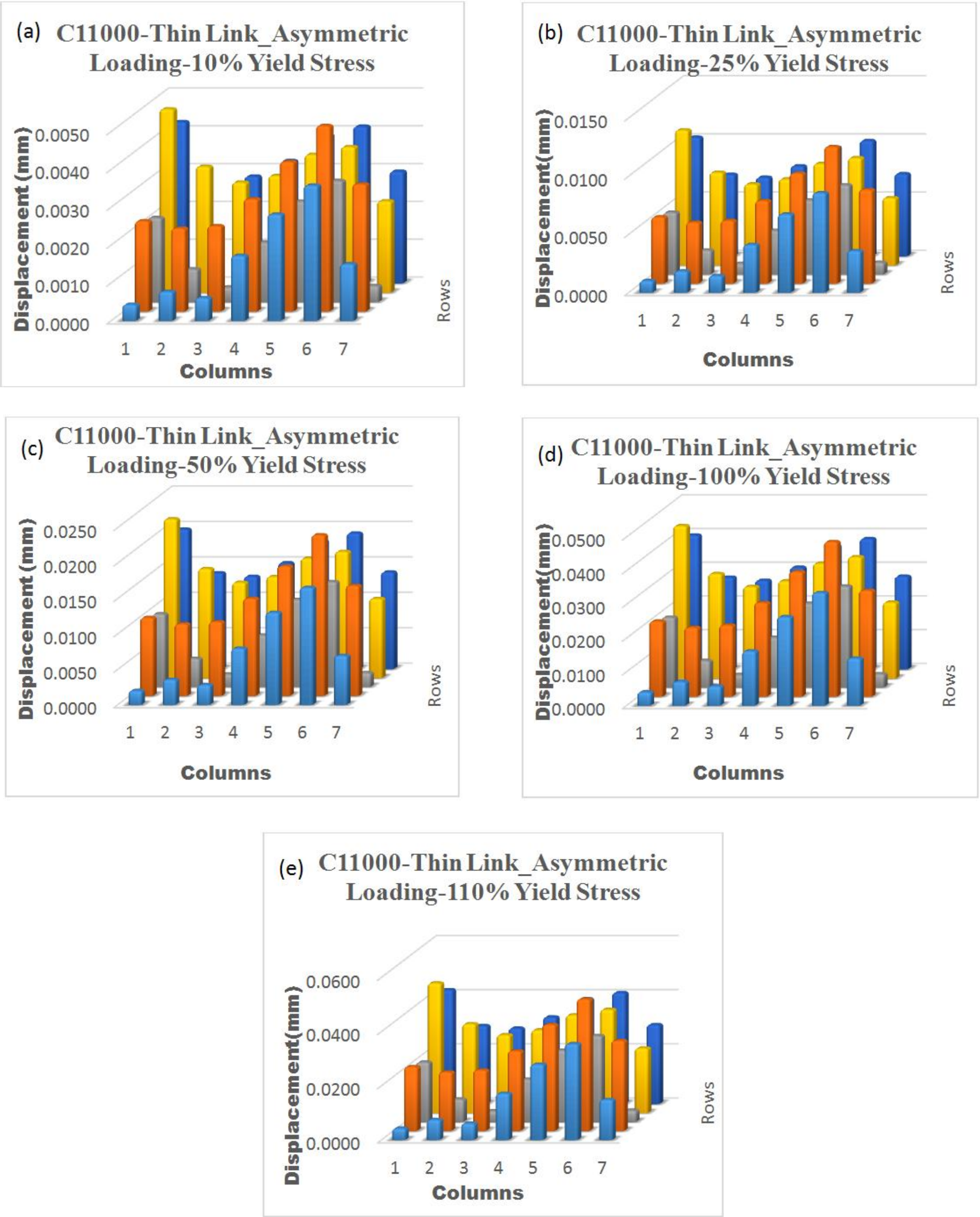

Fig. 10. Profile showing the displacement experienced by the different links of the "thin" linked structure of commercial copper C11000 (referred to as asymmetric loading) when subjected to load as percentage of the elastic limit, applied at Node (2,6) and Node (4,2) i.e. (a) 10%, (b) 25%, (c) 50%, (d) 100% and (e) 110%

Table 5. Displacement data for structure containing thin links at the yield point

Thin links	Maximum displacement			
	Symmetric (mm)	**Grid location**	**Asymmetric (mm)**	**Grid location**
Aluminum Alloy	0.328	52	0.355	26
Copper	0.041	52	0.045	41

4.2.1 Symmetric loading

In this case, when the structure containing a network of thick links was subject to loading, it experiences deformation at every node.For aluminum alloy 6061-T6, the deformation was distinctly observed at the upper node (4,2), which incidentally experienced the maximum amount of deformation. The displacement was overall uniform in the elastic range.However, when the material started to yield, the values of displacement revealed a non-linear trend.Upon examining the data represented in the 3-D bar graphs the upper half of the linked metal structure experiences more deformation quantified by displacement, while the lower half of the linked metal structure experiences observably less deformation or displacement of the nodal points. In Fig. 11 and Fig. 13 is shown the linked metal structure of aluminum alloy 6061-T6 to experience greater deformation of the links and nodal points when compared to the linked metal structure of copper.In fact, the ratio of deformation or displacement experienced by the links in aluminum alloy 6061 is noticeably higher than the deformation or displacement experienced by the fine network of links in pure copper. Also, for copper the severity of displacement experienced by both the links and nodal points shifts to the upper right corner of the metal structure, which is evident from the figures. The stress experienced at the mid-portion of the overall linked structure is low and gradually decreases to the sides.

4.2.2 Asymmetric loading

Upon changing the load from symmetric to asymmetric, the deformation behavior of the links in the linked metal structure does reveal an observable change. In Fig. 12 and Fig. 14 is shown the pattern of displacements observed and recorded for aluminum alloy 6061-T6 containing thick links and copper containing a network of thick links. For aluminum alloy 6061-T6 the only node, which experiences a higher level of deformation was Node (4,2) at which point the actual load was applied. Further, the overall deformation by way of displacement experienced by the link elements was concentrated towards the right half of the metal structure made up of thick links. For the case of copper, the deflection observed and recorded was also noticeably more at the point of application of load, while the nearby grids and adjacent links experienced lower deformation, quantified by displacement. Also, a similar behavioral pattern with a shift towards the right half of the linked metal structure was observed. In Table 6 is provided the maximum values of displacement recorded for the 4 cases and location of its occurrence. From the values of displacement recorded it is observed that further case of asymmetric loading of aluminum alloy 6061-T6 experiences an observable amount of displacement of the links while symmetric loading of the linked metal structure of copper experiences the least.

Results obtained from the finite element simulation also provide the following highlights:

1. The displacement experienced by both the links and the centroid nodes was noticeably high for the case of asymmetric loading of aluminum alloy 6061 and observed to be concentrated towards the lower half of the structure. For asymmetric loading of linked structure of copper experienced the least amount of deformation or displacement of the link and the centroid nodes.
2. Mechanical response of the linked metal structure to symmetric loading shows the very same response, when the structure begins to yield and the pattern of deformation or displacement experienced by both the link elements and the nodes reveals a “U” shape as can be easily inferred from the 3-D bar graphs. When the loading is slightly shifted to ensure asymmetric nature of loading, the deformation pattern reveals an observable shift or inclination to the left half of the linked metal structure.

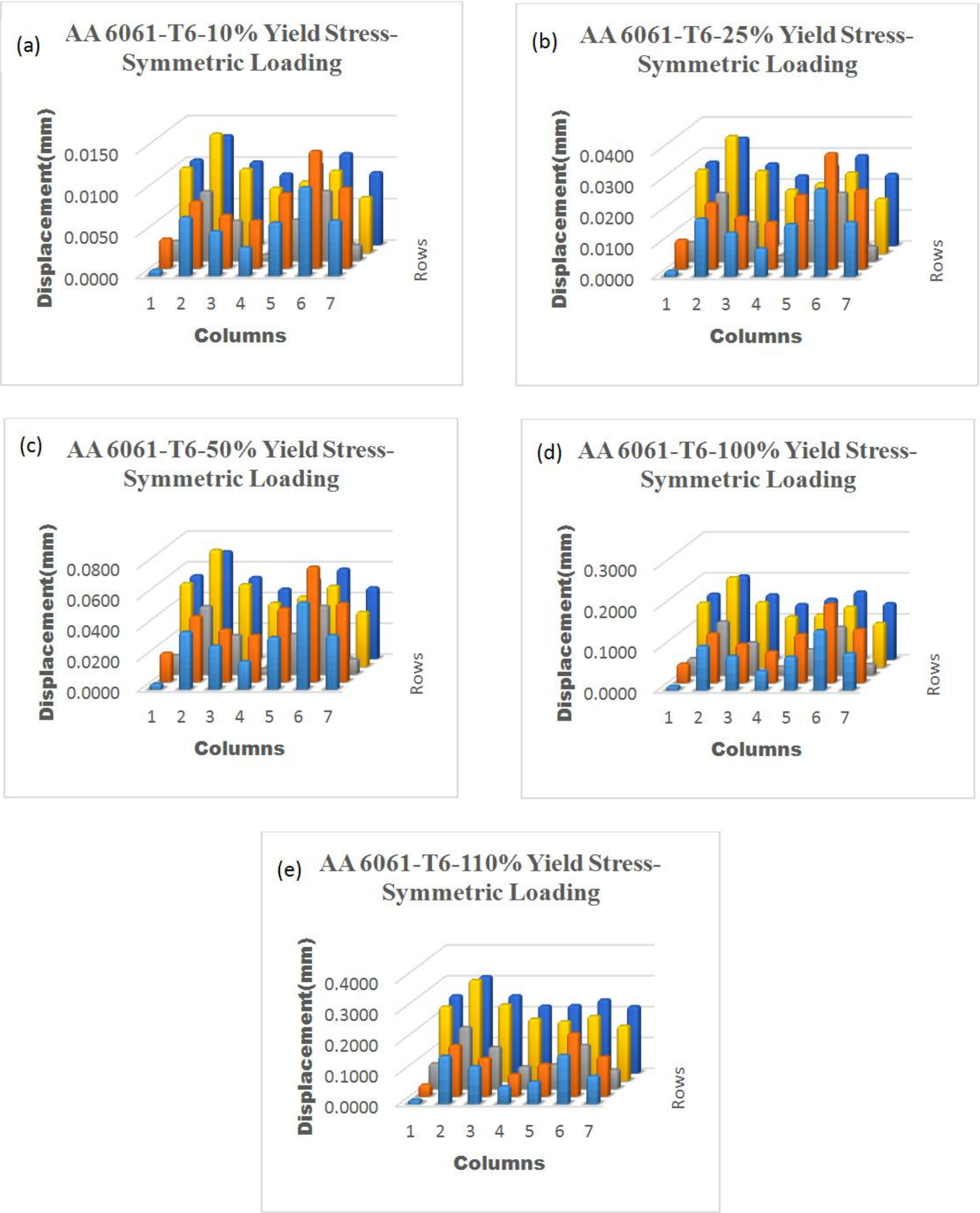

Fig. 11. Profile showing the displacement experienced by the different links of the "thick" Linked structure of aluminum alloy 6061-T651 (referred to as symmetric loading) when subjected to load as fraction of the elastic limit and applied at Node (2,6) and Node (4,2) i.e. (a) 10%, (b) 25%, (c) 50%, (d) 100% and (e) 110%

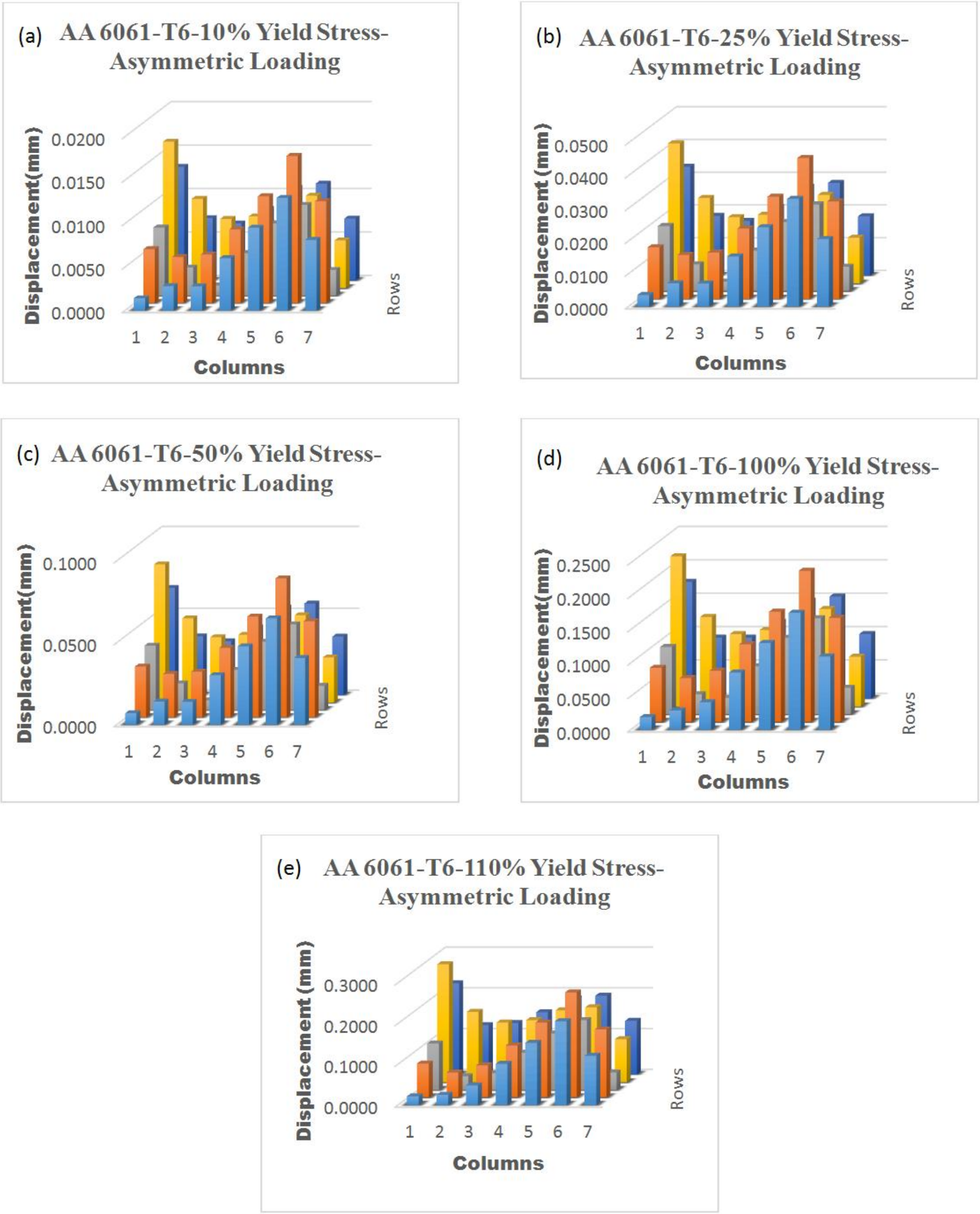

Fig. 12. Profile showing the displacement experienced by the different links of the "thick" Linked structure of aluminum alloy 6061-T651 (referred to as asymmetric loading) when subjected to load as percentage of the elastic limit and applied at Node (2,6) and Node (4,2) i.e. 10%, (b) 25%, (c) 50%, (d) 100% and (e) 110%

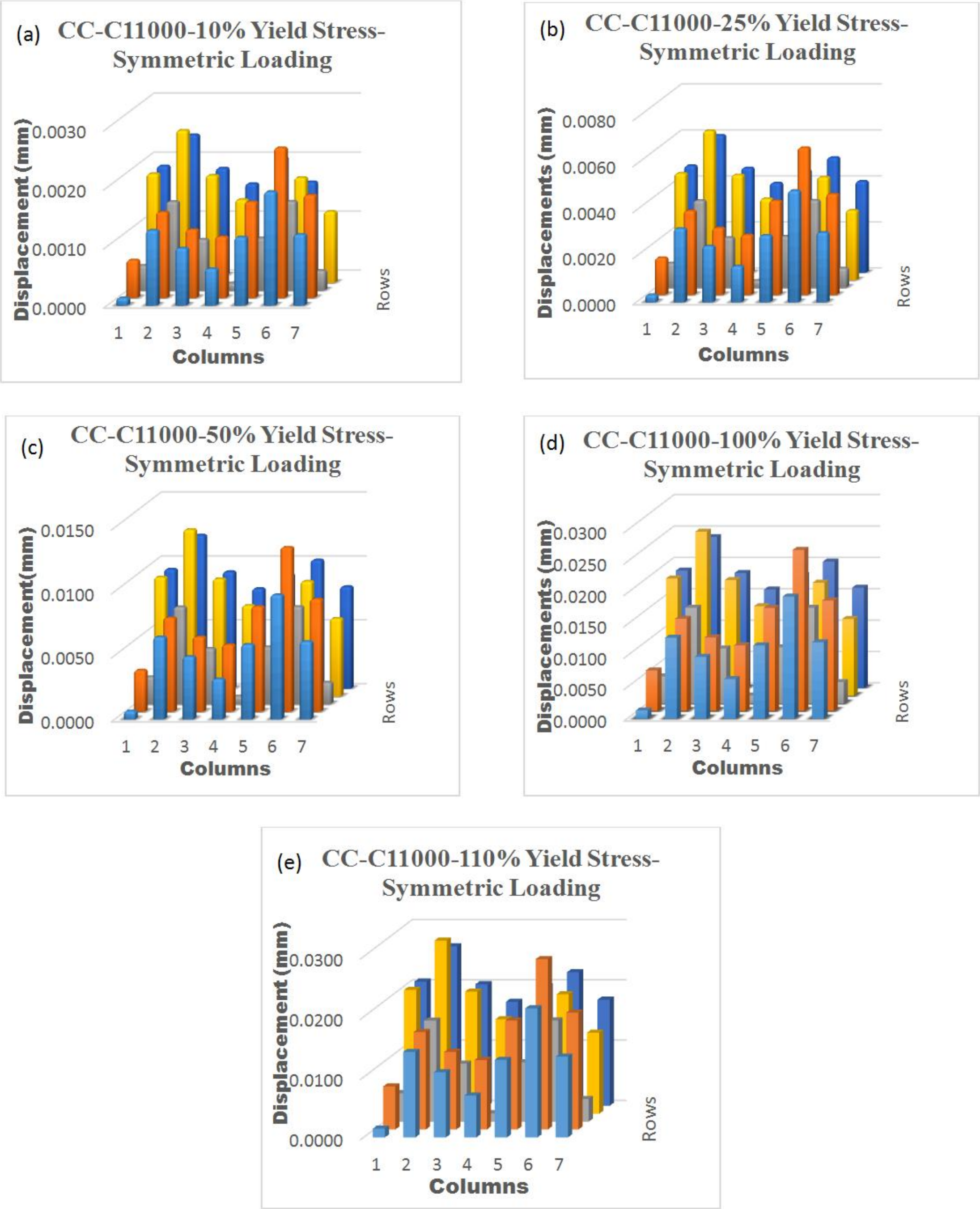

Fig. 13. Profile showing the displacement experienced by the different links of the "thick" linked structure of commercial copper C11000 (referred to as symmetric loading) when subjected to load as percentage of the elastic limit that was applied essentially at Node (2,6) and Node (4,2) i.e. (a) 10%, (b) 25%, (c) 50%, (d) 100% and (e) 110%

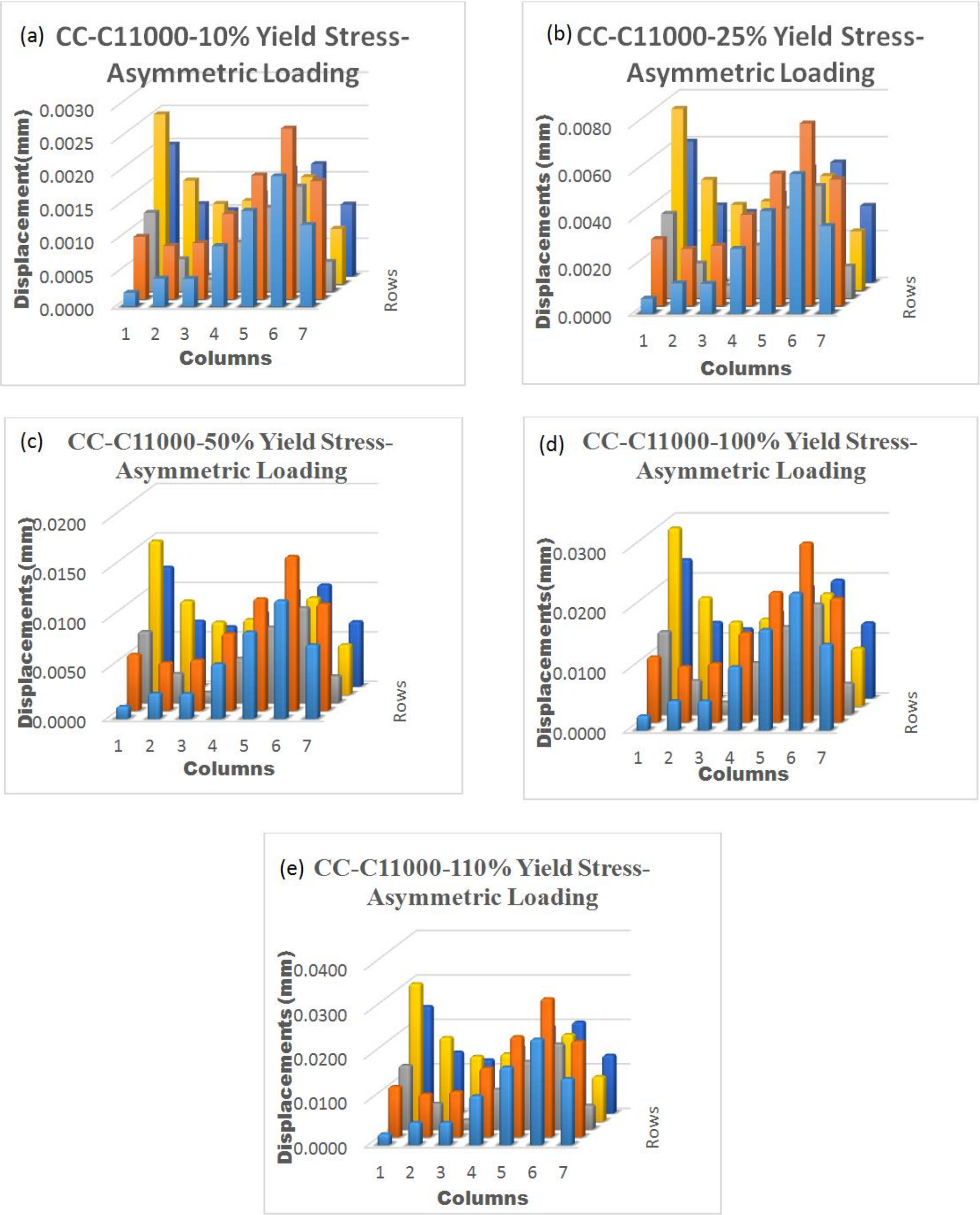

Fig. 14. Profile showing the displacement experienced by the different links of the "thick" linked structure of commercial copper C11000 (referred to as asymmetric loading) when subjected to load as fraction of the elastic limit applied at Node (2,6) and Node (4,1) i.e. 10%, (b) 25%, (c) 50%, (d) 100% and (e) 110%

Table 6. Displacement data for the thick linked structure at the yield point

Thick links	**Maximum displacement**			
	Symmetric	**Grid location**	**Asymmetric**	**Grid location**
Aluminum alloy 6061	0.22	42	0.227	26
Copper	0.026	42	0.03	26

5. CONCLUSIONS

Based on a study on the use of finite element analysis for purpose of assessing the mechanical response of a linked structure, having links that can be classified as being thin and thick, and upon being subject to both symmetric and asymmetric loading following are the key findings:

1. The finite element method was successfully used to study the mechanical response of the linked metal structure, quantified in this study by deformation or displacement experienced by the links and centroid node upon application of a load.This was made possible for structure containing thick links and a structure containing thin links and the materials chosen for the overall linked structure being an aluminum alloy and pure copper.
2. From the results obtained when the nature of loading is changed from symmetric to asymmetric the linked structure does experience a noticeable increase in the extent of deformation or displacement experienced by both the links and the centroid nodes. Higher the magnitude of applied load greater and distinctly evident was the extent of deformation or displacement experienced by the different links and greater was the displacement occurring at both the centroid nodes and at the point of application of load.
3. The analysis helps predict the variation of stress with strain for the chosen material, which is conventionally obtained using a tensile test thereby conforming to exact results from an engineering view point for the case of linked metal structures. The approach used in this analysis is simple because a static general analysis using the displacement approach provides consistent results, when compared to an analysis using applied load.
4. The finite element analysis was used to compare the two-chosen light-weight metals both containing a network of thin links and a network of thick links. Since the linked metal structure contains several junctions that experience high ‘local’ stress concentration, the corresponding value of displacement calculated for both the link elements and the nodes is noticeably lower.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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