A thesis report on

TOWARDS OPTIMAL DESIGN OF MODULAR ROBOTIC ARMS

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CERTIFICATE

This is certify that the thesis titled, **"TOWARDS OPTIMAL DESIGN OF MODULAR ROBOTIC ARMS"** being submitted by **Mr. Sameer Gupta**, in partial fulfillment of the requirements for the award of degree of **Master of Engineering** in **CAD/CAM & Robotics** at **Thapar University, Patiala** is a bonafide work carried out by him under our guidance and supervision and that no part of this work has been submitted before in part or full to any other university or institute for the award of any degree.

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ABSTRACT

The space environment in industries is shrinking due to vast number of machines. The manipulator should have variability to change the DH parameters at the time of installation for such environment. Such variability comes from modular manipulators.

Modularity is the key in state-of-the-art technology to accommodate changes in complex systems. Product modularization has resulted in advances for computers, electronics, and softwares. However, modular robotic systems sans this success. The modular link is a self-contained element of a modular manipulator. Modular manipulators are made up of inter-connecting simple, multiple and similar units. The arms of modular manipulators can be made by using same type of module.

The modular link for development of a modular manipulator is presented in this thesis. The main aim for the development of modular link is to lower down the cost of fabrication for link-joint components used in manipulator by providing flexibility for variation in DH parameters of modular link.

Module is developed in three parts which are joined with the help of keys. First and second parts have been used for variation in twist angle whereas second and third parts have been used for variation in link length.

After development of module, analyses of modular link under different condition have been carried out using ANSYS software, which was used to optimize the design.

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CHAPTER-1

INTRODUCTION

1.1 GENERAL

A robot can be defined as a programmable, self-controlled device consisting of electronic, electrical, or mechanical units. It is a computer-controlled machine that is programmed to move, manipulates objects, and accomplishes work while interacting with its environment. Robots are able to perform repetitive tasks more quickly, economically, and accurately than humans. The term robot originates from the Czech word 'robota', meaning 'compulsory labor'. The word robot has been used since to refer to a machine that can work with humans, assist them or sometimes replace them in many engineering applications.

More generally, it is a machine that functions in place of a living agent. Robots are especially desirable for certain works as, unlike humans, they never get tired; they can endure physical conditions that are uncomfortable or even dangerous; they can operate in airless conditions; they do not get bored by repetition; and they cannot be distracted from the task at hand. The present chapter gives the details of various terms and types of robots.

1.2 MANIPULATOR

A mechanical device which can handle remote objects or material even in the absence of any worker is called Manipulator. It consists of links and joints to make a long chain, which can manipulate in its workspace. The number of joints gives the degree of freedom. Manipulators are broadly classified into two categories namely: Serial manipulators and Parallel manipulators.

1.2.1 Serial Manipulators

These are the most common industrial robots. Often they have links joined one to another in an open chain like structure, as shown in Fig. 1.1. One of their major advantages is that, they have large workspace with respect to their own volume and occupied floor space.

Some of their limitations are:

(i) Have low stiffness due to an open kinematic structure.

(ii) If there is any error present at the base joint, it gets accumulated and amplified along the chain length.

(iii) These manipulators have to carry and move the large weight of most of the actuators.

(iv) They can manipulate relatively small loads.

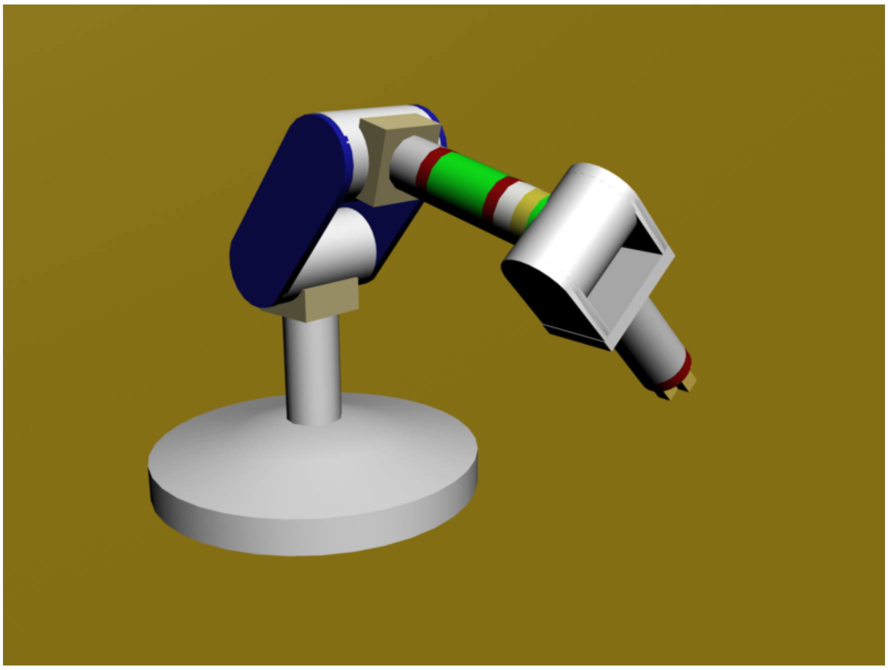


Figure 1.1 Serial Manipulator [24]

To reach at any position and orientation in workspace, minimum of six degree of freedom (3 for position and 3 for orientation) are required. Hence, most of the manipulators are made with six degree of freedom. The four degree of freedom robots are only used for pick and place applications.

1.2.2 Parallel Manipulators

These manipulators use some base to move the arms parallelly, which are attached to it. These are different from the serial manipulator in the respect that the end effector is connected to its base by a number of separate and independent linkages working in parallel. The parallel word is taken from the topological point of view rather than geometrical. These links works altogether in parallel but it does not mean that they always remain parallel to each other; they may be skewed to each other. A parallel manipulator is shown in Fig. 1.2.

When a joint moves then there should be a proper movement of all parallel joints, which are controlled by actuators. If there is unwanted sloppiness then the other joints are also affected.

Parallel robots are alternate approach to manipulation. Each chain is usually short, simple and can thus be rigid against unwanted movement as compared to a serial arm. Errors in chain positioning are averaged in conjunction with the others, rather than being cumulative. Each actuator must still move within its own degree of freedom, as for a serial robot; however in the parallel robot the off-axis flexibility of a joint is also constrained by the effect of the other chains. It is this closed-loop stiffness that makes the overall parallel manipulator stiff relative to its components, unlike the serial chain that becomes progressively less rigid with more components.

One more advantage of the parallel manipulator is that the heavy actuators may often be centrally mounted on a single base platform, the movement of the arm taking place through struts and joints alone. This reduction in mass along the arm permits a lighter arm construction, thus lighter actuators and faster movements. This centralization of mass also reduces the robot's overall moment of inertia, which is an advantage for a mobile or walking robot.

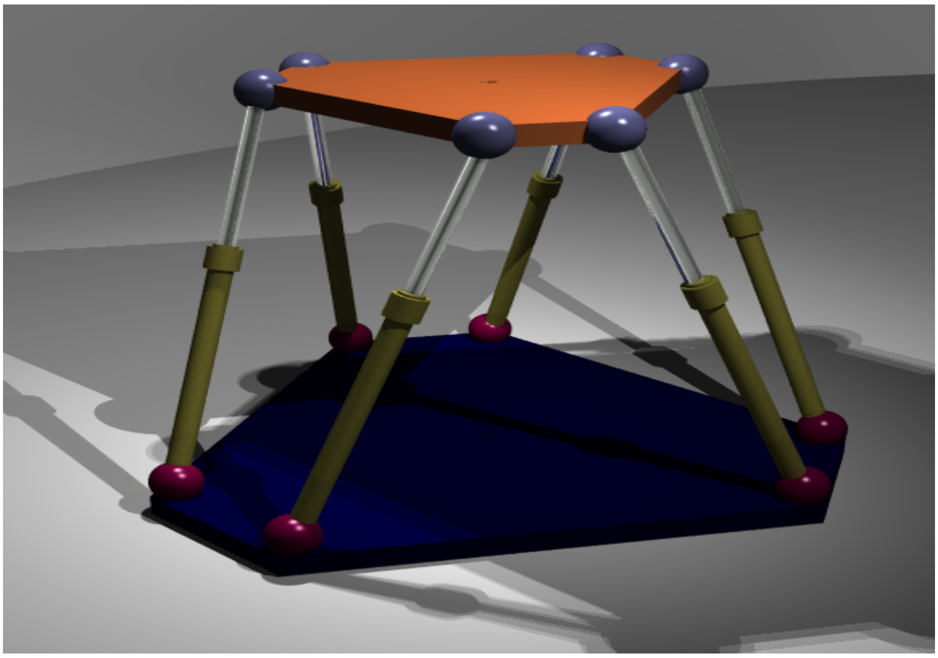


Figure 1.2 Parallel Manipulator [24]

Limited workspace is their one of main disadvantage, because the legs can collide and in addition each leg has some passive joints, each has their own mechanical limits. Also, they lose stiffness in singular positions completely. This means that the mapping from joint space to Euclidian space becomes singular.

1.3 KINEMATIC DESCRIPTION OF A SERIAL MANIPULATOR

Manipulators are made up of links and joints. They have degree of freedom in between each link which depends upon the type of joint. The links of manipulators are connected by joints allowing either rotational (such as in an articulated robot) or translational (linear displacement). The links of the manipulator are connected in a manner to form an open kinematic chain. The end of the kinematic chain of the manipulator is called the end effector, which is analogous to the human hand. The end effector can be designed to perform any desired task such as welding, gripping, spinning etc., depending on the application.

The links and joints are completely defined by the use of Denavit-Hartenberg (DH) parameters [23]. These parameters are divided into two categories:

(i) Link parameters

(ii) Joint parameters

Link parameters defines the link itself and Joint parameters defines the connection of link to its neighbouring next link, as shown in Fig. 1.3, Link '*i-1*' is defined between axis '*i-1*' and axis '*i*' and it is connected to link '*i*' at axis '*i*'.

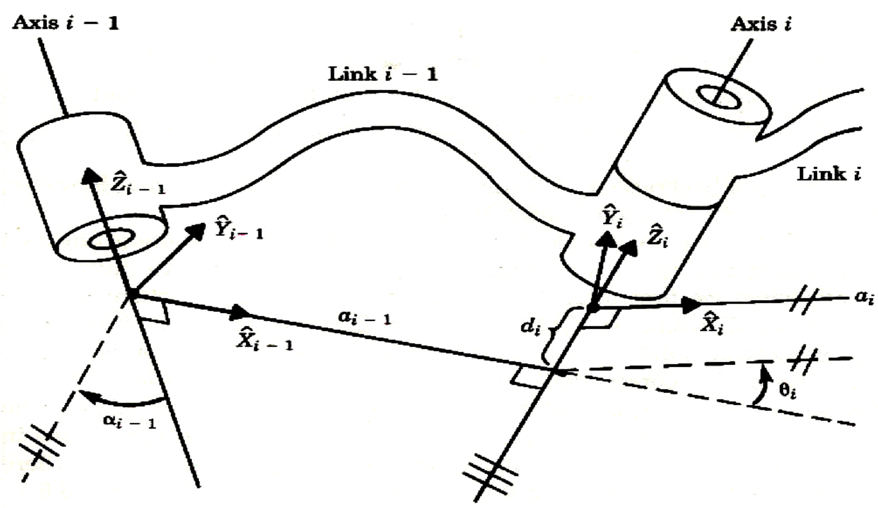


Figure 1.3 DH Parameters [23]

Link Parameters:

(i) Link Length (a_i) –– The distance from Z_i to Z_{i+1} measured along X_i

(ii) Link Twist (α_i) –– The angle between Z_i and Z_{i+1} measured about X_i

Joint Parameters:

(iii) Joint Angle (θ_i) –– The distance from X_{i-1} to X_i measured along Z_i

(iv) Joint Offset (d_i) –– The angle between X_{i-1} and X_i measured about Z_i

In case of revolute joint only **joint angle, θ_i** is variable and all other parameters remain fixed and in case of prismatic joint the **joint offset, d_i** is variable and others are fixed.

1.4 CUSTOMIZED MANIPULATORS

Conventional manipulators are sometimes considered to be general-purpose manipulators. It can be said that the system is general purpose only if it is able to do the tasks assigned to it. But if the task is defined then it is a ‘task oriented manipulator’.

Task Oriented or Task Based manipulator means it can perform the specified task. General Purpose can also be defined based on, if for every task in the set of tasks, it is possible to find a manipulator that can be created from the given set of modules to do the task, then we define the system of modules (or the system of all possible manipulators) as general purpose with respect to the set of tasks. Such a system is called as Reconfigurable Modular Manipulator System (RMMS) [1, 6].

1.5 REDUNDANT MANIPULATORS

Manipulators having more than six numbers of actuable degree of freedom are called as redundant manipulators. Manipulator in which degree of freedom is very high, it becomes Hyper-Redundant manipulators. The benefits of Hyper-Redundant robots include the ability to avoid obstacles, increased robustness with respect to mechanical failure, and the ability to perform new forms of robot locomotion and grasping.

Snake-like robots, technically termed as Hyper-Redundant robots, are, as their name suggests, elongated robotic devices that are designed to mimic their biological counterparts not only in shape but also in functionality. These types of robots are highly maneuverable, have inherent high mechanical redundancy, and are flexible. This allows such robots to easily maneuver through complex environments cluttered with many obstacles, when compared to their conventional counterparts. Generally, Hyper-Redundant robots are constructed by connecting several rigid links via joints. Moreover, since snake-like robots have a serial kinematic structure, any external load will be resisted by all joints throughout the snake-like robot as opposed to parallel kinematic structures where the external loads are divided among several limbs. This high strength requirement will not add to the joints size and weight. Moreover, the joint should have high maneuverability to demonstrate complex motions and attain small radii of curvature. Finally, each of the joints should have a reasonable speed of motion [2, 3, 19].

1.6 MODULAR MANIPULATORS

Modularity is the key in state-of-the-art technology for accommodating changes in complex systems. Product modularization has resulted in advances for computers, electronics, and softwares. However, modular robotic systems have not achieved the same success. Although prototypes of modular robotic systems have been developed, few have become commercially available. Some possible reasons are low precision, low capability, and the higher initial investment of modular systems, and most importantly, the lack of a systematic and efficient methodology for automated architectural design, modeling, and synthesis of modular configurations [18].

A "module" is a self-contained element of a robot. Each module is equipped with its own power supply, processor, communication system, sensors and actuators. Modular manipulators are made up of interconnecting multiple, simple, similar units. It means that long arms of a serial manipulator can be made by using same type of module.

Modular robotics is an approach for building robots for various complex tasks. Instead of designing a new and different mechanical robot for each task, many copies of one simple module are built. The module cannot do much by itself, but when many of such modules are connected together, a system is evolved that can do complicated things. These are like cells in human body, which are few in type but many in numbers. The modular manipulator holds the three main promises – versatility, robustness and low cost.

Versatility stems from the many ways the modules can be connected, if there are hundreds of modules then millions of combinations are possible. Robustness comes from the type of work it can perform. It can perform the work which is impossible by simple manipulators. It has low cost as volume production of single module is done.

Some of the applications of modular manipulators are:

(i) To reach inaccessible places e.g. welding of cars.
(ii) To explore the surface of different planets.
(iii) Waste removal from un-symmetric surfaces.
(iv) Under sea mining.
(v) Medical diagnostics etc.

Some of the modular manipulators can even reconfigure itself; they can change their shape by moving their modules around, to meet the demands of different tasks or different working environments.

Modular Self Reconfigurable Systems consist of many identical robots that are very limited in their actions. As the number of modules in a system increases, the range of behaviors of the group of robots grows exponentially. The task of self-reconfiguration is important for developing self-sufficient systems. The overall system can reconfigure itself to help accomplish certain tasks such as locomotion, object manipulation, sorting, or interaction with other systems, especially when there is a need to adapt to the environment.

Modular manipulators are divided into two types:

(i) Chain type modular manipulator

(ii) Lattice type modular manipulator

Robots that use chain reconfiguration form serial chains (like average robot arm) and connect and reconnect many of these arms together by forming a loop. Chain reconfiguration robots tend to be more easily applicable to standard robot tasks.

Robots that use lattice reconfiguration are self-reconfigurable robots that rearrange their positions by moving from one position on a lattice to a neighbouring position on the lattice; the important characteristic is that the number of neighbours is discrete and finite. The type of lattice leads to different forms of hardware and motions. The easiest ones to think about are the common lattices found in crystalline packing like that of atoms. The lattice structure makes planning the motions of when and where to move module about other module. An interesting plan can be obtained from computer science point of view as the space of possible motions is easy to represent in a computer. It is also interesting but difficult because the space of possible sequences grows exponentially with the number of modules.

Different types of modular manipulators are explained in the following section.

1.6.1 Active Cord Mechanism

The Active Cord Mechanism (ACM) is a snake-like robotic mechanism. The ACM is a homogeneous modular robot which can be used to mimic snake movement, shown in Fig. 1.4. Both manipulation and locomotion have been implemented in for the ACM. ACM operates in 3D but does not have the ability to self-reconfigure.

1.6.2 TETROBOT

TETROBOT is a modular system for the design, implementation, and control of a class of highly redundant parallel robotic mechanisms. In this robot, 18 nodes, 48 links and 15 actuators novel spherical joints were used to design a homogeneous truss structure [5], shown in Fig. 1.5. It is an actuated robotic structure which may be reassembled into many different configurations while still being controlled by the same hardware and software architecture. The TETROBOT systems have application in space, undersea, mining, and construction, where adaptation to unstructured and changing environments and custom design for rapid implementation are required.

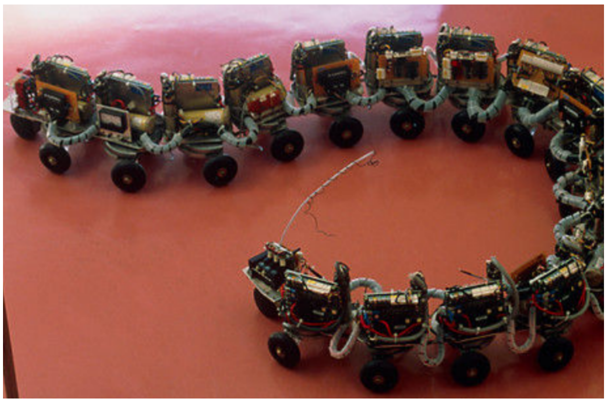


Figure 1.4 Active Cord Mechanism [10]

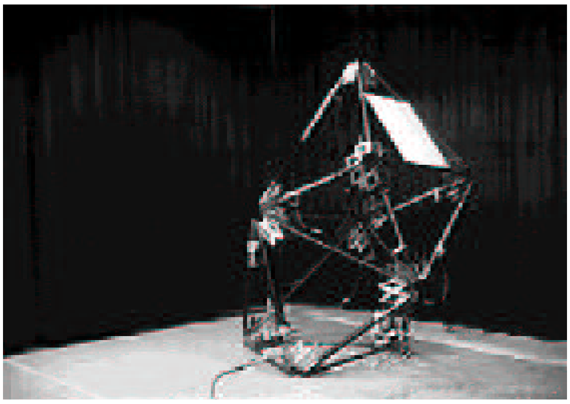


Figure 1.5 TETROBOT [5]

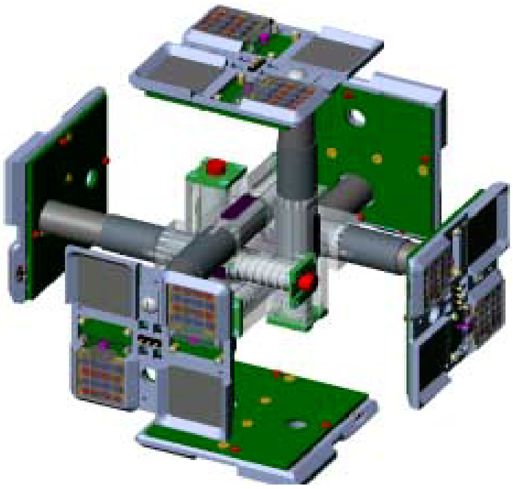


Figure 1.6 Telecube [17]

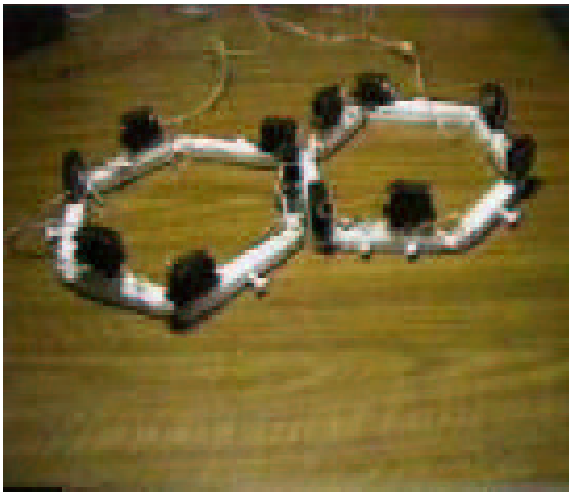


Figure 1.7 Metamorphic [10]

Figure 1.8 Fracta [10]

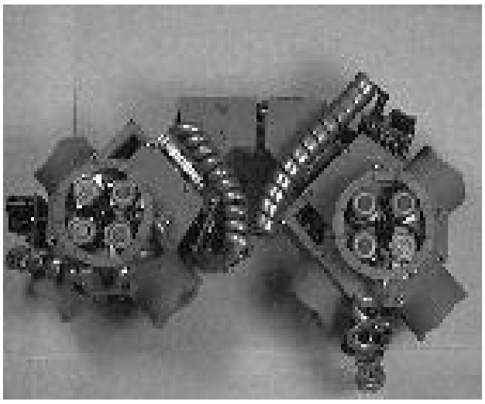


Figure 1.9 Molecule [10]

1.6.3 Cellular Robotic System

A cellular robotic system (CEBOT) is a homogeneous modular robot where each cell has limited sensing and computation. It comprises of cells having arms which can be independently extended and retracted in both directions along three orthogonal axes by actuators and coupling members at the distal ends of the arms for coupling adjacent cells. The arrangement of the cells can be modified by extending and retracting the arms and coupling and uncoupling the members [4].

1.6.4 Telecube

Telecube is a cubic module that has six prismatic degrees of freedom whose sides can expand more than twice its original length and has the ability to magnetically attach/detach to other modules as shown in Fig. 1.6. Many of these modules can be connected together to form a modular self-reconfigurable robot. The Telecube module has two basic mechanical functions: contracting/expanding; and connecting/disconnecting from the faces of neighbouring modules. This is accomplished by having each of the six faces attached to independent linear actuators. Each face, called a connection plate, has a means to reversibly clamp onto the neighbouring modules connection plate, and to transmit power and data to it. The devices which produce the linear extension/contraction and module-to-module clamps are called the telescoping-tube linear actuator and the switching permanent magnet devices [17].

1.6.5 Metamorphic Robotic System

Each module is a planar hexagonal shape with three degree of freedom that can combine with others with varying geometry. Each module has abilities to connect, disconnect and rotate around its neighbours as shown in Fig. 1.7. However, it is limited to only planar mechanisms and cannot be implemented to three dimensional workspaces.

1.6.6 Fracta

Fracta has three symmetric axes with twelve degrees of freedom. Figure 1.8 shows a unit composed of a 265 mm cube weighing 7 kg with connecting arms attached to each face [10]. Self-reconfiguration is performed by means of rotating the arms and an automatic connection mechanism. Each unit has an on-board microprocessor and communication system. The drawback of this approach is that each module is quite big and heavy. The connection mechanism uses six sensors and encoders, further increasing system complexity. However, this is one of the few systems that can achieve 3D self-reconfiguration. This system perfectly illustrates the problems with a homogeneous design: the modules become big and cumbersome.

1.6.7 Molecule

Molecules can be the basis for building self-reconfiguring robots. They support multiple modalities of locomotion and manipulation. Each molecule consists of a pair of two degrees of freedom atoms, connected by a link (called a bond). Figure 1.9 represents a Molecule type module. By suitably connecting a number of modules, 3D shapes can be formed. Twelve movements of each atom can perform self-reconfiguration. Independent movement on a substrate of molecules including straight-line traversal and 90° convex and concave transitions to adjacent surface can be performed [10].

1.6.8 Proteo

A metamorphic robot is known as Proteo. Figure 1.10 shows a Proteo robot, in which each module is a rhombic dodecahedron with twelve identical connection faces which allow other modules to be attached. Electromagnets are used for module connection. Motion is simply composed of a number of rotations about the edges of the faces [8]. This robot consists of compact homogeneous rhombus units. It is an interesting concept but the use of twelve connecting faces leads to high complexity and high cost.

1.6.9 Crystalline

The concept of a crystalline module was described by Rus and Vona [12]. Each module has a square cross-section with a connection mechanism using channels and rotating keys to lock modules together. A distributed robotic system is actuated by expanding and contracting each module. Each module can expand double its size. The module has an onboard CPU, IR communication and power supply. The crystalline robot is planar but it could be extended to 3D. The connection mechanism has male and female parts which limits possible mating configurations as shown in Fig. 1.11.

1.6.10 Semi-Cylindrical Reconfigurable Robot

It is composed of two semi-cylindrical boxes (with a servo each) connected by a link mechanism. The connecting mechanism utilizes rare-earth magnets for attaching and SMA coil springs for detaching (on one side of the connection). Processor and communication systems are embedded in each module [9]. The proposed mechanism allows robot to global move in 3D by moving each local module. The attachment and detachment are limited by the force of the magnets; therefore, a problem might occur if a module has to lift several other modules. Figure 1.12 represents a Semi-Cylindrical type of module.

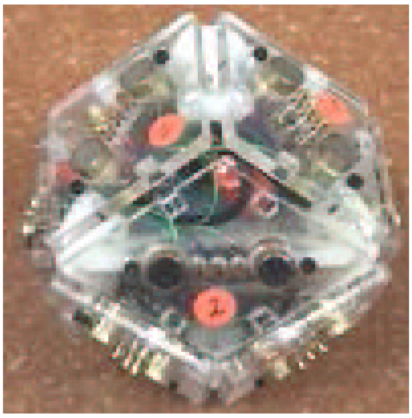


Figure 1.10 Proteo [8]

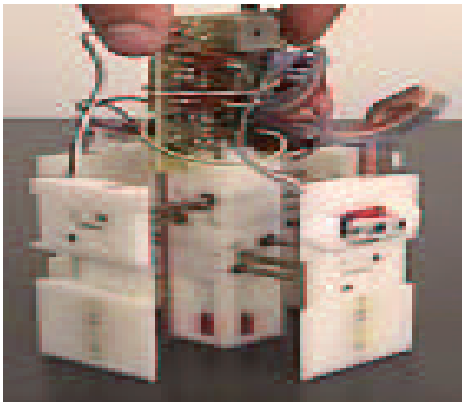


Figure 1.11 Crystalline [12]

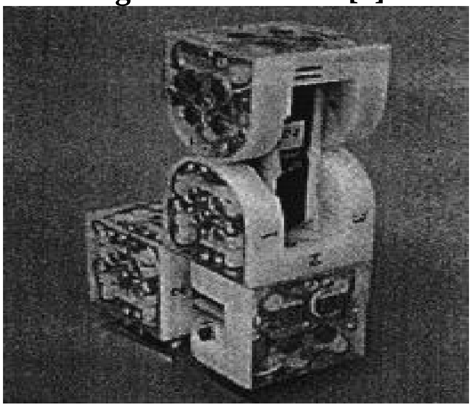


Figure 1.12 Semi-Cylindrical [9]

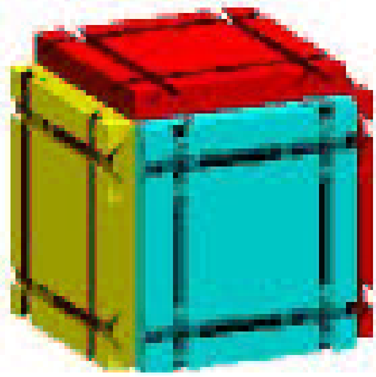


Figure 1.13 Fractal Robot [10]

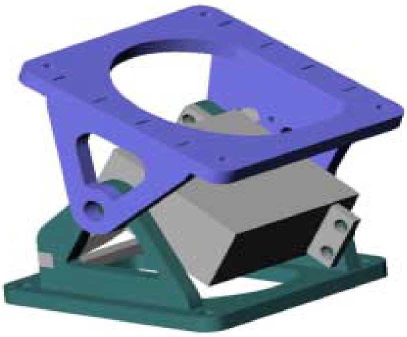


Figure 1.14 PolyBot [7]

1.6.11 Fractal Robot

A novel polymorphic robot is known as Fractal robot, shown in Fig. 1.13. It is composed of homogeneous cubes with screw and groove mechanisms at each cubic face to allow the robot to perform geometry changes and tasks. The structure formation is performed by sliding one or a group of cube to another location along attached face [10].

1.6.12 PolyBot

PolyBot is a modular reconfigurable robot system that uses hermaphroditic connection ports. The system is composed of two types of modules, one called a segment and another called a node, as shown in Fig. 1.14. Most of the functionality is found in the segment module; it has one degree of freedom and two connection ports, a DC motor and a computer. Since segments have only two connection ports, they can only be attached end-to-end and thus form single chains. The node module is rigid with no internal degree of freedom, six connection ports and a computer. Its primary purpose is to allow near arbitrary topologies (more than single chains). With enough segments and nodes, it is easy to approximate arbitrary structures. PolyBot has demonstrated the versatility promise, by implementing locomotion over a variety of terrain and manipulation versatility with a variety of objects. PolyBot is the first robot to demonstrate sequentially two topologically distinct locomotion modes by self-reconfiguration [7].

The present chapter gave a brief overview of the different modules that exists till date. The next chapter gives a literature review of the work done with modular manipulators.

CHAPTER-2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter covers the literature on the work done so far in the field of modular manipulators, in particular, on the importance of modular and reconfigurable robots. The types of modules proposed and designed by several researchers are also discussed in this chapter.

2.2 LITERATURE REVIEW

Yim et al. [7] presented examples and issues in realizing the promises like versatility, robustness and low cost for a modular manipulator. PolyBot system was used to explore the hardware reality of a robot with a large number of interchangeable modules. PolyBot demonstrated the versatility promise, by implementing locomotion over a variety of terrain and manipulation versatility with a variety of objects. PolyBot was the first robot to demonstrate sequentially two topologically distinct locomotion modes by self-reconfiguration. PolyBot had raised issues regarding software scalability and hardware dependency and as the design evolved the issues of low cost and robustness while exploring the potential of modular, self-reconfigurable robots.

Yim et al. [11] proposed a way to achieve large effective forces from weak actuators by exploiting large mechanical advantage that results from systems near singularities. While large mechanical advantages have been applied near singularities in many instances, the method allows the application of large force over a large distance. It is applied specifically to closed chain mechanisms and demonstrated on the PolyBot modular self-reconfigurable robot. Method for obtaining large variable mechanical advantage for closed chain serial manipulators with rotational degree of freedom was presented. A key additional requirement is some form of lock or brake to these degree of freedoms, i.e., a method by which the degree of freedom can be made rigid independent of the strength of the actuator. This can be an additional active brake, or self-locking actuator. The method can apply to any mechanical system that has all of the following four properties:

(i) **Redundancy** or extra degrees of freedom.

(ii) **Locking mechanism** or rake on each DOF.

(iii) **Parallelism** (or closed chain) configuration.

(iv) **Singularness,** there must be a configuration where the Jacobian is singular

Rus and Vona [12] proposed a robotic system composed of Crystalline Modules. Crystalline modules can aggregate together to form distributed robot systems. Crystalline modules can move relative to each other by expanding and contracting. This actuation mechanism permits automated shape metamorphosis. Crystalline module concept along with the basic motions that enable a crystalline robot system to self-reconfigure was dealt. 4×4 meta-modules for complete 2D reconfiguration for expanding cube style modules were used. A system composed of a specific unit module is self-reconfigurable, if the unit module satisfies the following two properties:

1. **Structure formation:** Groups of unit modules can be assembled into arbitrarily shaped rigid structures.
2. **Module relocation:** In every structure composed of unit modules; some unit module can be relocated to each location on the surface of the structure without human intervention.

Experiments were performed to evaluate the feasibility of multiple atoms to demonstrate reconfiguration. The first experiment was designed to determine if an atom could reliably expand and then connect with a neighbour. The second experiment was designed to evaluate whether atoms could work together to effect a reconfiguration. In the third experiment, the motion primitives for Crystal modules in a structure constructed out of ten modules was explored.

Fromherz et al. [13] presented a parametric model for robotic control. The complexity of related but simpler problems were studied by analyzing two classes of artificial constraint satisfaction problems inspired by (discrete) 3-SAT problems, which have a strong relation between structure and search cost. A generic benchmarking model was proposed for continuous constraint satisfaction problems. Continuous constraint satisfaction is embedded in the core of many real-world applications. Casting the control problem as a constraint problem is a promising approach for robustly handling a variety of non-standard constraints found in such robots. The experiments with generalized, sine-based CSPs appear to show that in general various problem properties need to be taken into account to characterize problem complexity. In particular, varying the constraint tightness seems to be important when generating and analyzing problems.

Kubica et al. [14] demonstrated how simple local rules, inspired by social insects, produce complex dynamic behaviors required for locomotion and navigation in modular self- reconfigurable robots. It was shown that systems made up of many modules respond dynamically to their environment, such as obstacles during navigation. The control algorithms tested on simulation experiments of Telecube, a modular robot, was presented.

Results for a typical mobile robot task: reach a target object by navigating through an environment with obstacles was presented. MSR robots present the additional requirement of reconfiguring into the appropriate shape as the task progresses. Complex interactions were produced through the propagation of information and local action guided by simple rules. The approach replaced an emphasis on global planning and centralized control with distributed behavior, local control and communications. The control primitives could be scaled up and down in the number of modules, and are general enough to fit most modular robot designs.

Vassilvitskii et al. [15] developed a versatile modular self-reconfigurable robotic systems consisting of identical units that individually were very limited in their actions. The theoretical limitations were studied for reconfiguration of metamorphic robots made up of Telecubes, six degree of freedom cube shaped modules being developed at Xerox PARC. It was shown that by using meta-modules composed of eight individual modules as a backbone for building the desired shape, it can be established a model of completeness for the reconfiguration as well as time and space bounds for the process. It was also proved that reconfiguration using meta-modules with free blocks was always possible between two systems with the same number of modules, n and, furthermore can always be done in place, with no additional space, in $O(n^2)$ total module movements. Finally several open problems in the field of reconfiguration were presented.

Vassilvitskii et al. [16] presented a complete, local, and parallel reconfiguration algorithm for metamorphic robots made up of Telecubes, six degree of freedom, cube shaped modules developed at Xerox PARC. It was shown that by using 2×2×2 meta-modules, completeness of reconfiguration space using only local rules can be achieved.

Furthermore, the reconfiguration can be done in place and massively in parallel with many simultaneous module movements. A simulator for the Telecube system was developed. The simulator written in Java, limited each module to the same exact primitives as those of the true physical module. Each module in the simulator had the opportunity to move once per time step. To simulate the asynchronous qualities of the system, the order in which the modules move was randomized and was different each turn. For simplicity, the state of the module arms to either fully extended or fully contracted. It was also assumed that the module arms were infinitely rigid so that they occupy the nodes of a perfect lattice structure at all times. During each simulated move actuator torque and stiffness constraints were imposed to make sure the modules were not dragging more than two other modules per move. The global connectivity constraint was also checked before every disconnect request.

Suh et al. [17] presented the intended functions, discussed the physical requirements of the modules and described two key mechanical components: a compact telescoping linear actuator and a switching permanent magnet device. The main design requirements for the module of Telecube were the shape, size, and number of degrees of freedom. The scheme required an expanded-to-contracted ratio of at least 2:1. To assist in making and breaking connections the insertion and uncoupling forces needed to be very low. Telecube module was designed as an assembly of two major sub-assemblies: the motor core and the six connection plates. The motor core holds all of the gear motors and was the structural center of the module. The six connection plates were attached to the ends of inner tube of the linear actuator. Each contains the switching permanent magnet devices, power interconnects, data transfer devices and printed circuit board.

Bi et al. [20] presented an automated method to build kinematic and dynamic models for assembling modular components of modular robotic systems. When compared with other approaches, the proposed method was applicable to any robotic configuration with serial, parallel, or hybrid structures. In addition, it was object oriented so that each modular component was an element with a sub-model and the overall model was assembled from sub-models subject to the connection constraints.

FEM model was used in extension to the automated kinematic and dynamic modeling of modular robotic systems. The proposed method separated the dynamic modeling from the kinematic modeling, and the dynamic model was treated after the kinematic model was complete. The proposed method supports the definition of complex modules in which multiple rigid bodies and joints were included. The proposed method was not only effective for the automated modeling of modular configurations; it could also be applied to other configurations including those with closed loop chains.

Bi et al. [21] proposed a more general architecture of modular manipulator systems. Based on this new architecture, proposed a systematic procedure to generate a mapping from modular design variables and the configuration description in terms of the DH notation. Analysis models were to describe the relationships between design variables and robotic kinematic and dynamic behaviors. In designing modular robotic system configuration, design variables were identified through the description of the modular system architecture. Once the design variables were determined, two alternative ways were employed to build kinematic and dynamic models from design variables i.e., direct modeling and indirect modeling. The first method builds up the kinematic and dynamic model directly based on design variables of the modular architecture, while the second method builds up the kinematic and dynamic model based on a set of the DH parameters, which was derived from design variables. The advantage of the second method is that most of analysis theories and tools, which were developed in designing non-modular robotic configurations, were utilized directly for designing modular robotic configurations.

Fei and Zhao [22] designed a novel, interactive, lattice-based self-reconfigurable modular robot. The presented module was composed of a cubic part and six rotary sides. There were two holes and two extension pegs on each side. Rotary motion was generated by a motor with a reducer by using cone-shaped gears. Its quick disconnect/connect mechanism were analyzed. A Face-Face Incidence Matrix (FFIM) was proposed to describe the relationship and motion between modules. The states of docking and constraint between modules were analyzed with the geometric method and the contact forces of docking were calculated. Finely, a self-reconfigurable robot consisting of five similar modules were developed which performed desired task and followed the exact path. The results verify the analysis.

2.3 CONCLUSIONS FROM LITERATURE REVIEW

Survey of the previous works in modular and reconfigurable robotic arms is presented in this chapter. Following key observations are made:

(i) The works are usually inclined towards versatility and robustness of the modules. This is in particular, required for self-reconfigurable robotic arms.

(ii) Not much work is done, related to the handling of DH parameters. It is concluded therefore, that a novel work of designing and developing modular design for fabrication of serial-manipulators for any value of DH parameters (robotic parameters) would be a great contribution to this field of modular manipulators.

CHAPTER-3

PROBLEM FORMULATION

3.1 PROBLEM FORMULATION

For the fabrication of *n*-link robotic manipulator – designed in a completely 'general' sense, through all the DH parameters as design variables – it is proposed in the present work to design highly generic link-joint modules. For such a robotic arm, it is required to handle the fabrication of each link which may have any real values of its length and rest of the parameters (DH parameters). Based on the complexity of such fabrication issues, this work emphasizes on presenting a solution for developing a Robotic arm.

To design a link-joint module, possible varying parameters are: link length (a), twist (α), joint angle (θ) and joint offset (d), so as to assist in fabrication of customized serial manipulators.

A brief description of these parameters is hereby given with Fig. 3.1.

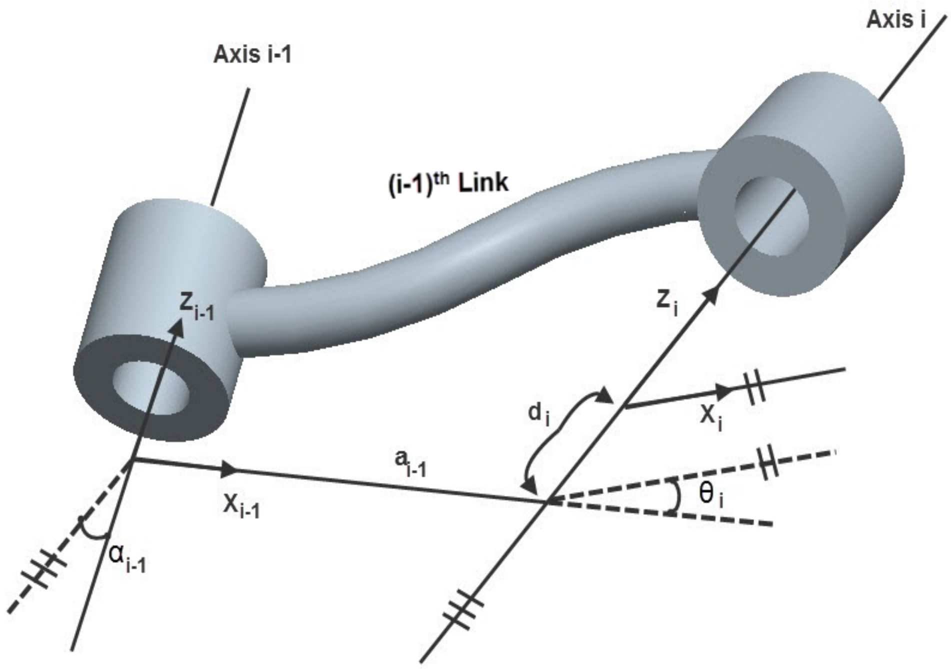


Figure 3.1 DH Parameters

Link Parameters:

(i) Link Length (a_i) –– The distance from Z_i to Z_{i+1} measured along X_i

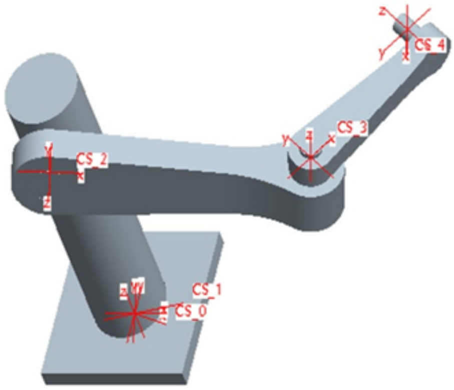
(ii) Link Twist (α_i) –– The angle between Z_i and Z_{i+1} measured about X_i

Joint Parameters:

(iii) Joint Angle (θ_i) –– The distance from X_{i-l} to X_i measured along Z_i

(iv) Joint Offset (d_i) –– The angle between X_{i-l} and X_i measured about Z_i

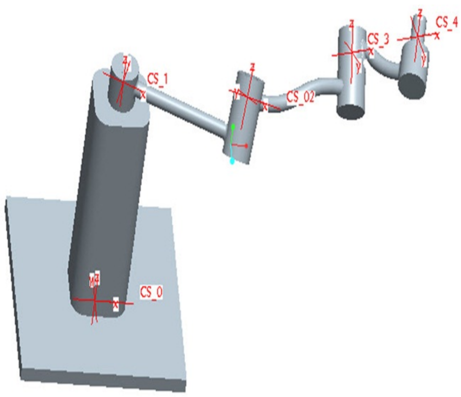
The fabrication of the link-joint is not much complicated for simple values of DH parameters. Such types of commonly used DH parameters are given in Table 3.1 and shown in Fig. 3.2.



S. No.	a_{i-1}	α_{i-1}	d_i	θ_i
1.	0	0	0	12^o
2.	175	$+90^o$	40	18^o
3.	170	-90^o	22.5	48^o
4.	110	90^o	20	90^o

Figure 3.2 Manipulator_1 4-R **Table 3.1 DH parameters of 4-R manipulator_1**

But with complicated values of link length and twist angle, the fabrication becomes difficult. The example of such DH parameters is given in Table 3.2 and Fig. 3.3.



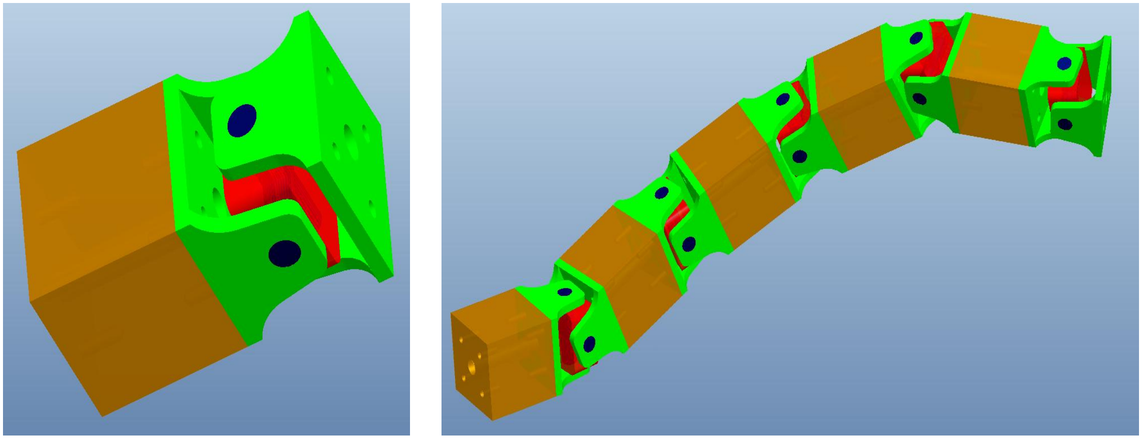
S. No.	a_{i-1}	α_{i-1}	d_i	θ_i
1.	0	0	345	-22^o
2.	220	-36^o	50	35^o
3.	200	-30^o	93.30	-52^o
4.	120	-18^o	16.71	0^o

Figure 3.3 Manipulator_2 4-R **Table 3.2 DH parameters of 4-R manipulator_2**

If there is a need for a manipulator with a large number of links like a Hyper-Redundant manipulator and each link is having different value of DH Parameters, then to fabricate each link for different Link Length and Twist Angle is very complicate, time consuming and costly.

To eliminate the problem of fabrication for such manipulators, a new concept of modular manipulators can be used. Such manipulators can be fabricated in parts, Fig. 3.4 (a) shows a module and Fig. 3.4 (b) shows a modular manipulator. And according to the adjustment of these parts required Link Length and Twist Angle can be obtained.

A module is a complete combination of link and joint which can be joined with its similar type of modules to do the complicated works as desired.



(a) (b)

Figure 3.4 (a) Module; (b) Modular Manipulator

3.1.1 Link Length Adjustment

For link length adjustment, a number of designs can be used. One such design is given in Fig. 3.5. The link can be developed in two parts –– male and female. The length can be adjusted by inserting a pin in one of the holes, which are provided along the length, as shown in Fig. 3.5.

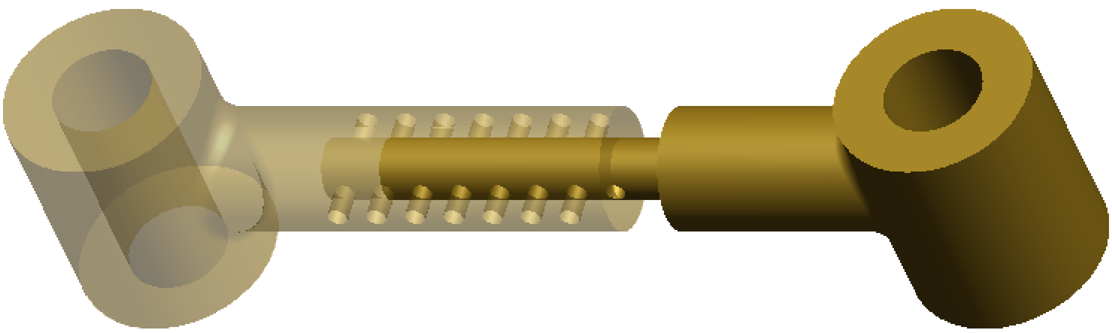


Figure 3.5 Link Length Adjustment

3.1.2 Twist Angle Adjustment

For adjustment of link twist, the end of two parts can be threaded, internally and externally. The twist angle can be adjusted by rotation of one part on the other, thus providing twist to the link axis, shown in Fig. 3.6.

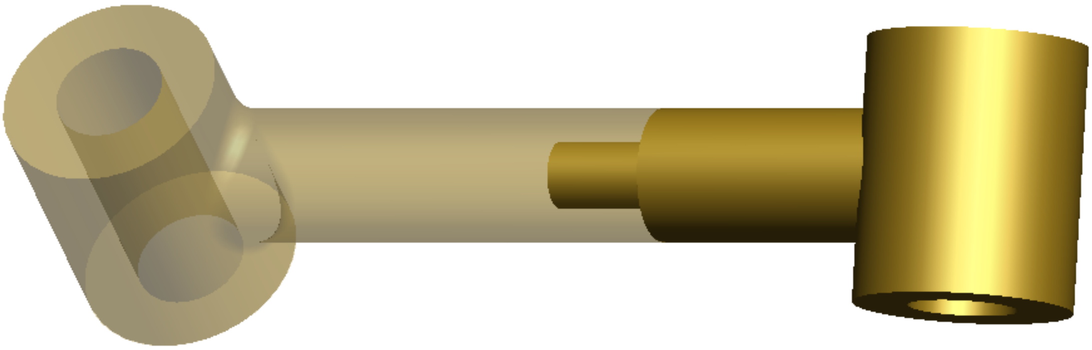


Figure 3.6 Twist Angle Adjustment

Figure 3.5 and 3.6 demonstrated a method for the length and angle adjustment. There can be many more ways to solve the same problem, which can be explored.

The benefit of doing the variable adjustment is that it will assist to develop the customized manipulator, which will increase its domain of workspace.

3.2 METHODOLOGY

The methodology to implement the strategy for solving the problem defined and described in previous section can be outlined as:

1. Study and selection of length adjustment strategies to handle – varying Link Length (a), varying Joint Offset (d).
2. On similar terms, the angle adjustment need to be performed, to be studied for varying Link Twist (α) and Joint Rotation (θ).
3. Solid modeling at each stage would be developed, for better visualization and for the analysis and demonstration of modules and complete robotic arm.

CHAPTER-4

MODULAR LINK DESIGN

4.1 MODULE DESIGN

If there is a need for a manipulator with a large number of links like a Hyper-Redundant manipulator and each link is having different value of DH Parameters, then to fabricate each link for different Link Length and Twist Angle it is very complicate, time consuming and costly.

To eliminate the problem of fabrication for such manipulators a new concept of modular manipulators can be used. Such manipulators can be fabricated in parts instead of a single piece. And according to the adjustment of these parts required Link Length and Twist Angle can be obtained.

The concept of adjustment of link length and twist angle can be further implemented as follow:

4.1.1 Link Length Adjustment

For adjustment of the link length the module can be developed in two parts; male and female. The male part is having a number of holes perpendicular to its axis and female part is having a single hole. Its desired length can be obtained by inserting a pin in the hole along the length of components, shown in Fig. 4.1.

4.1.2 Twist Angle Adjustment

Twist Angle can be adjusted by a mechanism attached to parts, shown in Fig. 4.2 and Fig. 4.3. In this mechanism a casing is provided on outer surface of female part. U-shaped rod with one end flattened can be used to attach the two parts to each other at specified twist angle. The flat end of rod is attached to female parts where it can rotate freely and other end having a threaded pin can be used to screw in any hole patterned about axis provided on outer surface of male part. According to the hole in which U-shaped rod is attached, desired twist angle can be obtained.

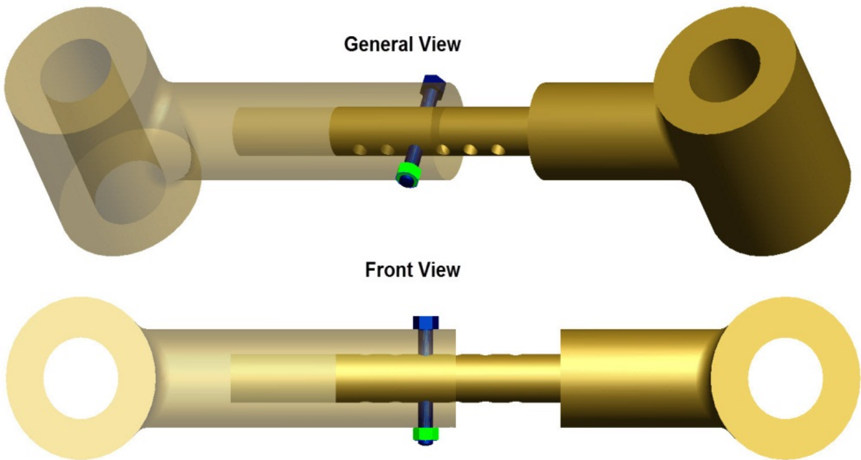


Figure 4.1 Link Length Adjustment

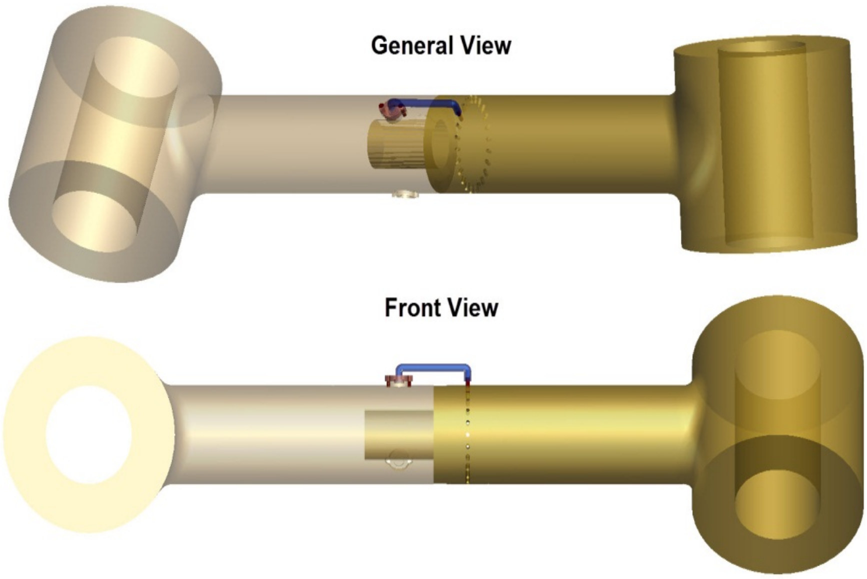


Figure 4.2 Twist Angle Adjustment

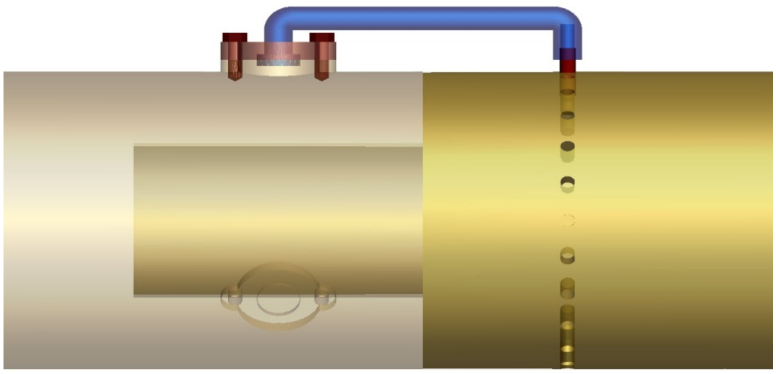


Figure 4.3 Twist Angle Adjustment Enlarged View

Now to obtain, configuration for different values of twist angle with limited number of holes on the male part, more number of casings can be provided on female part to hold the U-shape rod. Only one casing is to be used for single configuration. For example, if there are *24* holes, then they are at the angle of $360^o/24$, i.e. 15^o each on the circumference.

Thus, using single casing the adjustment of Twist Angle can be made by 15^o. The Twist angles obtained are *0, 15, 30, 45 … 345, 360*. If the numbers of casing on the female parts are increased say three as in Fig. 4.4, where the angle between casing at top to casing at lower-left side is 125^o, which when used give Twist Angles in the pattern of *5, 20, 35, 50 … 335, 350*. And in case of lower-right casing which is further at an angle of 125^o from the lower-left casing provides the Twist angles of *10, 25, 40, 55 … 340, 355*. Its variation in twist angle twist angle can be further reduced by increasing the number of casings.

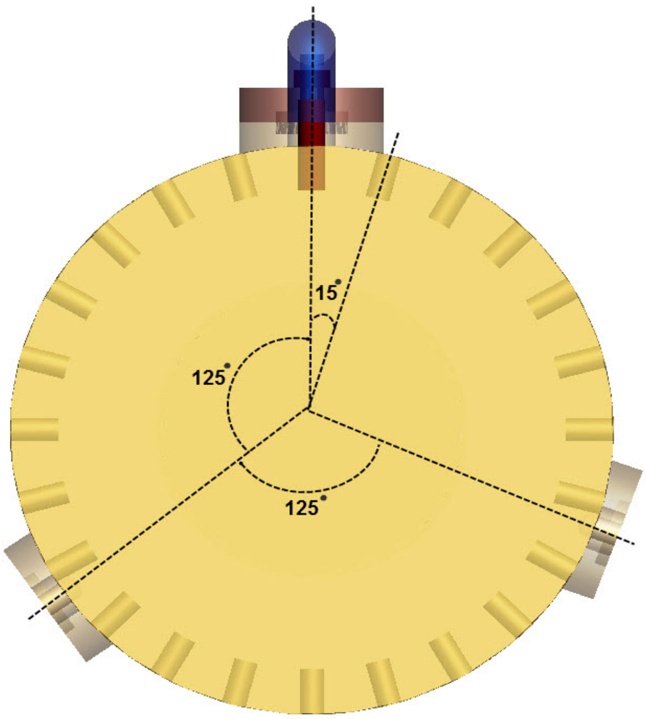


Figure 4.4 Twist Angle Variation with Different Casing

4.1.3 Combined Link Length And Twist Angle Adjustment

The above two designs are combined in a single module as shown in Fig. 4.5 and Fig. 4.6.

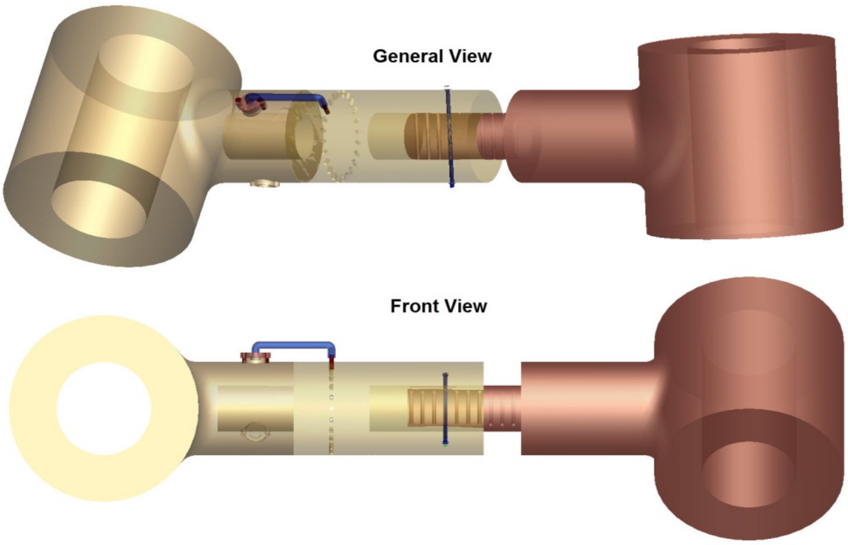


Figure 4.5 Combined Adjustment of Link Length and Twist Angle

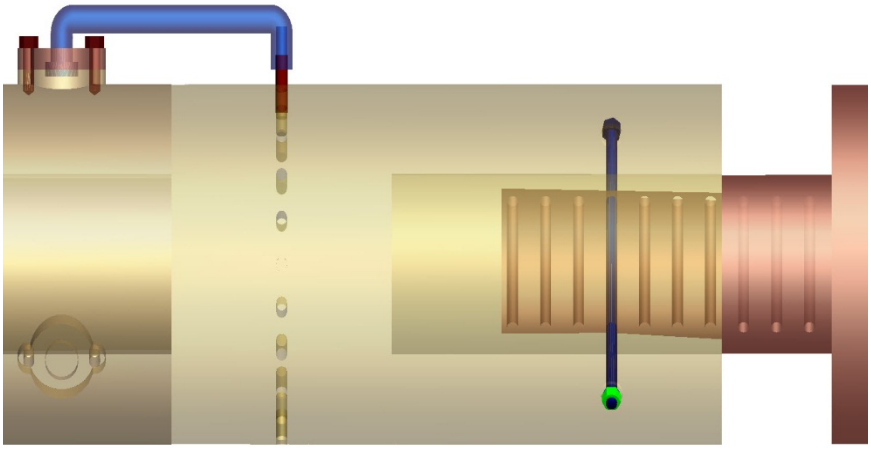


Figure 4.6 Combined Enlarged View

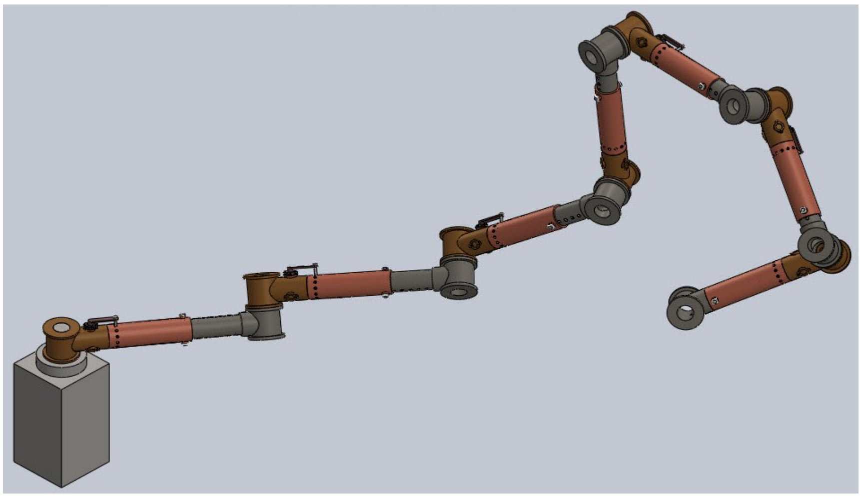


Figure 4.7 Manipulators using Modules

These modules can be joined to obtain complicated valued of DH parameters as shown in Fig. 4.7.

CHAPTER-5

MODULAR LINK ANALYSIS

5.1 INTRODUCTION TO ANALYSIS

After modeling the modular link in 3D modeling software, Pro/Engineer, the analysis of modular link is carried out in ANSYS, which provides a platform for the interface to import the files from various 3D modeling software as well as support IGES file format.

The modular link is considered as a cantilever beam. Its one end remains fixed and other end if it is last one in robotic arm act as free end. Analyses were carried out by varying in link length, outer diameter and inner diameter of link, and varying the load at the end-point. These results were also compared with the analytical results. Analytical formulas for a cantilever beam have been used.

5.1.1 Analytical Formulas for a Cantilever Beam

Bending moment equation,

$$\frac{M}{I} = \frac{\sigma_b}{y} = \frac{E}{R}$$

Where:

$I = \frac{\pi(D_o^4 - D_i^4)}{64}$, moment of inertia for hollow cylindrical section

$y = D_o$, distance of outermost layer from neutral axis

E = Young's modulus

R = Radius of curvature

M = Maximum bending moment

$= -\frac{WL^2}{2}$, for cantilever beam with UDL on entire beam

$= -\frac{WL^2}{2} + P \times L$, for cantilever beam with UDL on entire beam and 'P' load at the end

Now,

Maximum stress, $\sigma_b = \frac{M}{I}$

Strain, $\epsilon = \frac{\sigma_b}{E}$

Deflection, $\delta = \frac{WL^4}{8EI}$, for cantilever beam with UDL on entire beam

$= \frac{WL^4}{8EI} + \frac{PL^3}{3EI}$, for cantilever beam with UDL on entire beam and ‘P’ load at the end

All of these analytical formulas were used in a MATLAB program. This program automatically varies the parameters and draws graphs corresponding to the results. And these results are compared with ANSYS results.

5.1.2 Link Length Variation

An analysis is carried out by ANSYS for link length variation. In case of link length variation, there is only change in length and other all parameters: inner diameter – *50* mm and outer diameter – *60* mm, had taken as constant and material for all results verification is taken as structure steel having properties given in Table 5.1. The ANSYS results for deformation with variation in link length are shown in Fig. 5.1(a) to Fig. 5.1(f). The corresponding link lengths are *5* mm, *75* mm, *150* mm, *250* mm, *350* mm and *400* mm. The results for strain due to link length variation are shown in Fig. 5.2(a) to Fig. 5.2(f) and results for stress due to link variation are shown in Fig. 5.3(a) to Fig. 5.3(f).

Property	Value
Density	7850 kg/m^3
Young's Modulus	2E+05 MPa
Poisson's Ratio	0.3
Tensile Yield Strength	250 MPa
Compressive Yield Strength	250 MPa
Tensile Ultimate Strength	460 MPa
Compressive Ultimate Strength	0 MPa

Table 5.1 Material properties of structure steel

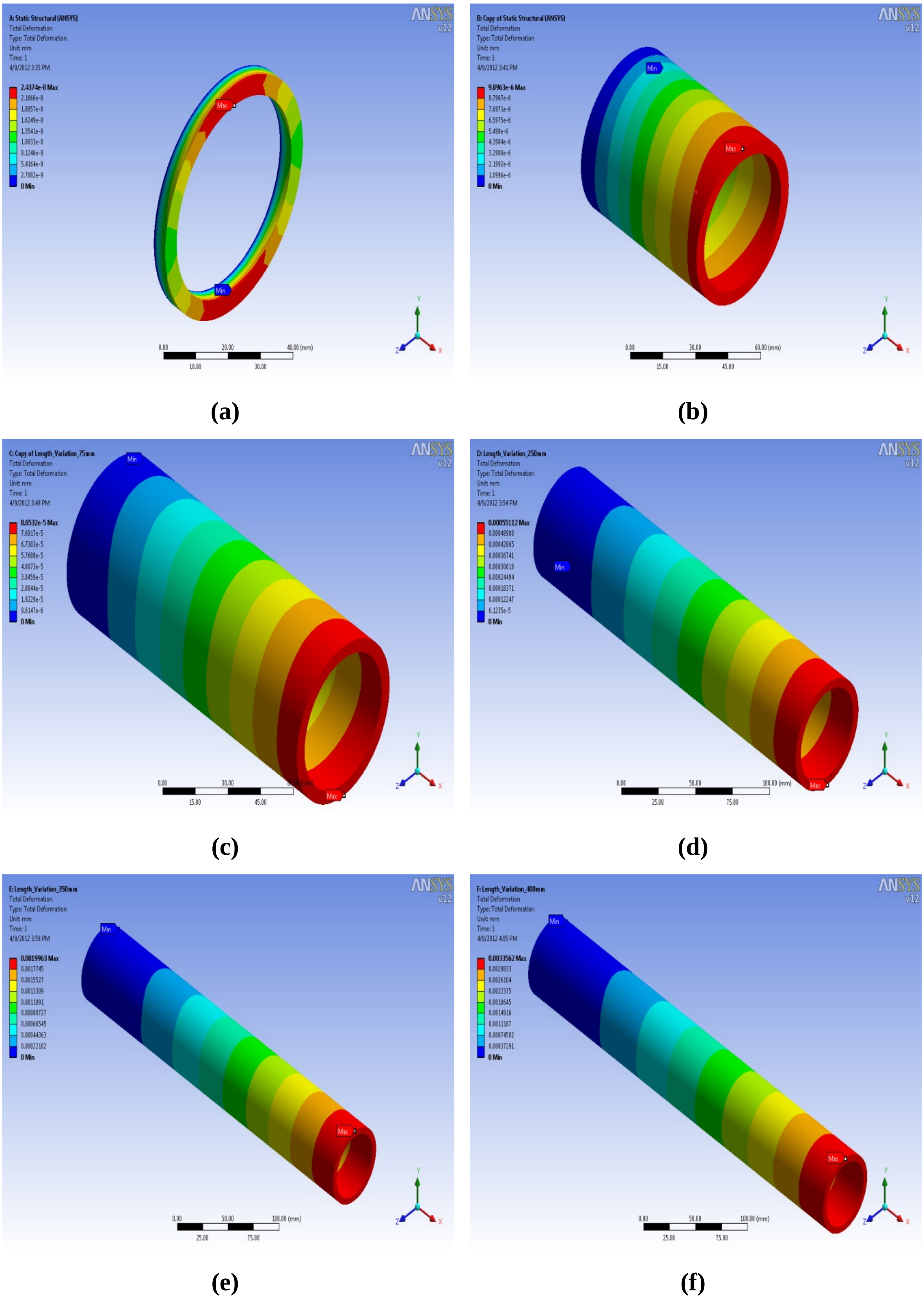
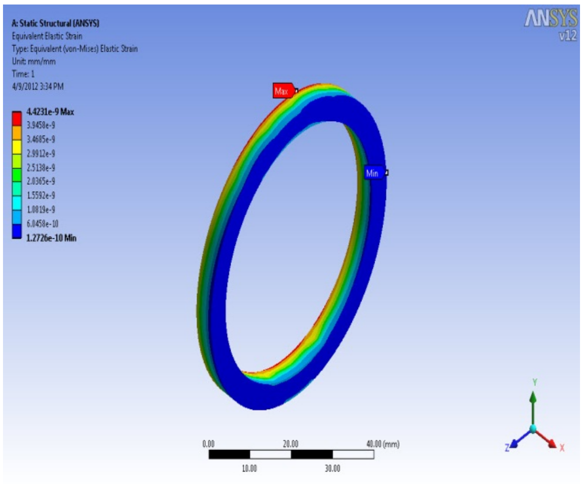
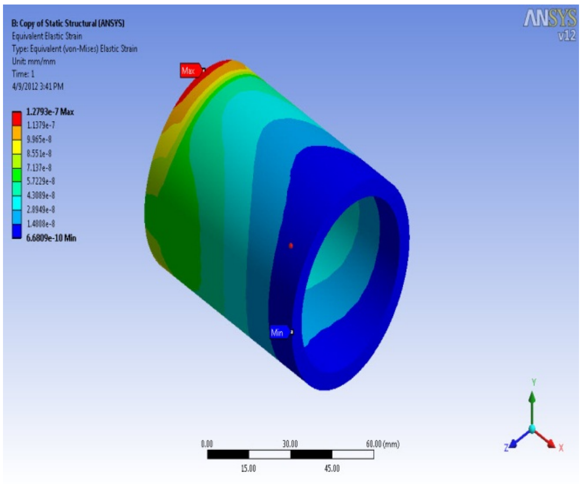


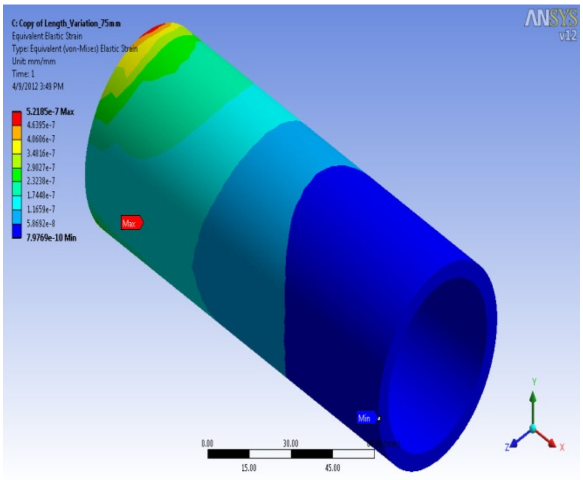
Figure 5.1 Deformation only with varying link lengths – (a) 5 mm, (b) 75 mm, (c) 150 mm, (d) 250 mm, (e) 350 mm, (f) 400 mm.



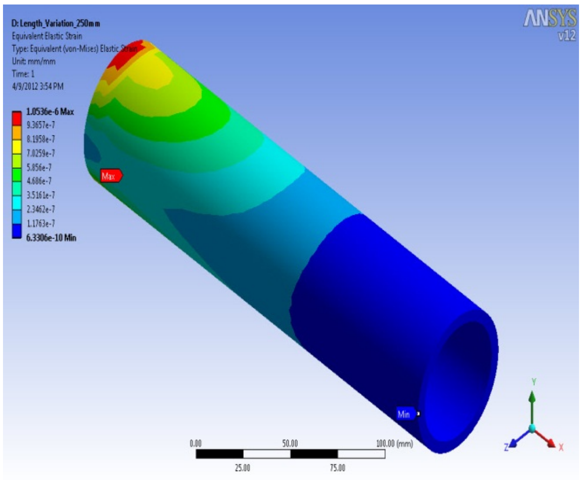
(a)



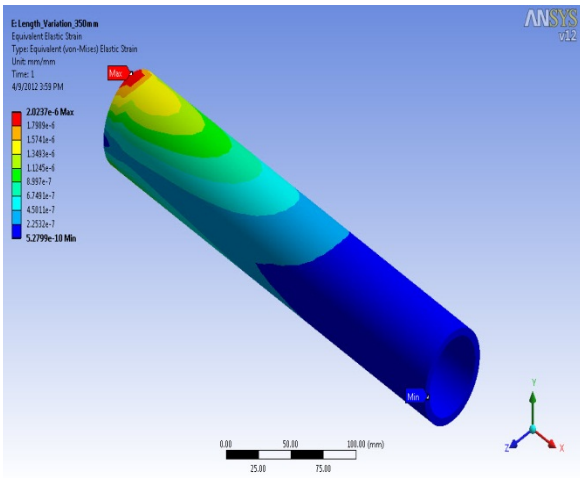
(b)



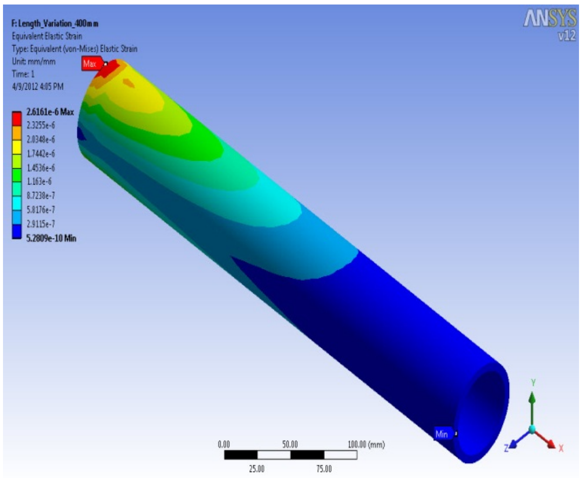
(c)



(d)



(e)



(f)

Figure 5.2 Strain only with varying link lengths – (a) 5 mm, (b) 75 mm, (c) 150 mm, (d) 250 mm, (e) 350 mm, (f) 400 mm.

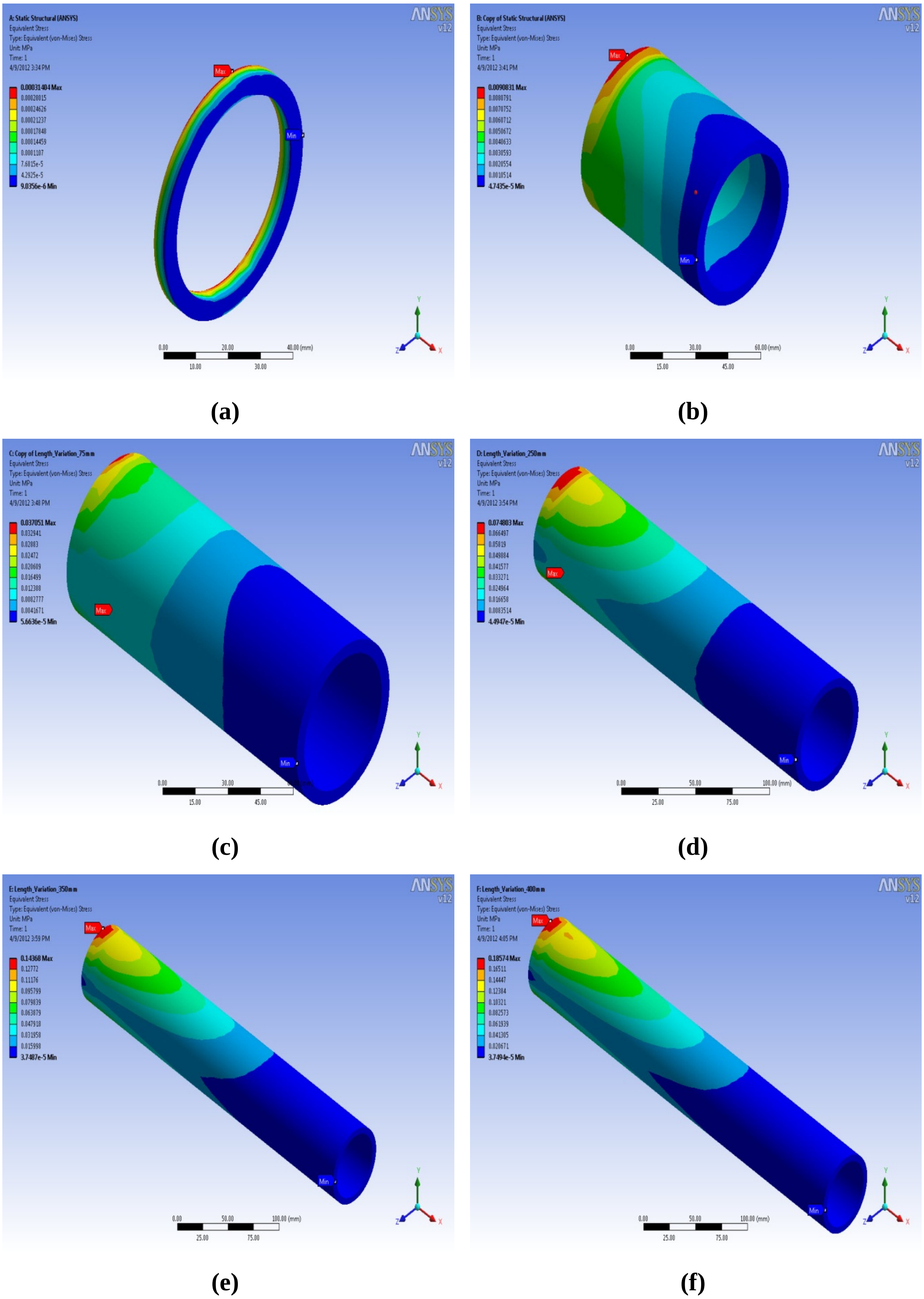


Figure 5.3 Stress only with varying link lengths – (a) 5 mm, (b) 75 mm, (c) 150 mm, (d) 250 mm, (e) 350 mm, (f) 400 mm.

Length Variation - Without any Loading, Only Gravity					
S. No.	**Length (mm)**	**Mass (kg)**	**Deformation (mm)**	**Strain (mm/mm)**	**Stress (MPa)**
1	5	1.20E-02	2.4374E-08	4.4231E-09	3.14E-04
2	75	0.17948	9.8963E-06	1.2793E-07	9.08E-03
3	150	0.35897	8.6532E-05	5.2185E-07	3.71E-02
4	250	0.59828	5.5112E-04	1.0536E-06	7.48E-02
5	350	0.83759	1.9963E-03	2.0237E-06	0.14368
6	400	0.95724	3.3562E-03	2.6161E-06	0.18574

Table 5.2 Result of link length variation

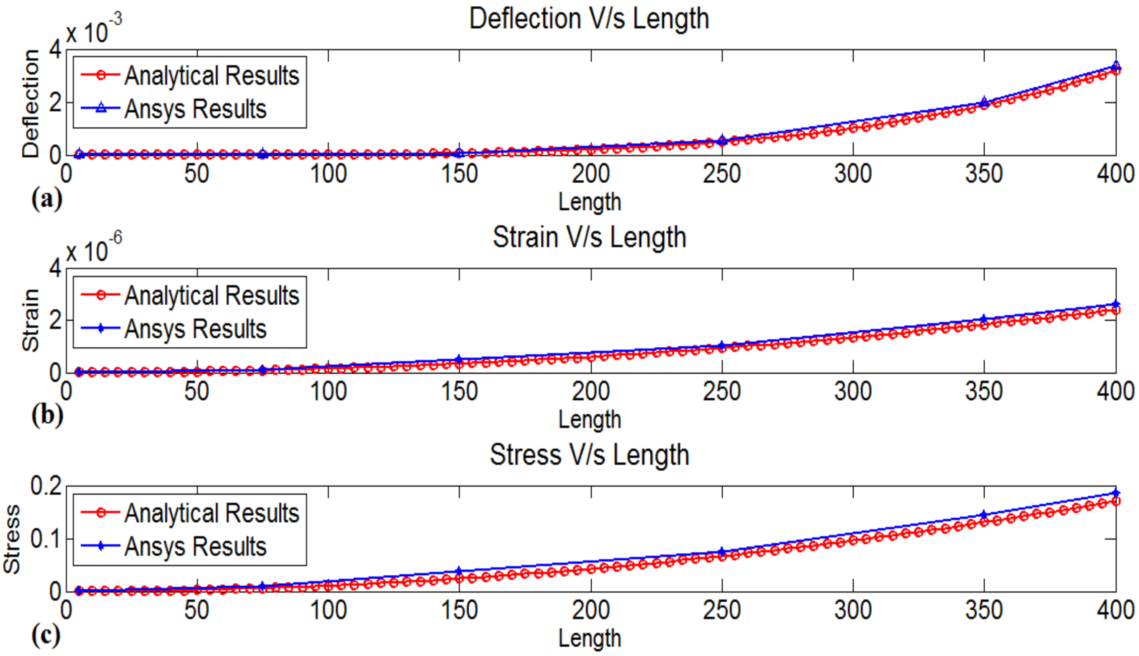


Figure 5.4 Comparison of Analytical v/s ANSYS results due to link length variation

The results for deformation, strain and stress due to link length variation are tabulated in Table 5.2. These tabulated result from Table 5.2, compared to the analytical results using a graph shown in Fig. 5.4. The following conclusions are drawn:

Variation in stress is parabolic as

$$\sigma_b \propto L^2$$

Variation in strain is also parabolic as

$$\epsilon \propto L^2$$

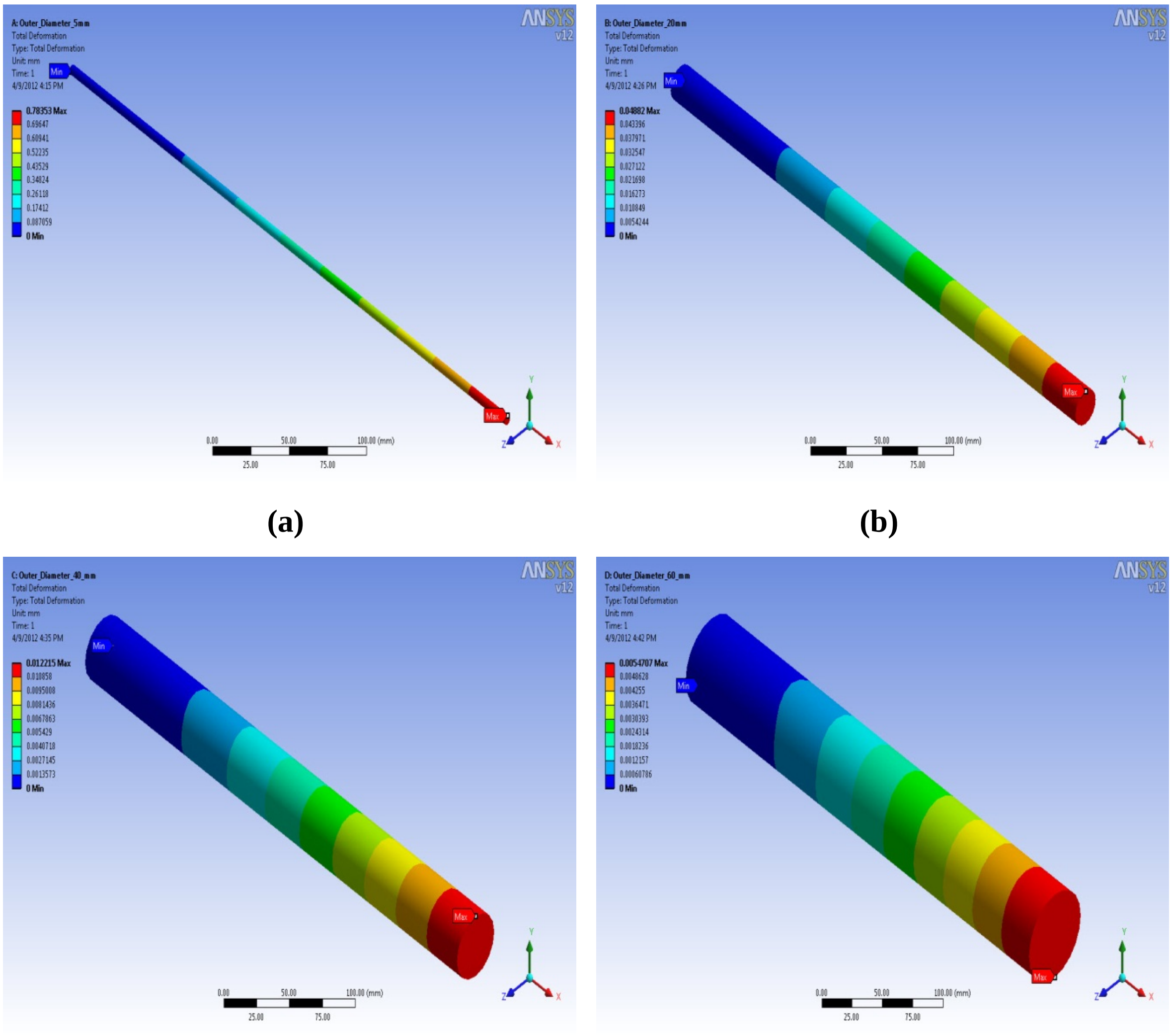
Deflection varies as 4th power of length

$$\delta \propto L^4$$

Results from analytical calculations and ANSYS calculations for link length variation are found in close agreement, which validated the authenticity of ANSYS results.

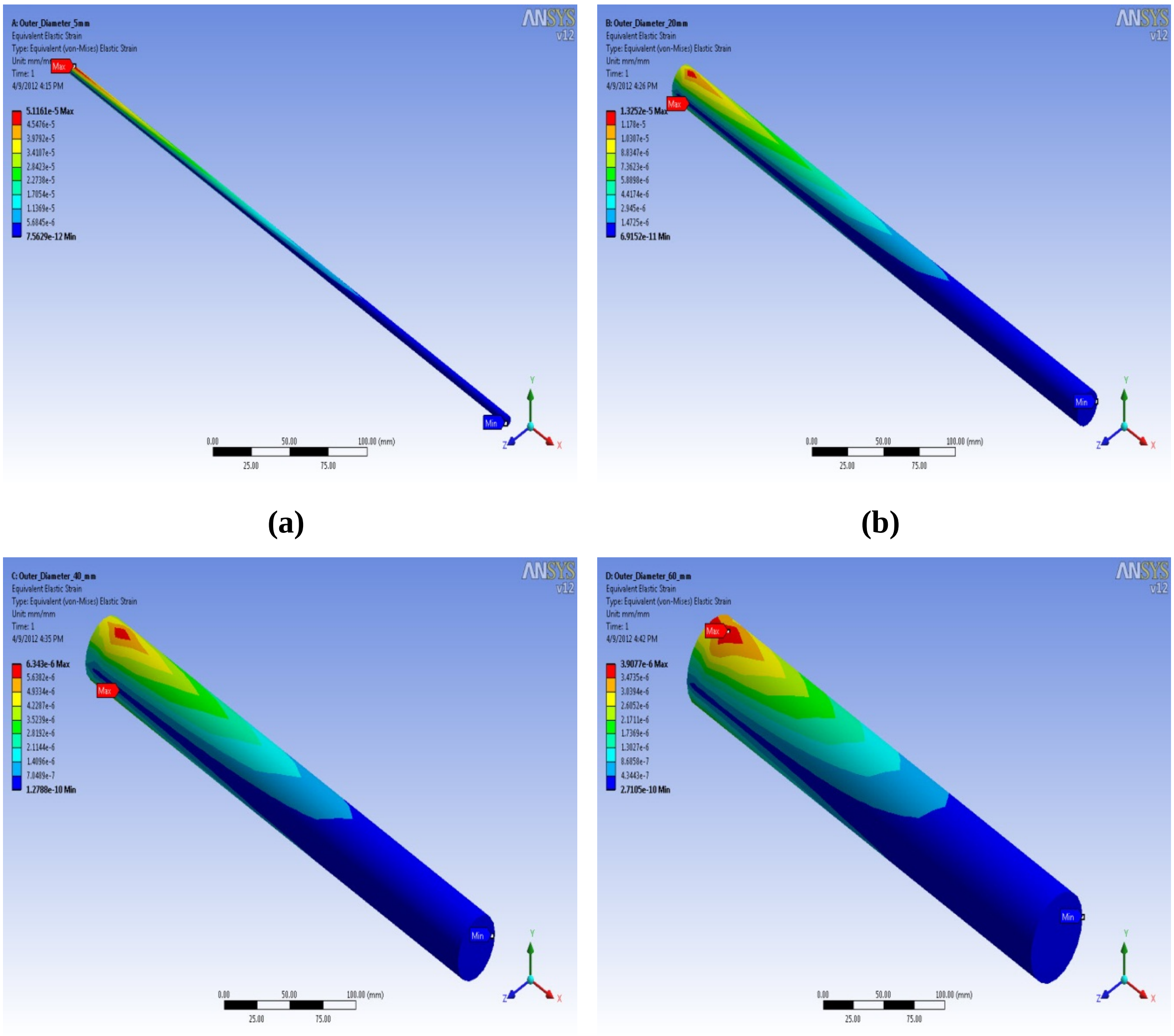
5.1.3 Outer Diameter Variation

The modular link is analyzed with link length to be constant as *400* mm and varying outer diameter. Its outer diameter is taken as *5* mm, *20* mm, *40* mm and *60* mm. The variation in Deformation, Strain and Stress due to variation in outer diameter is shown in Fig. 5.5(a) to Fig. 5.5(d), Fig. 5.6(a) to Fig. 5.6(d) and Fig. 5.7(a) to Fig. 5.7(d) respectively. The results obtained are tabulated in Table 5.3.



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

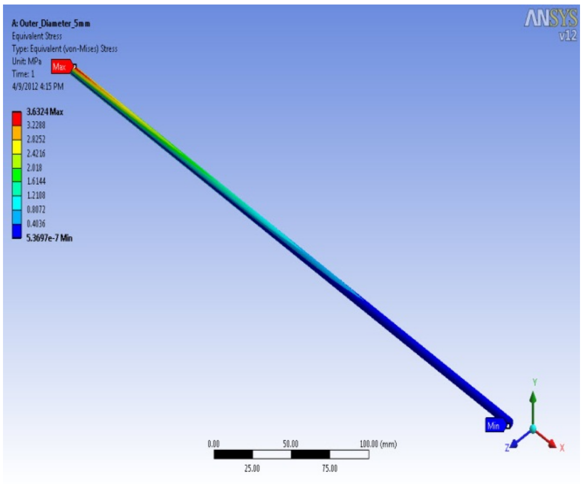
Figure 5.5 Deformation only with varying outer diameter – (a) 5 mm, (b) 20 mm, (c) 40 mm, (d) 60 mm.



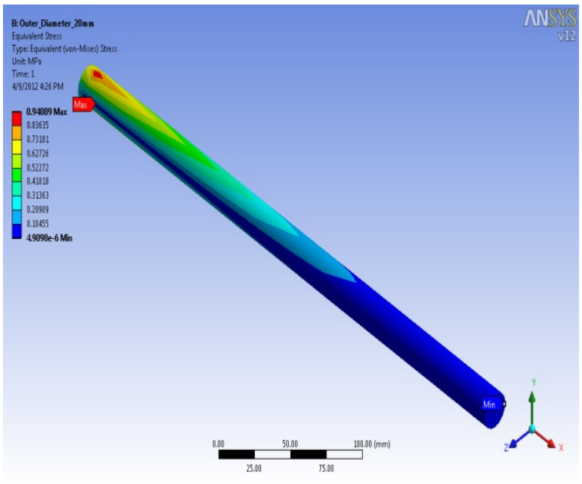
(a) **(b)**

(c) **(d)**

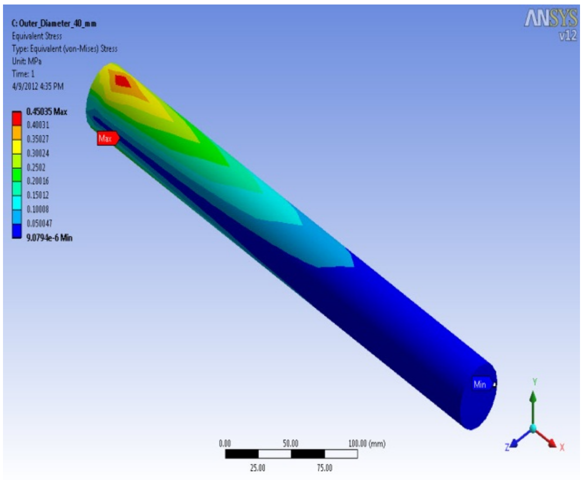
Figure 5.6 Strain only with varying outer diameter – (a) 5 mm, (b) 20 mm, (c) 40 mm, (d) 60 mm.



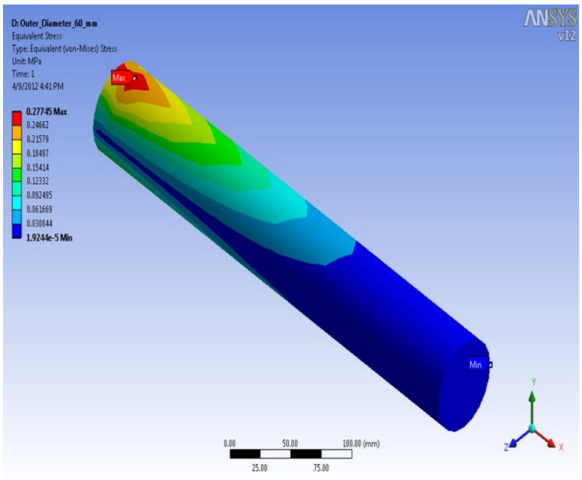
(a)



(b)



(c)



(d)

Figure 5.7 Stress only with varying outer diameter – (a) 5 mm, (b) 20 mm, (c) 40 mm, (d) 60 mm.

Outer Diameter Variation - Without any Loading, Only Gravity					
S. No.	**Outer Diameter (mm)**	**Mass (kg)**	**Deformation (mm)**	**Strain (mm/mm)**	**Stress (MPa)**
1	5	2.18E-02	7.8353E-01	5.1161E-05	3.6324
2	10	8.70E-02	1.9554E-01	2.6998E-05	1.9168
3	20	0.34809	4.8820E-02	1.3252E-05	0.94089
4	40	1.3924	1.2215E-02	6.3430E-06	0.45035
5	60	3.1328	5.4707E-03	3.9077E-06	0.27745

Table 5.3 Result of outer diameter variation

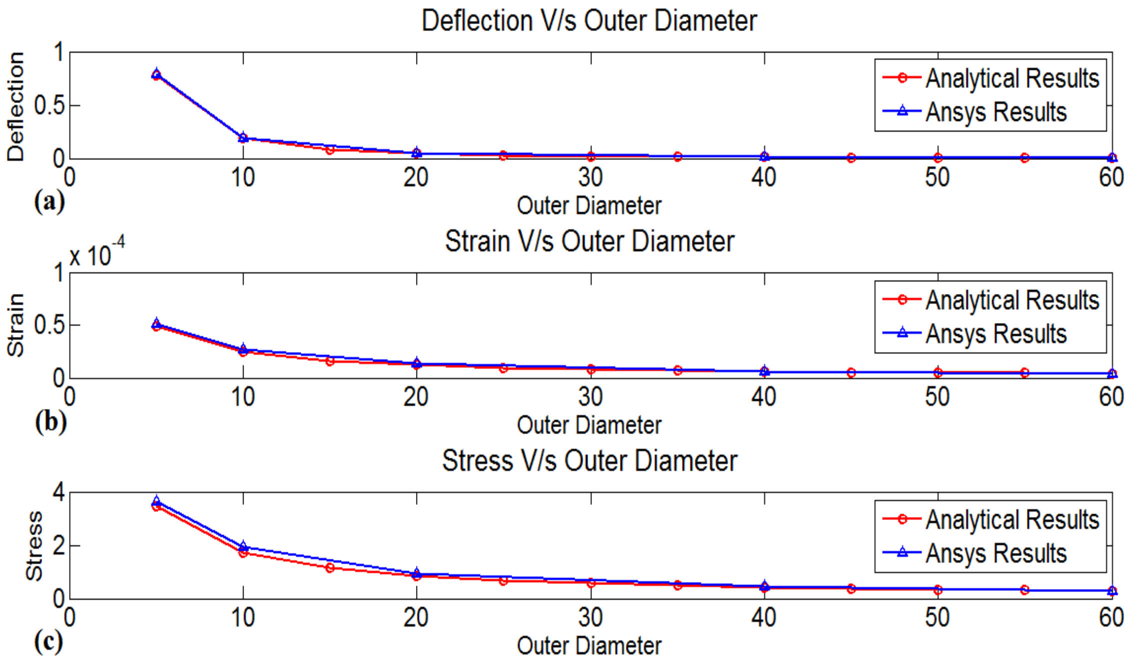


Figure 5.8 Comparison of Analytical v/s ANSYS results due to outer diameter variation

Comparative graph for variation in deformation, stress and strain due to outer diameter variation using analytical formulas and using ANSYS is shown in Fig. 5.8(a) to Fig. 5.8(c). The following conclusion obtained:

Variation in stress is found as

$$\sigma_b \propto \frac{1}{D_o^4}$$

Variation in strain is found as

$$\in \propto \frac{1}{D_o^4}$$

Deflection depends upon weight and weight is inversely proportional to volume and volume is directly proportional to square of outer diameter. Thus

Variation in deflection is found as

$$\delta \propto \frac{1}{D_o^2}$$

Results from Analytical calculations and ANSYS calculation for outer diameter variation are found in closed agreement, which validates the authenticity of ANSYS results.

5.1.4 Inner Diameter Variation

The deformation, strain and stress due to variation in inner diameter are shown in Fig. 5.9(a) to Fig. 5.9(f), Fig. 5.10(a) to Fig. 5.10(f) and Fig. 5.11(a) to Fig. 5.11(f) respectively. Here, the Inner diameter is taken as *5* mm, *10* mm, *20* mm, *30* mm and *40* mm and *50* mm while keeping other parameters fixed as link length *400* mm and outer diameter as *60* mm. The results are tabulated in Table 5.4.

Comparative graph for variation in deformation, stress and strain using analytical formulas and using ANSYS is shown in Fig. 5.12(a) to Fig. 5.12(c). The conclusion drawn out from graph is as follows:

Variation in stress is found as

$$\sigma_b \propto \frac{1}{{D_o}^4} - \frac{1}{{D_i}^4}$$

Variation in strain is found as

$$\epsilon \propto \frac{1}{{D_o}^4} - \frac{1}{{D_i}^4}$$

Deflection depends upon weight and weight is inversely proportional to volume and volume is directly proportional to square of negative of inner diameter. Thus

Variation in deflection is found as

$$\delta \propto \frac{1}{{D_o}^2} - \frac{1}{{D_i}^2}$$

Results from Analytical calculations and ANSYS calculation for inner diameter variation are found in close agreement, which validates the authenticity of ANSYS results.

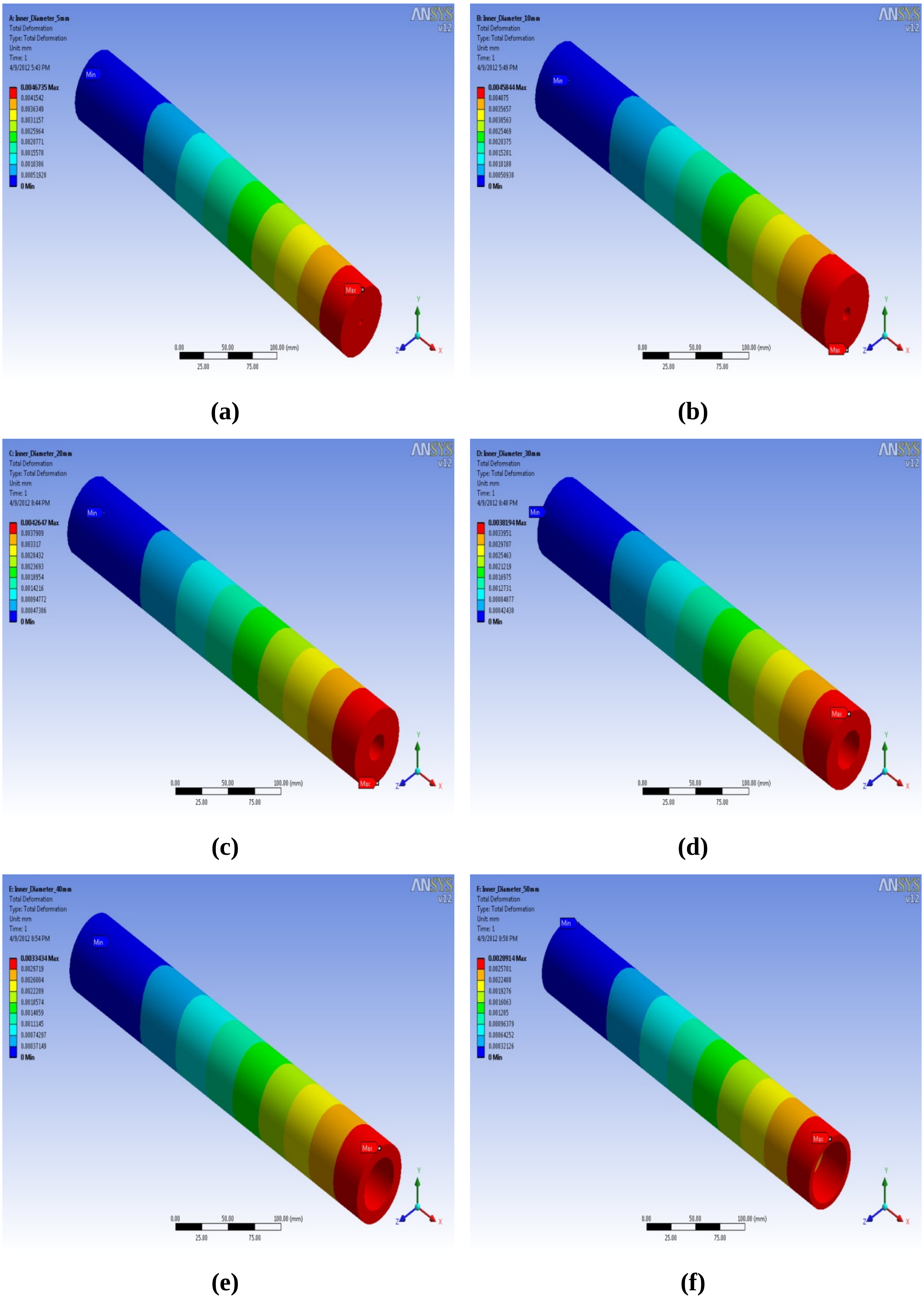


Figure 5.9 Deformation with varying inner diameter – (a) 5 mm, (b) 10 mm, (c) 20 mm, (d) 30 mm, (e) 40 mm, (f) 50 mm.

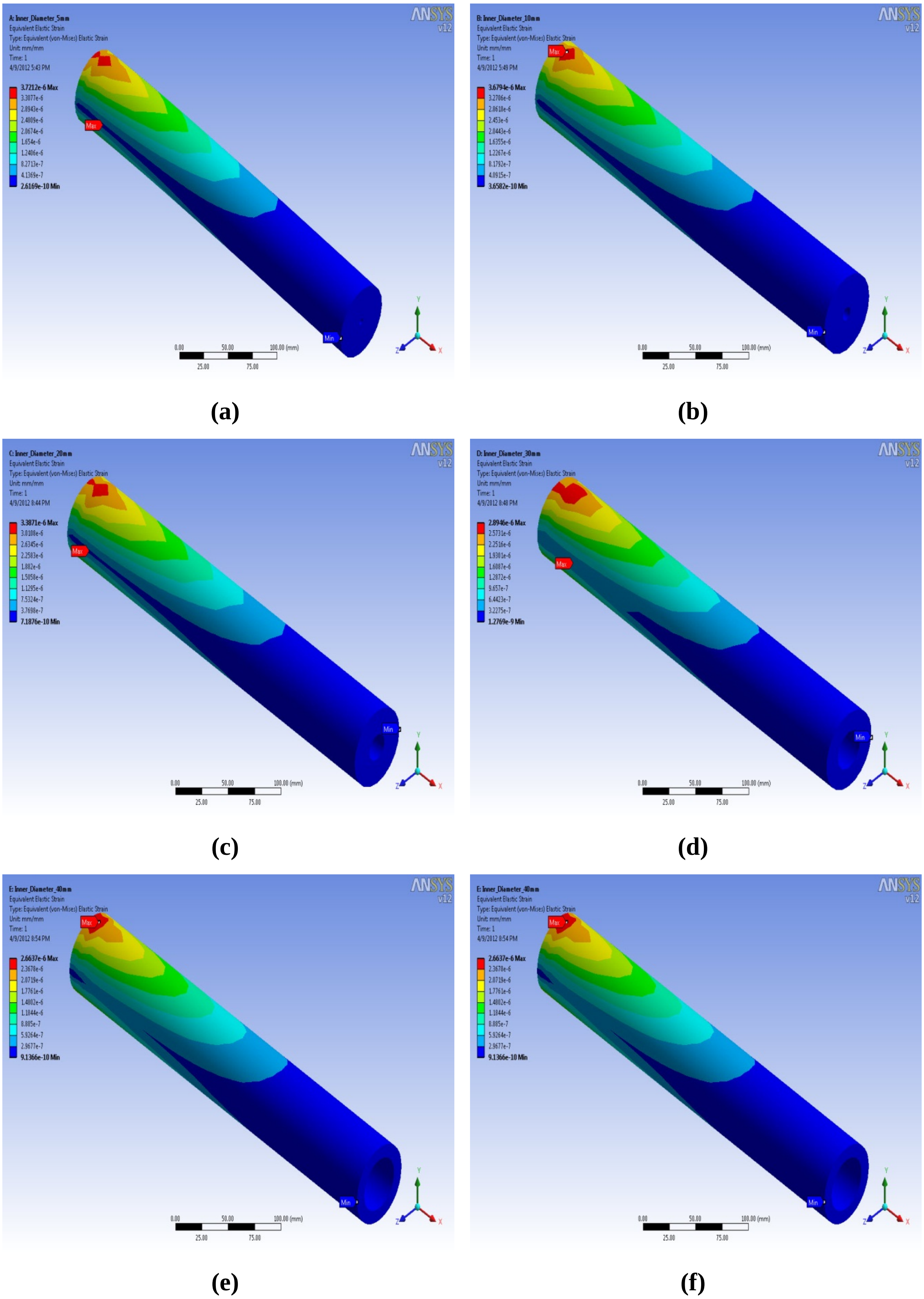
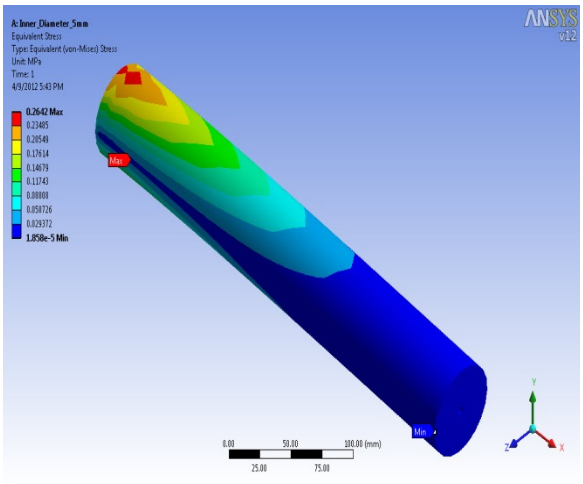
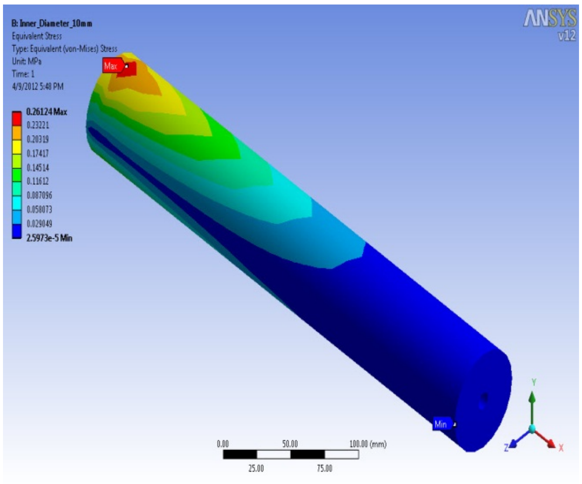


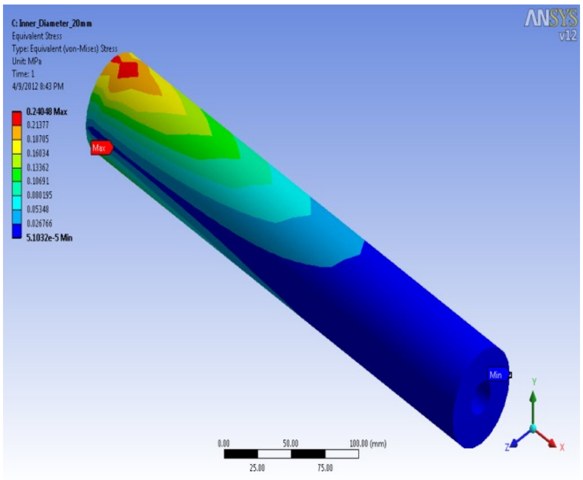
Figure 5.10 Strain with varying inner diameter – (a) 5 mm, (b) 10 mm, (c) 20 mm, (d) 30 mm, (e) 40 mm, (f) 50 mm.



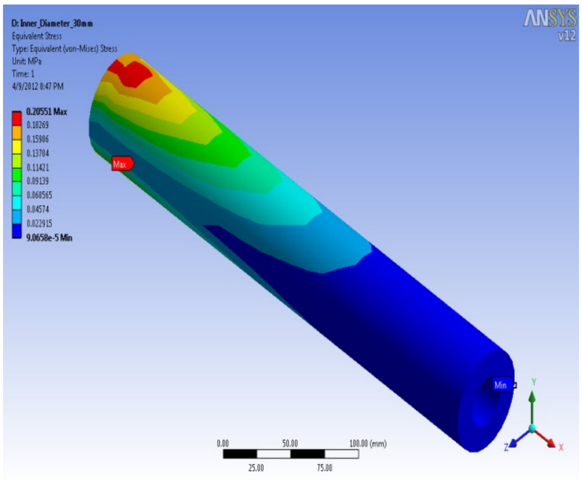
(a)



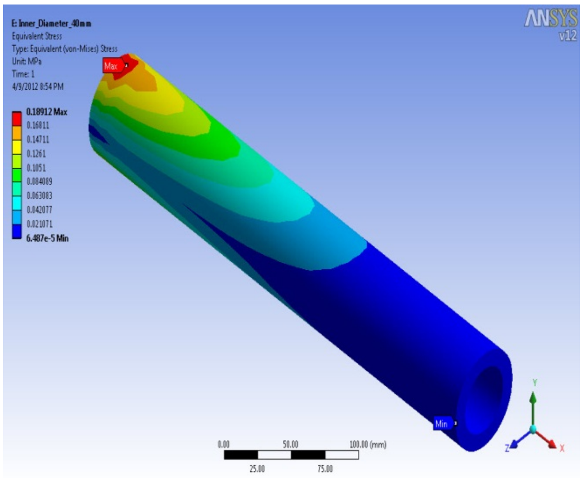
(b)



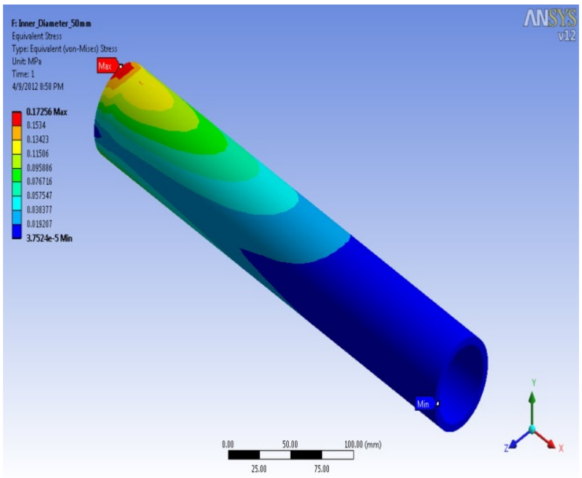
(c)



(d)



(e)



(f)

Figure 5.11 Stress with varying inner diameter – (a) 5 mm, (b) 10 mm, (c) 20 mm, (d) 30 mm, (e) 40 mm, (f) 50 mm.

Inner Diameter Variation - Without any Loading, Only Gravity					
S. No.	**Inner Diameter (mm)**	**Mass (kg)**	**Displacement (mm)**	**Strain (mm/mm)**	**Stress (Mpa)**
1	5	2.9944	4.6735E-03	3.7212E-06	0.2642
2	10	2.9316	4.5844E-03	3.6794E-06	0.26124
3	20	2.6803	4.2647E-03	3.3871E-06	0.24048
4	30	2.2615	3.8194E-03	2.8946E-06	0.20551
5	40	1.6752	3.3434E-03	2.6637E-06	0.18912
6.	50	0.92135	2.8914E-03	2.4305E-06	0.17256

Table 5.4 Result of inner diameter variation

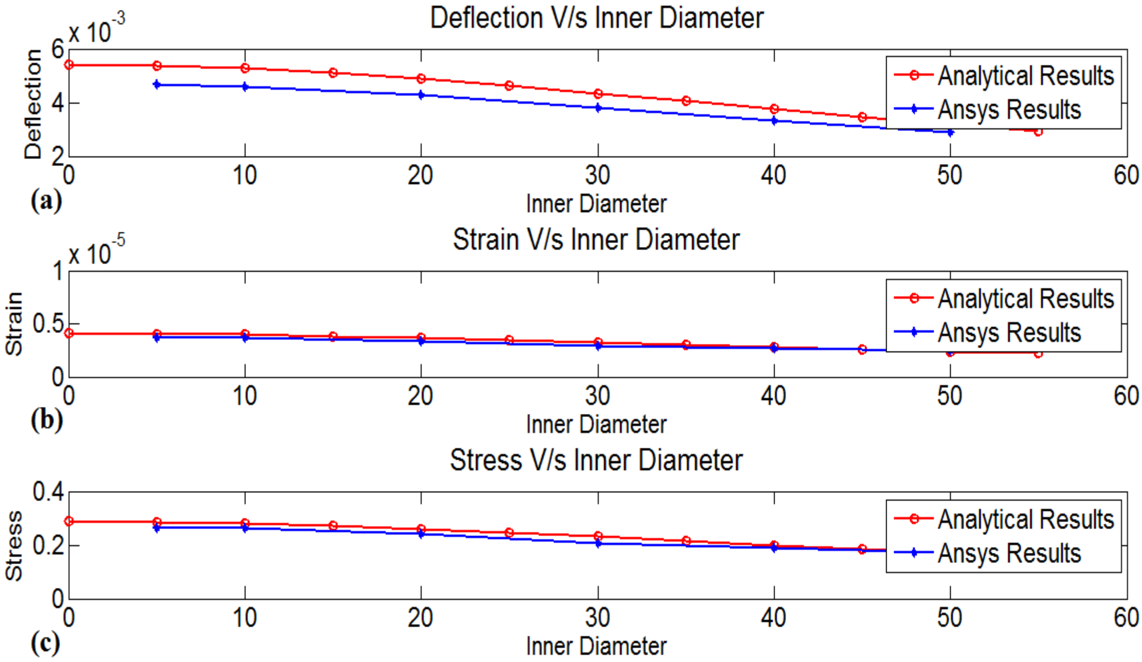
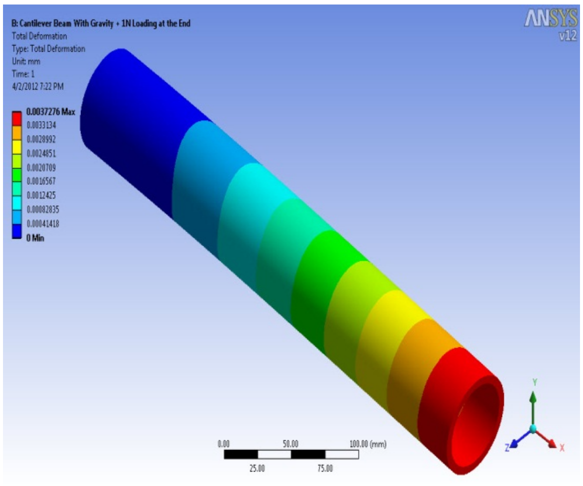


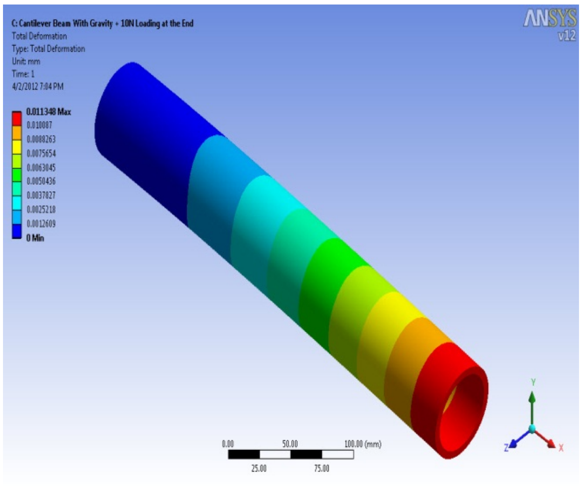
Figure 5.12 Graph due to Variation in Inner Diameter

5.1.5 End-Point Load Variation

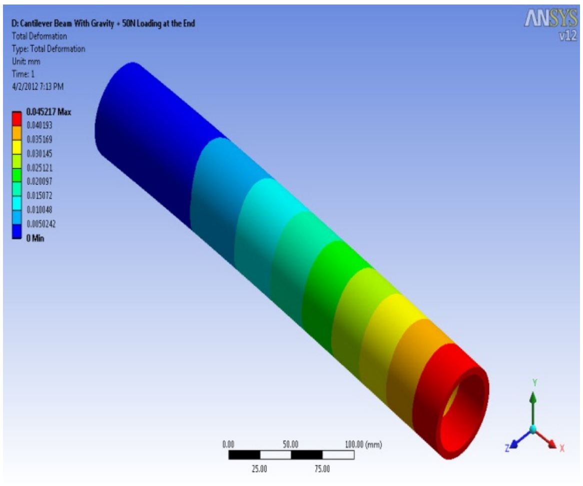
The analyses are carried using ANSYS for End-Point load variation. Its analysis is carried out with outer diameter 60 mm, inner diameter 50 mm and link length 400 mm. the load is varied as 1 N, 10 N, 50 N and 100 N. The result for deformation is shown in Fig. 5.13(a) to Fig. 5.13(d), strain is shown in Fig. 5.14(a) to Fig. 5.14(d) and stress is shown in Fig. 5.15(a) to Fig. 5.15(d). All these variations of results are tabulated in Table 5.5 and comparative graph is drawn between variation of results using Analytical formulas and for ANSYS results.



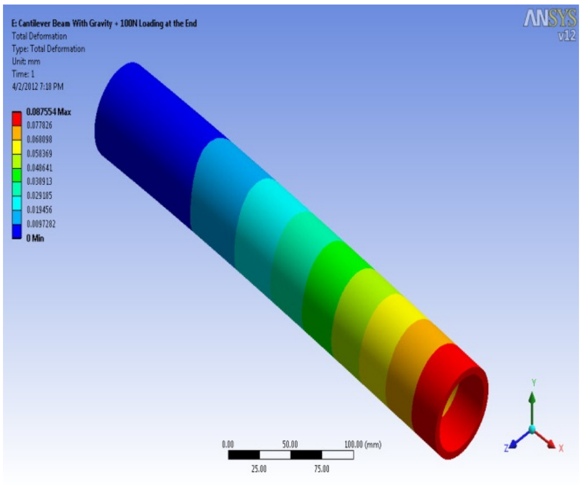
(a)



(b)

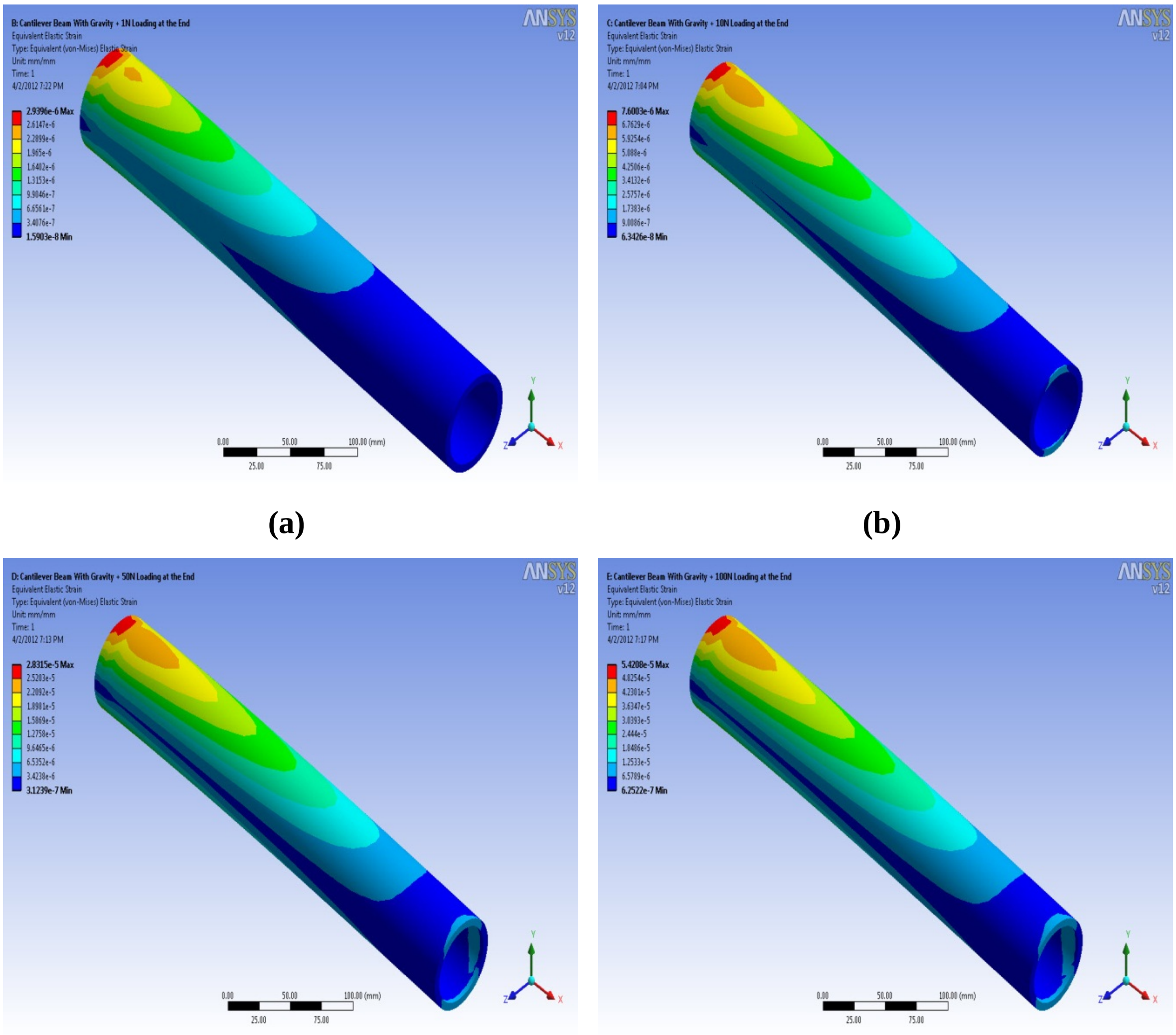


(c)



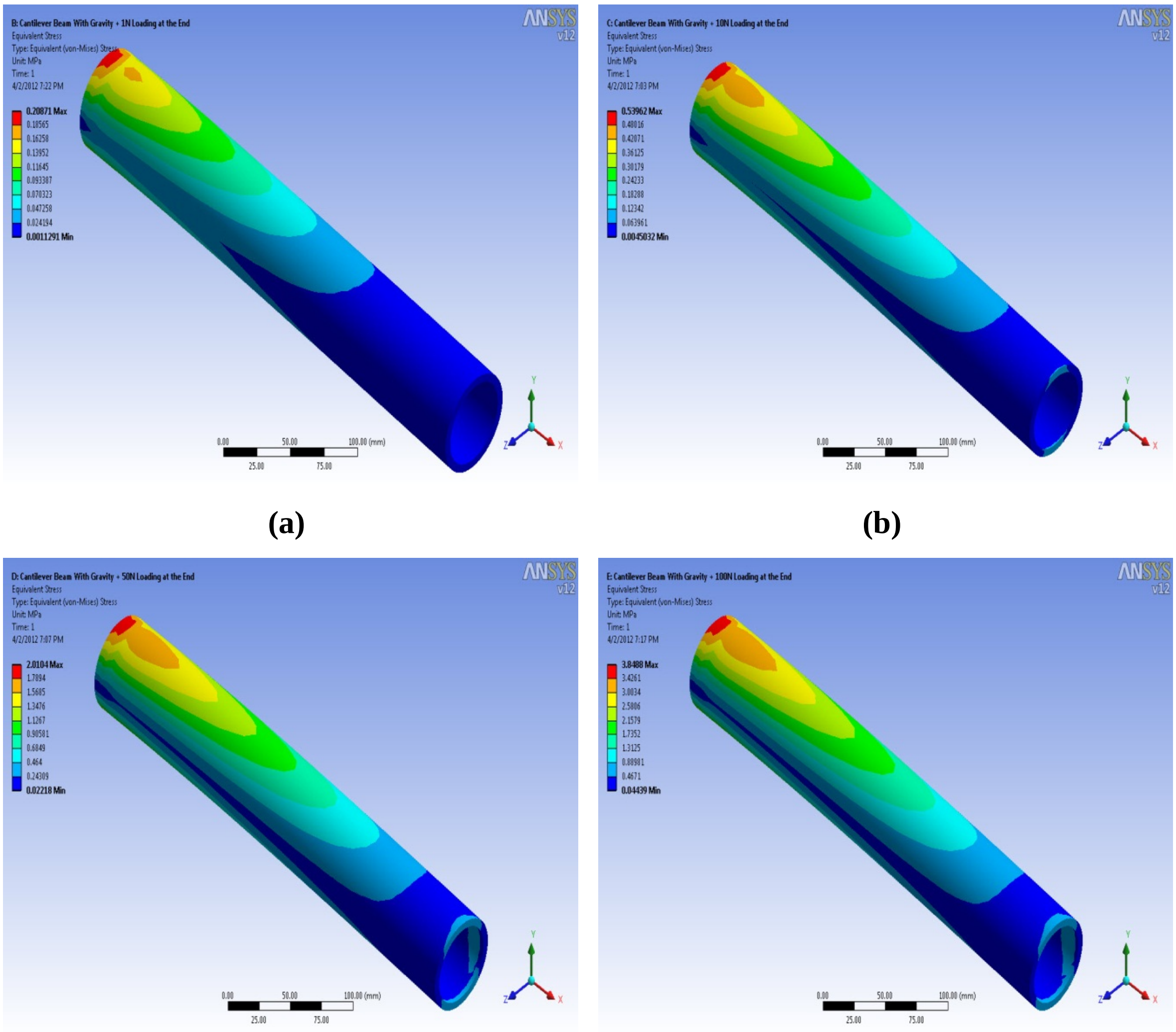
(d)

Figure 5.13 Deformation with varying End-Point load – (a) 1 N, (b) 10 N, (c) 50 N, (d) 100 N.



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

Figure 5.14 Strain with varying End-Point load – (a) 1 N, (b) 10 N, (c) 50 N, (d) 100 N.



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

Figure 5.15 Stress with varying End-Point load – (a) 1 N, (b) 10 N, (c) 50 N, (d) 100 N.

Load Variation - With Gravity					
S. No.	**Load (N)**	**Mass (kg)**	**Displacement (mm)**	**Strain (mm/mm)**	**Stress (Mpa)**
1	0	0.91802	2.8809E-03	2.4217E-06	0.17194
2	1	0.91802	3.7276E-03	2.9396E-06	0.20871
3	10	0.91802	1.1348E-02	7.6003E-06	0.53962
4	50	0.91802	4.5217E-02	2.8315E-05	2.0104
5	100	0.91802	8.7554E-02	5.4208E-05	3.8488

Table 5.5 Results of End-Point load variation

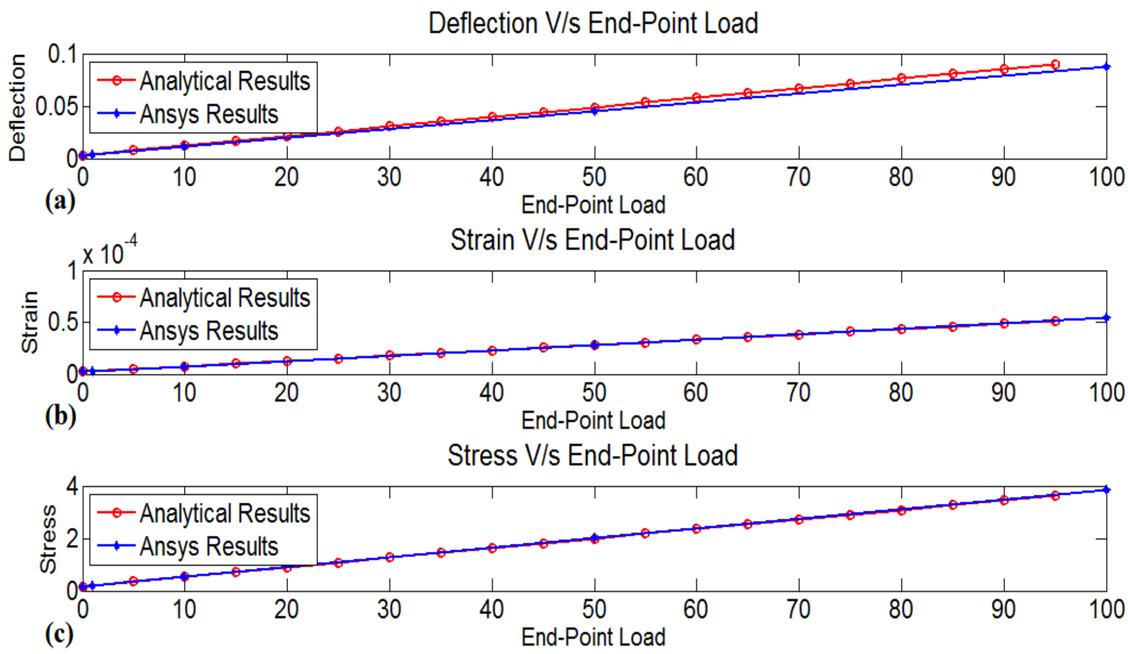


Figure 5.16 Comparison of Analytical v/s ANSYS results due to End-Point load variation

Conclusions drawn out from the graph shown in Fig. 5.16(a) to Fig. 5.16(c) are as follows:

Variation in stress is linear due to End Point load

$$\sigma_b \propto P$$

Variation in strain is linear due to End-Point load

$$\epsilon \propto P$$

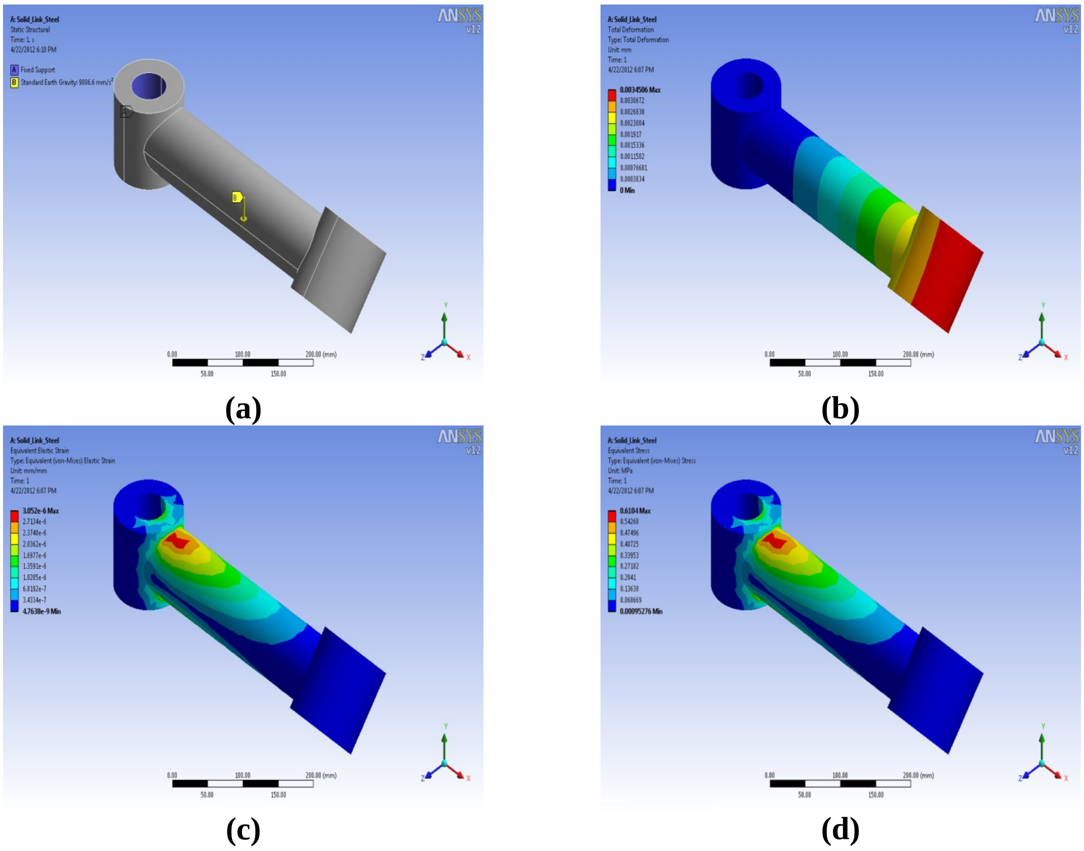
Variation in deflection is also linear due to End-Point load

$$\delta \propto P$$

Results from Analytical calculations and ANSYS calculation for End-Point load variation are found in close agreement. From all the above four cases, it is found that the results from ANSYS and Analytical formulas are in close agreement. Thus we can use ANSYS software for the analysis of modular link which is like a cantilever beam but complex in geometry, for which analytical solutions are difficult to calculate.

5.2 SINGLE MODULAR LINK ANALYSIS UNDER GRAVITY LOAD

Now the modular link is analysed for its deformation, strain and stress using the ANSYS software. Here one end of modular link is kept fixed and other end is free. The modular link is subjected to uniformly distributed load due to its weight. Loading conditions are shown in Fig. 5.18(a), and the results for deformation, strain and stress are shown in Fig. 5.18(b) to 5.18(d) respectively. The relative values for deformation, strain stress in key are shown in Fig. 5.18(e) to Fig. 5.18(g) respectively. These values of deformation, strain and stress are found to be less in keys as compared to the modular link as there is loss of material near the hole, due to which strength of material decreases.



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

Figure 5.17 Solid link of steel (a) loading, (b) deformation, (c) strain, (d) stress.

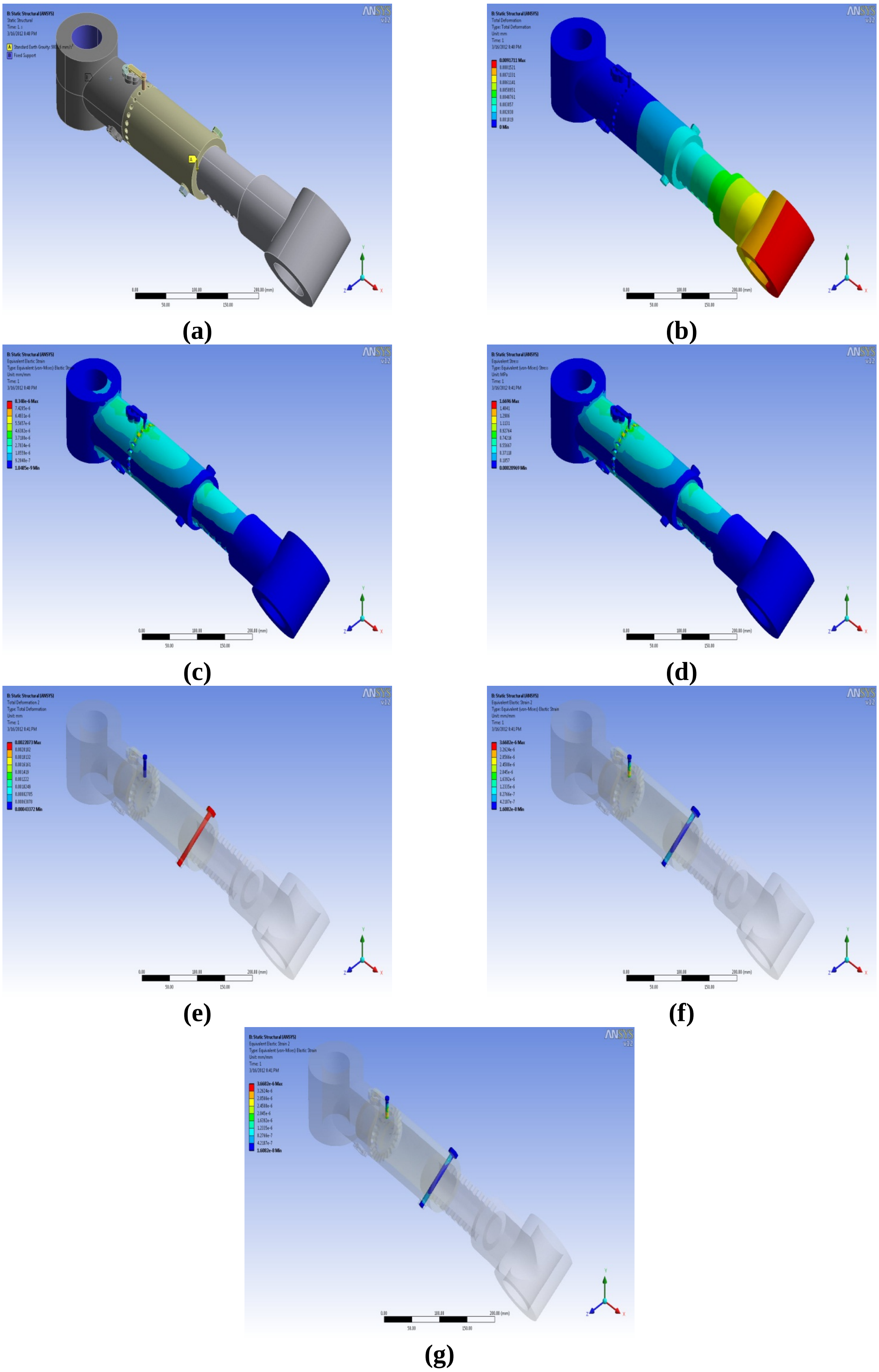


Figure 5.18 Modular link of steel (a) loading, (b) deformation, (c) strain, (d) stress, (e) keys deformation, (f) keys strain, (g) keys stress.

After this the results of modular link are compared to solid link, which is made with the same dimensions and material. Loading of solid link is shown Fig. 5.17(a) and deformation, strain and stress developed solid link are shown in Fig. 5.17(b) to Fig. 5.1(d). The result comes in both cases are tabulate below in Table 5.6. These results show that stresses in modular link are more as compared to solid link, as expected.

Type	Modular Link	Solid Link
Mass (kg)	16.31	20.64
Deformation (mm)	9.17e-3	3.45e-3
Strain (mm/mm)	8.34e-6	3.05e-6
Stress (MPa)	1.66	0.61
Key-Deformation (mm)	2.207e-3	—
Key-Strain (mm/mm)	3.66e-6	—
Key-Stress(MPa)	0.733	—

Table 5.6 Comparison of modular link and solid link

Now, here one important thing which is noted that the mass of the modular link is very high. To reduce the mass of modular link to some reliable value, first the material is changed from structure steel to aluminum, material properties of aluminum compared to structure steel are given in Table 5.7 and after this the dimensions are also changed to some extent to reduce the weight, and collars are developed at the ends for placement of motors. Analysis of improved modular link is explained in next section.

Property	Values for structure steel	Values for aluminum
Density	7850 kg/m^3	2770 kg/m^3
Young's Modulus	2E+05 MPa	71000 MPa
Poisson's Ratio	0.3	0.33
Tensile Yield Strength	250 MPa	280 MPa
Compressive Yield Strength	250 MPa	280 MPa
Tensile Ultimate Strength	460 MPa	310 MPa
Compressive Ultimate Strength	0 MPa	0 MPa

Table 5.7 Comparison of material properties of structure steel and aluminum

5.3 ANALYSIS OF THE IMPROVED MODULAR LINK

The improved modular link is analyzed for deformation, strain and stress. The Modular link can have length variation of 10mm with a range from 185mm to 245mm. Now, separate files are made for all possible length, in this case seven different lengths obtained, and these all seven are numbered from 1 to 7 starting from 245mm to 185mm. deformation, strain and stress in 1st modular link with length of 245mm is shown in Fig. 5.19(a), Fig. 5.20(a) and Fig. 5.21(a) respectively and with 7th modular link with length 185mm is shown in Fig. 5.19(b), Fig. 5.20(b) and Fig. 5.21(b) respectively. For brevity, the analyses of in-between lengths are not reported here.

After this, the modular links are combined with each other in fashion of decreasing length and numbered as 1-2, 1-2-3, 1-2-3-4, 1-2-3-4-5, 1-2-3-4-5-6 and 1-2-3-4-5-6-7. And their deformation, strain and stress results are shown in Fig. 5.19(c) to Fig. 5.19(h), Fig. 5.20(c) to Fig. 5.20(h) and Fig. 5.21(c) to Fig. 5.21(h) respectively. Also the Deformation, strain and stress values in keys are shown in Fig. 5.22(c) to Fig. 5.22(h), Fig. 5.23(c) to Fig. 5.23(h) and Fig. 5.24(c) to Fig. 5.24(h) respectively.

The results of analysis are tabulated in Table 5.8 for deformation, strain and stress in modular link and in Table 5.9 the results are for the keys that are used in modular link are tabulated. These analyses are carried out at maximum extension representing the worst configuration, as in case of worst configuration the stresses developed are always more as compared to other cases.

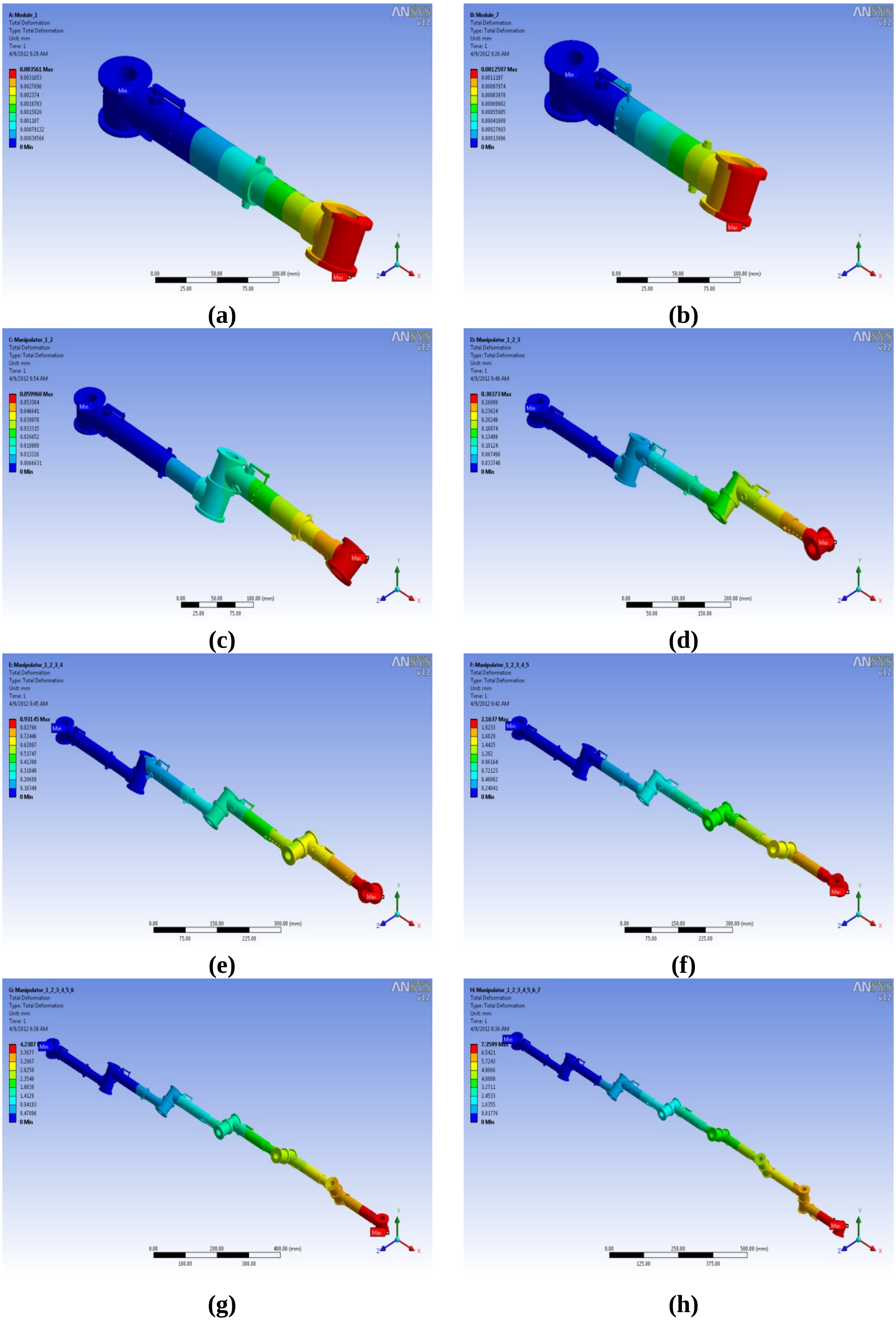
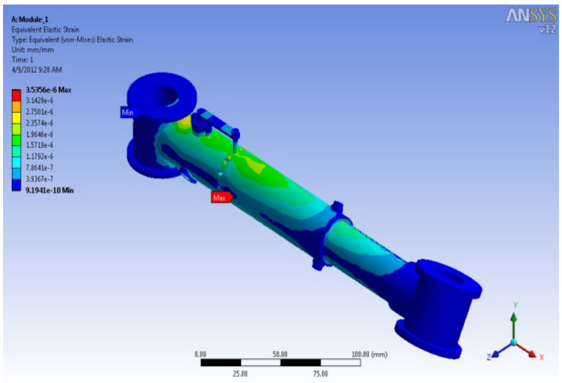
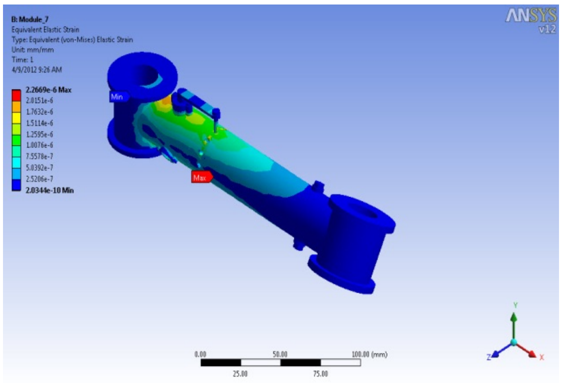


Figure 5.19 Deformation analysis for modular links (a) 1st, (b) 7th, (c) 1-2, (d) 1-2-3, (e) 1-2-3-4, (f) 1-2-3-4-5, (g) 1-2-3-4-5-6, (h) 1-2-3-4-5-6-7



(a)



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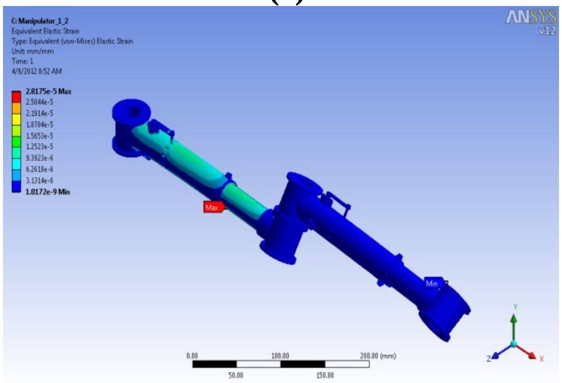
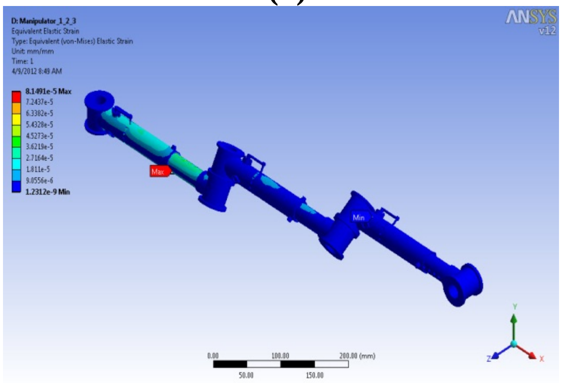
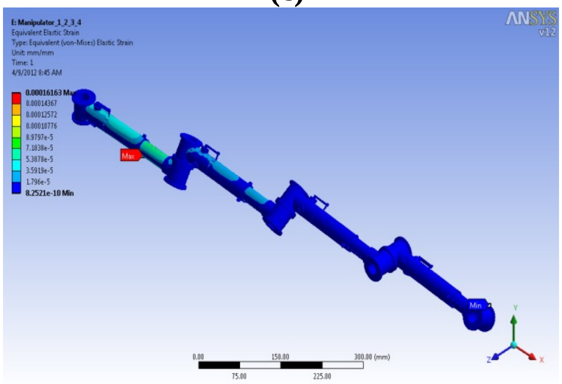


(c)



(d)



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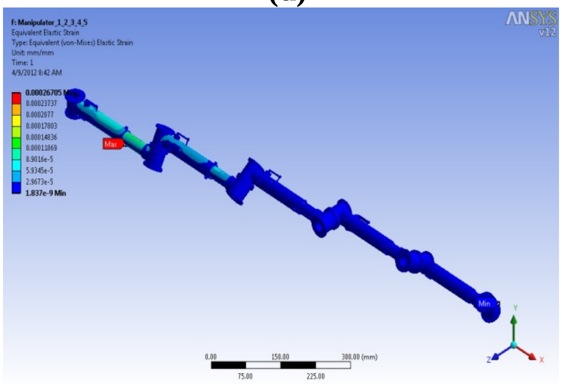
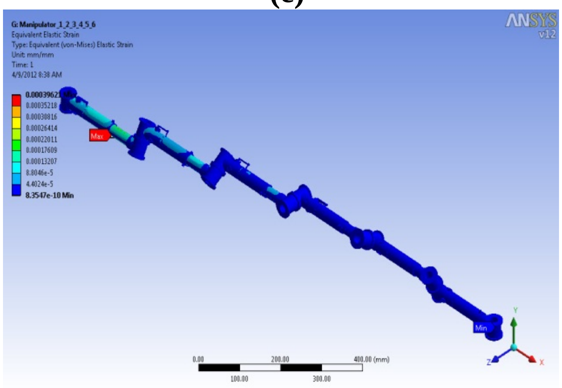
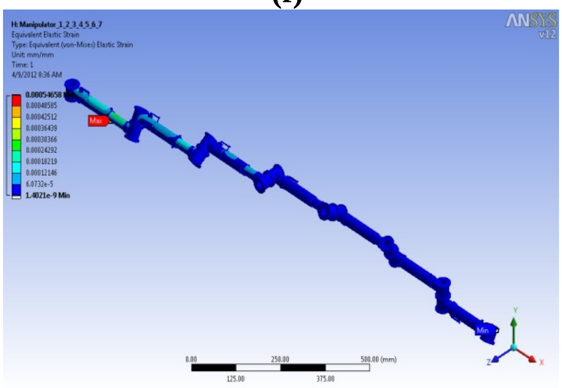


(f)



(g)



(h)

Figure 5.20 Strain analysis for modular links (a) 1st, (b) 7th, (c) 1-2, (d) 1-2-3, (e) 1-2-3-4, (f) 1-2-3-4-5, (g) 1-2-3-4-5-6, (h) 1-2-3-4-5-6-7

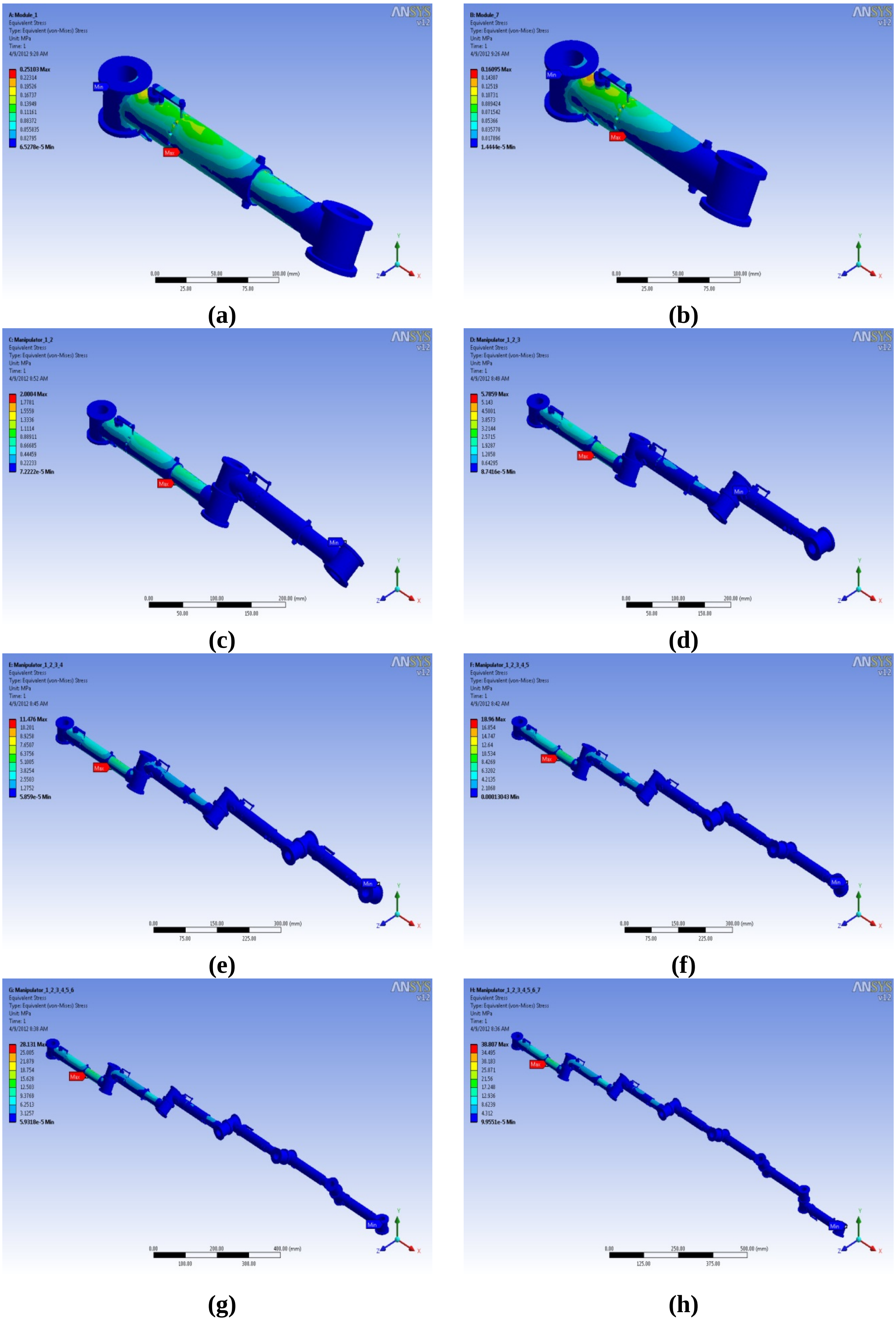
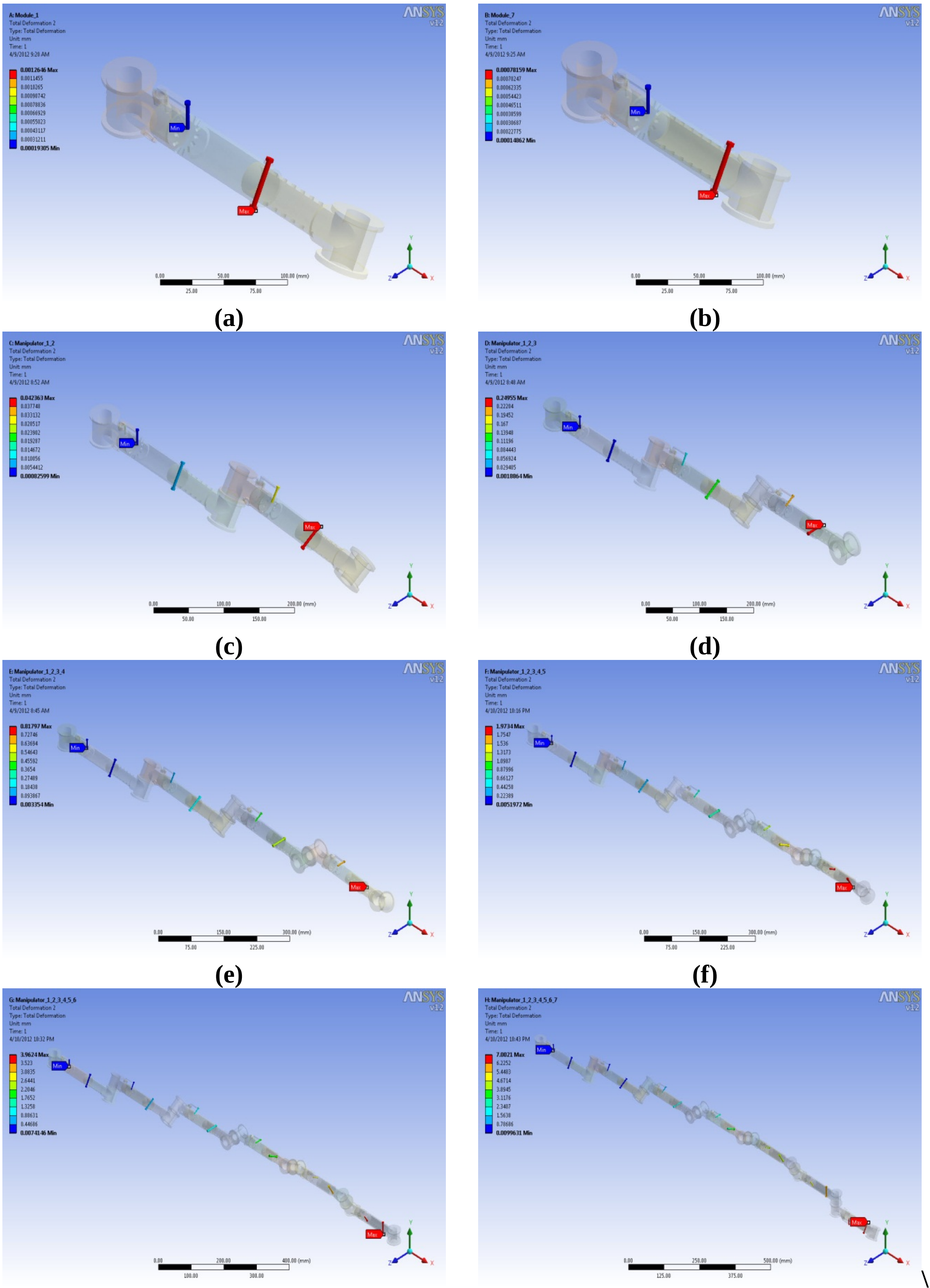


Figure 5.21 Stress analysis for modular links (a) 1st, (b) 7th, (c) 1-2, (d) 1-2-3, (e) 1-2-3-4, (f) 1-2-3-4-5, (g) 1-2-3-4-5-6, (h) 1-2-3-4-5-6-7



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 5.22 Deformation analysis for keys in modular links (a) 1st, (b) 7th, (c) 1-2, (d) 1-2-3, (e) 1-2-3-4, (f) 1-2-3-4-5, (g) 1-2-3-4-5-6, (h) 1-2-3-4-5-6-7

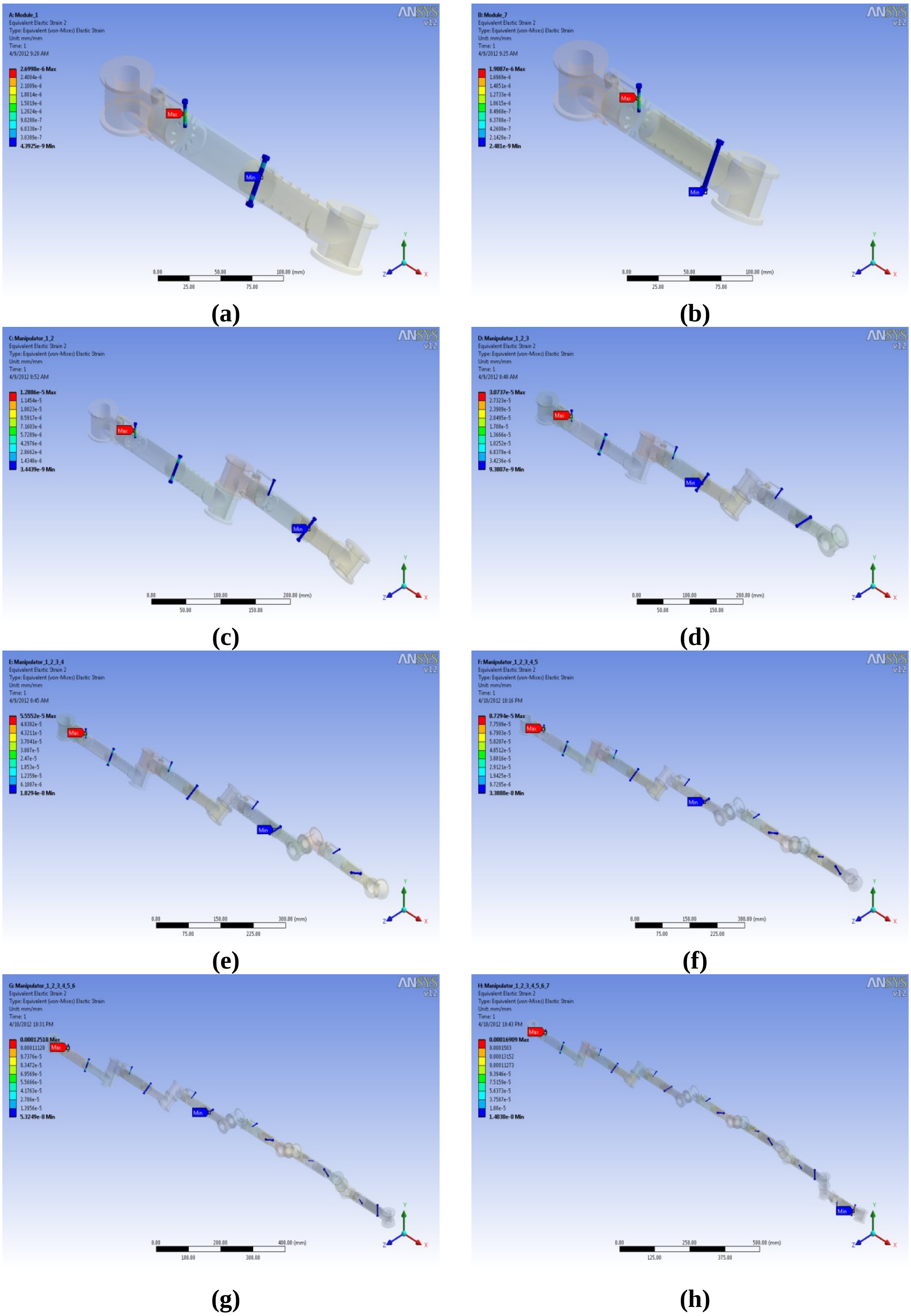


Figure 5.23 Strain analysis for keys in modular links (a) 1^{st}, (b) 7^{th}, (c) 1-2, (d) 1-2-3, (e) 1-2-3-4, (f) 1-2-3-4-5, (g) 1-2-3-4-5-6, (h) 1-2-3-4-5-6-7

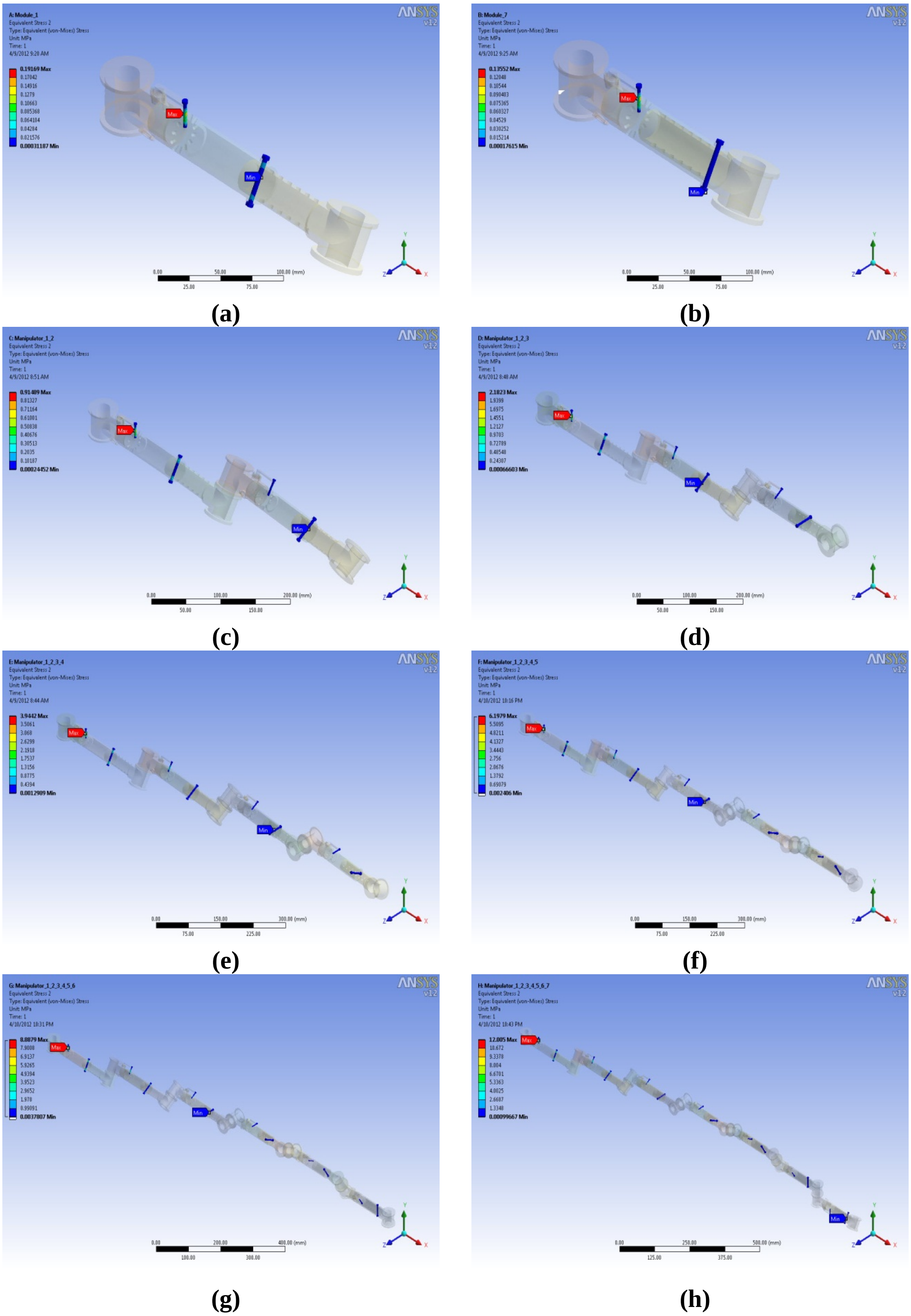


Figure 5.24 Stress analysis for keys in modular links (a) 1st, (b) 7th, (c) 1-2, (d) 1-2-3, (e) 1-2-3-4, (f) 1-2-3-4-5, (g) 1-2-3-4-5-6, (h) 1-2-3-4-5-6-7

Type of Manipulator	Mass (kg)	Deformation (mm)	Strain (mm/mm)	Stress (MPa)
Manipulator_1	0.3327	3.5610E-03	3.5356E-06	0.25103
Manipulator_7	0.3327	1.2597E-03	2.2669E-06	0.16095
Manipulator_1_2	0.66539	4.2363E-02	2.8175E-05	2.0004
Manipulator_1_2_3	0.99809	3.0373E-01	8.1491E-05	5.7859
Manipulator_1_2_3_4	1.3308	9.3145E-01	1.6163E-04	11.476
Manipulator_1_2_3_4_5	1.6635	2.1637E+00	2.6705E-04	18.96
Manipulator_1_2_3_4_5_6	1.9962	4.2387E+00	3.9621E-04	28.131
Manipulator_1_2_3_4_5_6_7	2.3289	7.3599E+00	5.4658E-04	38.807

Table 5.8 Results of analysis for modular manipulator

Type of Manipulator	Mass – kg	Key Deformation (mm)	Key Strain (mm/mm)	Key Stress (MPa)
Manipulator_1	0.3327	1.2646E-03	2.6998E-06	0.19169
Manipulator_7	0.3327	7.8159E-04	1.9087E-06	0.13552
Manipulator_1_2	0.66539	4.2363E-02	1.2886E-05	0.91489
Manipulator_1_2_3	0.99809	2.4955E-01	3.0737E-05	2.1823
Manipulator_1_2_3_4	1.3308	8.1797E-01	5.5552E-05	3.9442
Manipulator_1_2_3_4_5	1.6635	1.9734E+00	8.7294E-05	6.1979
Manipulator_1_2_3_4_5_6	1.9962	3.9624E+00	1.2518E-04	8.8879
Manipulator_1_2_3_4_5_6_7	2.3289	7.0021E+00	1.6909E-04	12.005

Table 5.9 Results of analysis for keys in modular manipulator

5.4 SOLID LINK ANALYSIS

After analysis of modular link it is required to compare the results with the results coming out from the analysis of solid link with same dimensions as that of modular link. The deformation, strain and stress in solid link are shown in Fig. 5.25(a) to Fig. 5.25(h), Fig. 5.26(a) to Fig. 5.26(h) and Fig. 5.27(a) to Fig. 5.27(h), respectively.

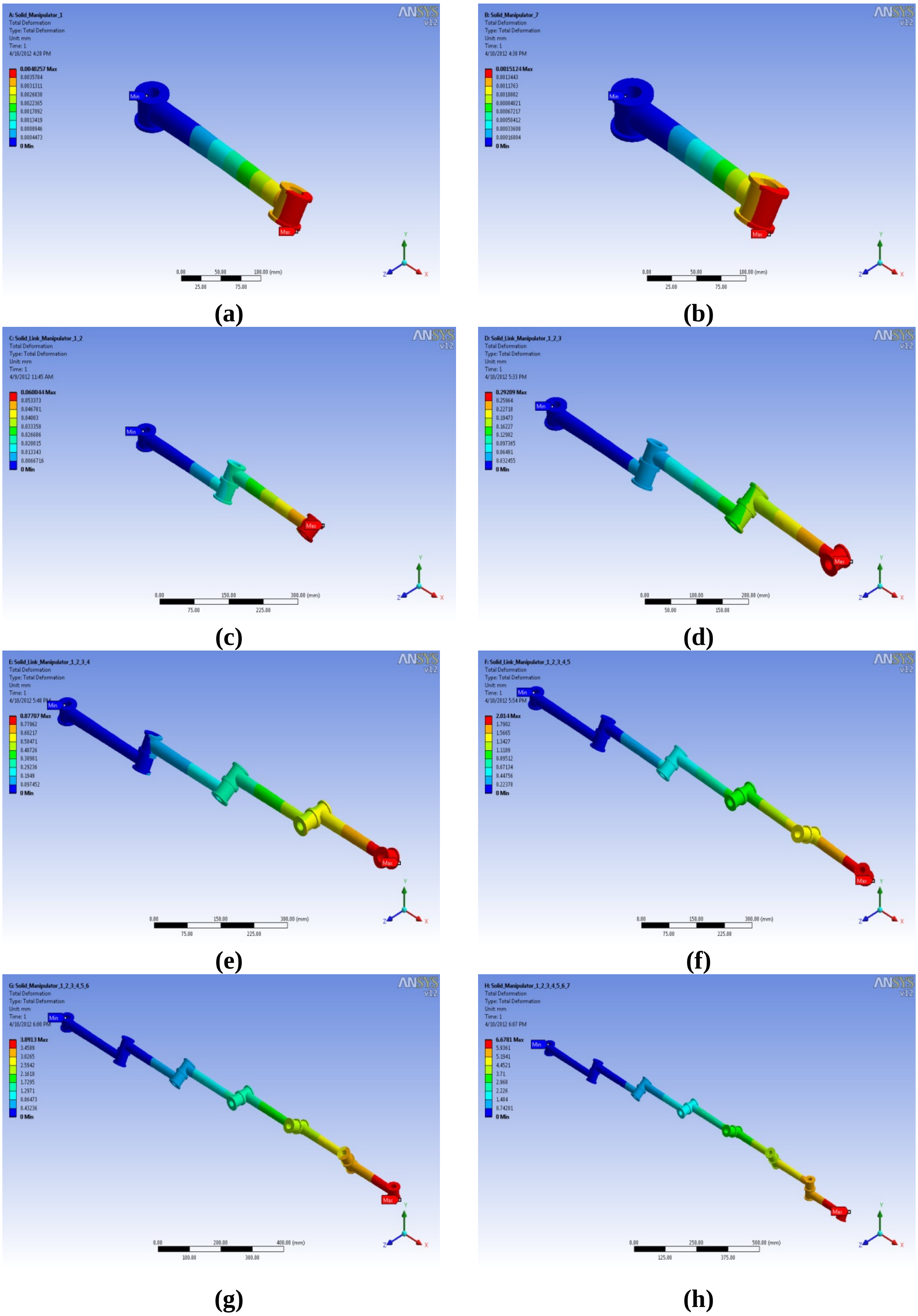


Figure 5.25 Deformation analysis for solid links (a) 1st, (b) 7th, (c) 1-2, (d) 1-2-3, (e) 1-2-3-4, (f) 1-2-3-4-5, (g) 1-2-3-4-5-6, (h) 1-2-3-4-5-6-7

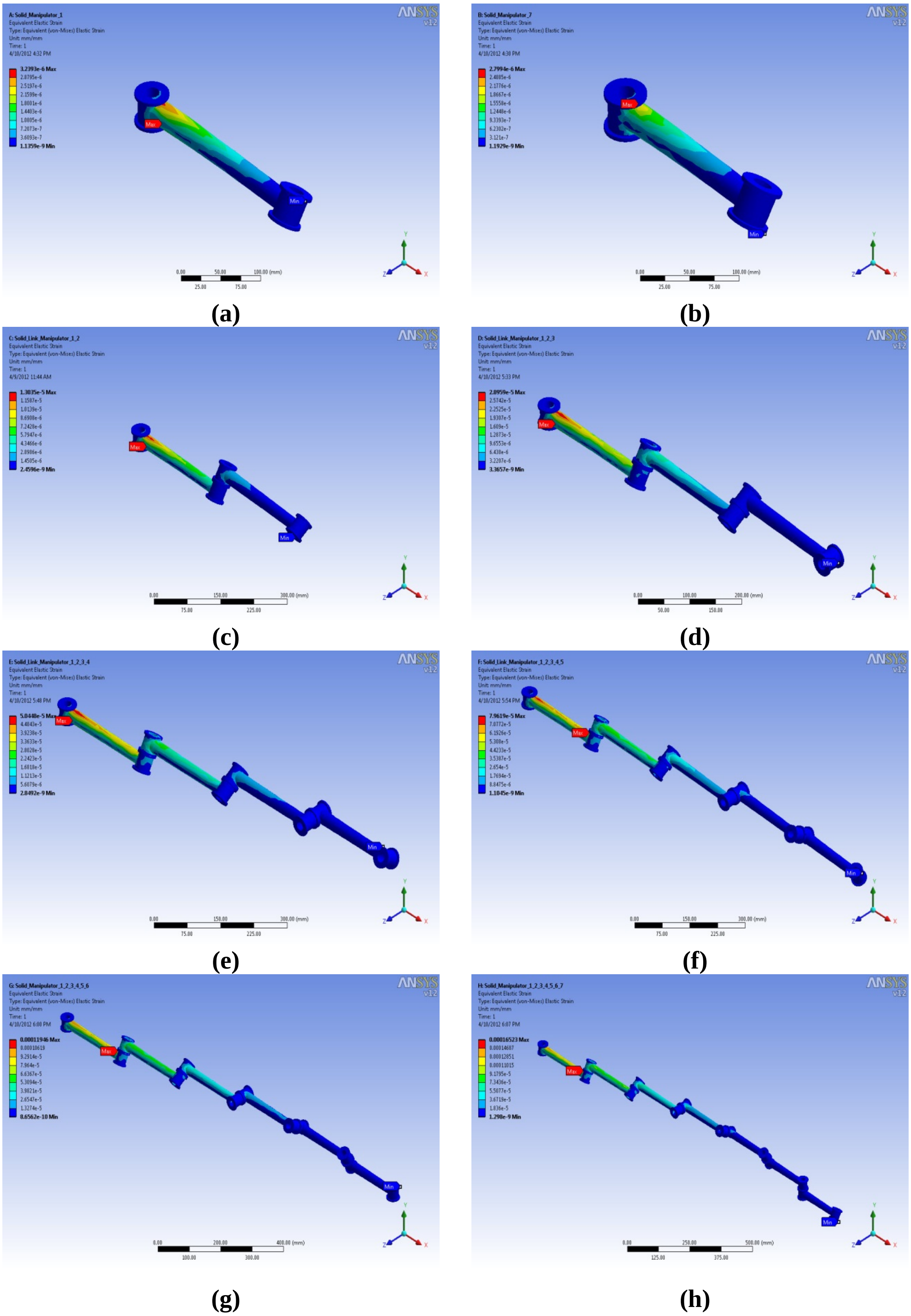
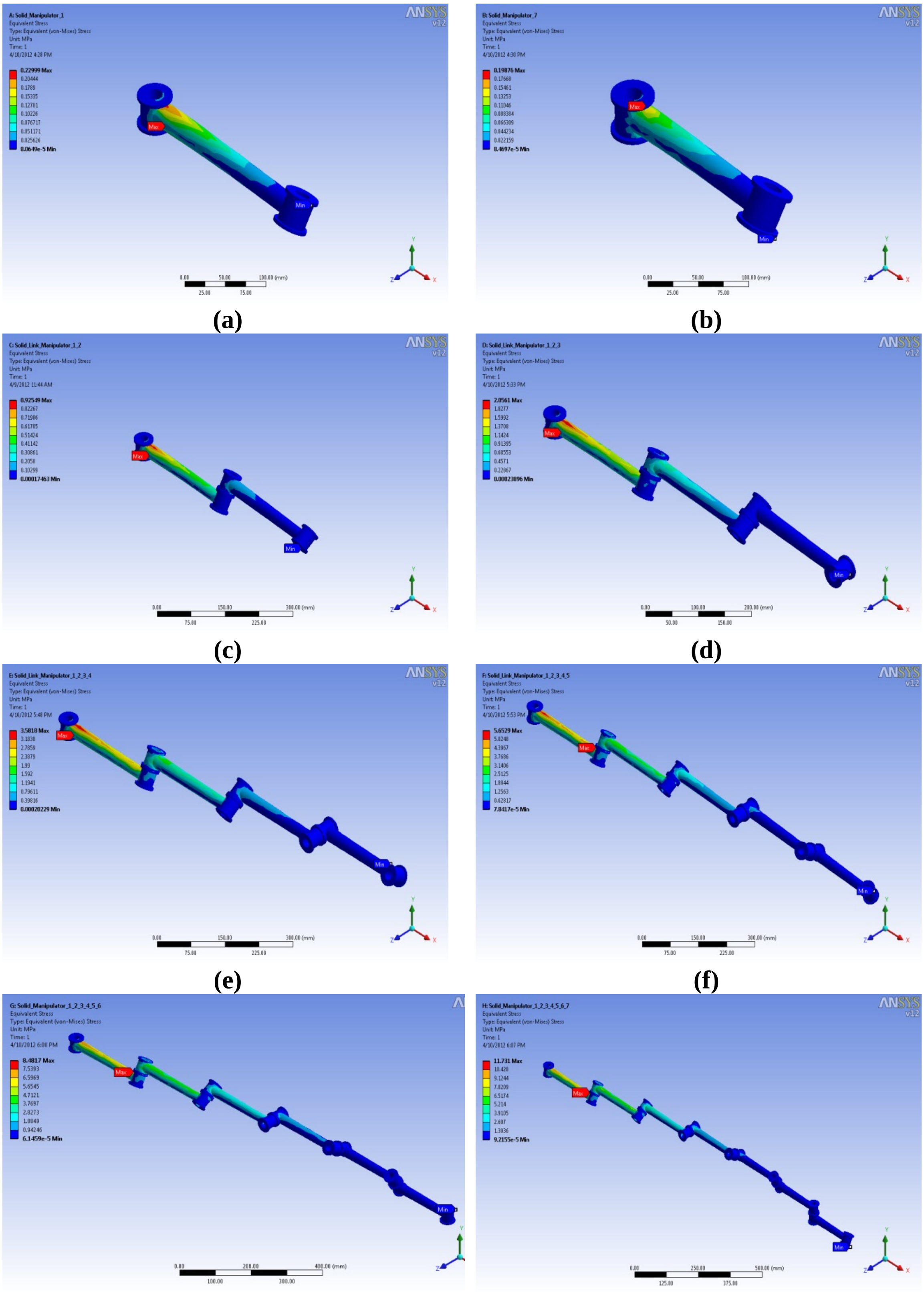


Figure 5.26 Strain analysis for solid links (a) 1st, (b) 7th, (c) 1-2, (d) 1-2-3, (e) 1-2-3-4, (f) 1-2-3-4-5, (g) 1-2-3-4-5-6, (h) 1-2-3-4-5-6-7



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 5.27 Stress analysis for solid links (a) 1st, (b) 7th, (c) 1-2, (d) 1-2-3, (e) 1-2-3-4, (f) 1-2-3-4-5, (g) 1-2-3-4-5-6, (h) 1-2-3-4-5-6-7

Type of Manipulator	Mass (kg)	Deformation (mm)	Strain (mm/mm)	Stress (MPa)
Solid_Manipulator_1	0.3595	4.0257E-03	3.2393E-06	0.22999
Solid_Manipulator_7	0.30583	1.5124E-03	2.7994E-06	0.19876
Solid_Manipulator_1_2	0.71005	6.0044E-02	1.3035E-05	0.92549
Solid_Manipulator_1_2_3	1.0517	2.9209E-01	2.8959E-05	2.0561
Solid_Manipulator_1_2_3_4	1.3843	8.7707E-01	5.0448E-05	3.5818
Solid_Manipulator_1_2_3_4_5	1.7081	2.0140E+00	7.9619E-05	5.6529
Solid_Manipulator_1_2_3_4_5_6	2.0228	3.8913E+00	1.1946E-04	8.4817
Solid_Manipulator_1_2_3_4_5_6_7	2.3287	6.6781E+00	1.6523E-04	11.731

Table 5.10 Results for analysis of solid-link manipulator

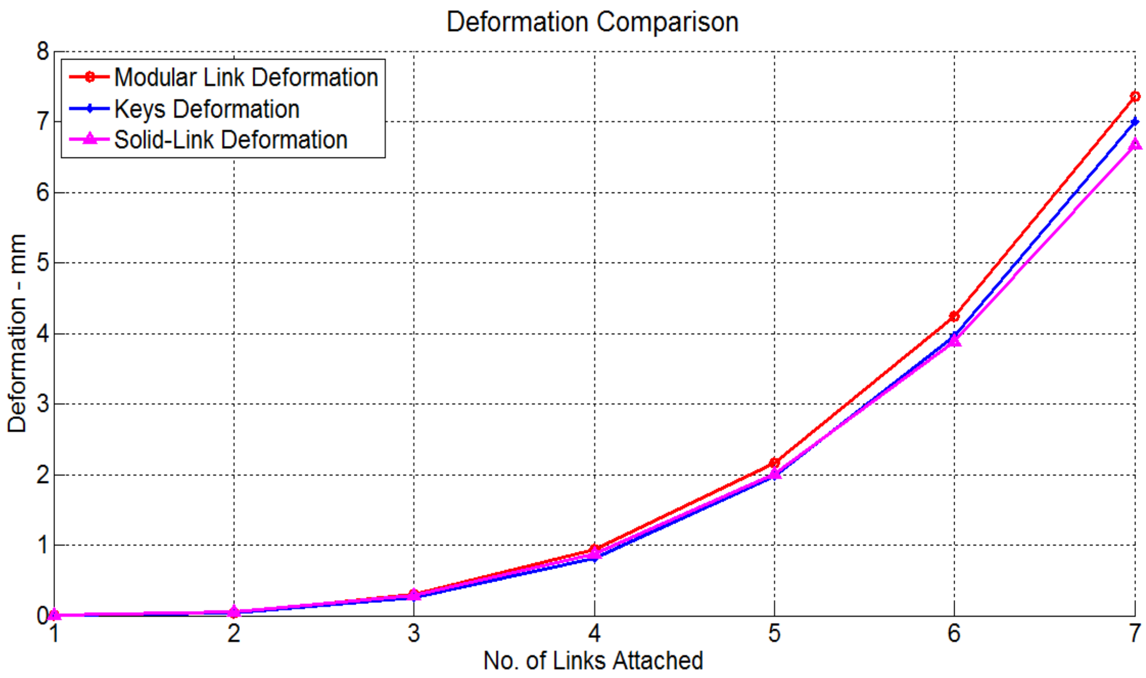


Figure 5.28 Comparative Deformation Analysis

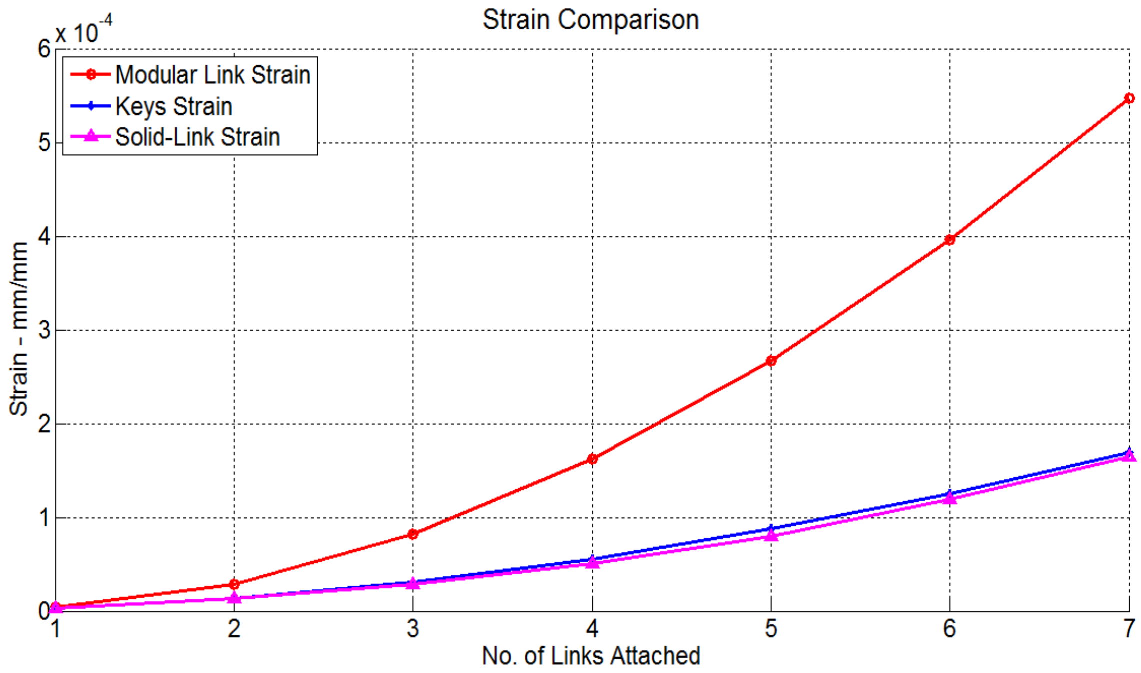


Figure 5.29 Comparative Strain Analysis

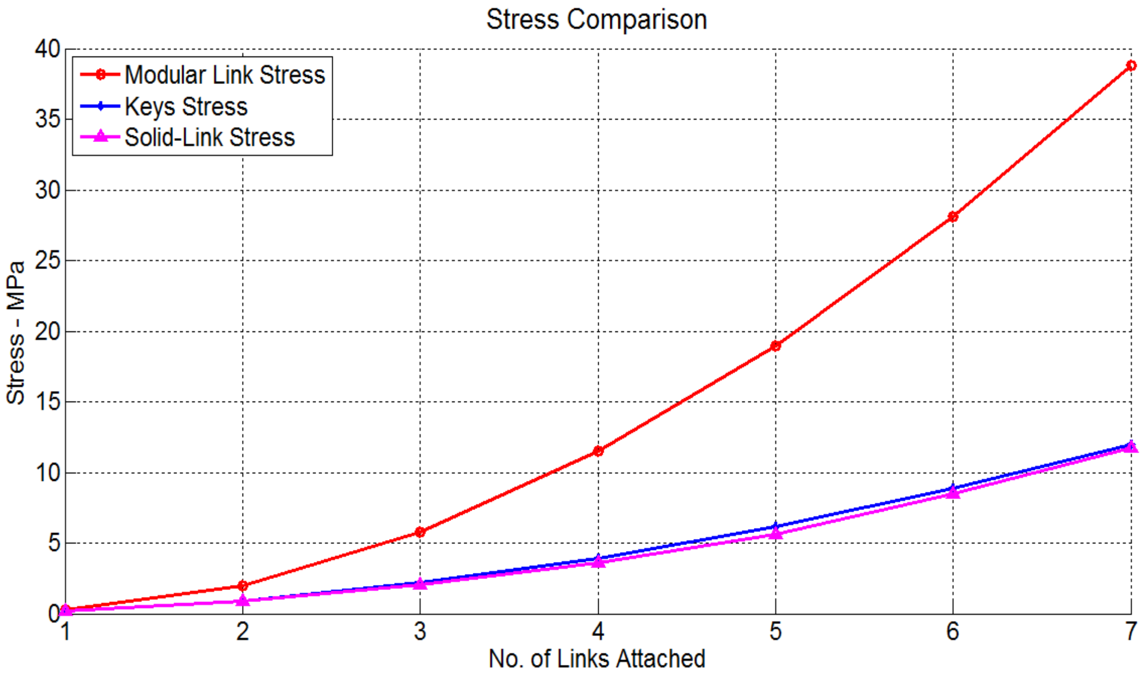


Figure 5.30 Comparative Stress Analysis

The results for deformation, strain and stress in case of solid-link manipulator analysis are tabulated in Table 5.10 and comparative graphs for relative term as deformation, strain and stress for modular manipulator – modular link manipulator and keys and solid-link manipulator are shown in Fig. 5.28 to Fig. 5.30 respectively. The conclusions drawn from these graphs are that stresses in modular link are more as compared to solid-link and stresses in keys lies in between results for modular link and solid-link. The main reason why the stresses in keys are less as compared to corresponding stresses in the modular links manipulator is that there is loss of material in modular link due to number of holes, due to which its strength is decreased.

5.5 GRAVITY AND LOADING EFFECTS ON MODULAR LINK AND KEYS

Now the modular link is analyzed under gravity load and end-point load from different directions, because while the manipulator is in motion this end point orientation changes and subsequently loading directions gets changed.

Here, Gravity_X stands for gravity in ‘X’ direction of modeled modular link and similar for ‘Y’ and ‘Z’. Also, 10N_X stands of end-point load in ‘X’ direction and similar for ‘Y’ and ‘Z’. Thus, total 12 cases arise and results for these 12 cases are tabulated for modular link in Table 5.11 and for keys in Table 5.12 respectively.

After this a comparative graphs are drawn where results for modular link are compared to results for keys in modular link. Graph for deformation is shown in Fig. 5.31 and it is concluded from the graph is that deformation is more in modular link as compared to key. Similarly, graphs for strain and stress are shown in Fig. 5.32 and Fig. 5.33. Also, similar trends are observed from these graphs as for deformation.

Type	Mass	Deformation	Strain	Stress
Gravity_X	0.3327	1.9906E-05	2.6200E-07	1.86E-02
Gravity_X_10N_X	0.3327	1.6175E-04	2.4051E-06	0.17076
Gravity_X_10N_Y	0.3327	2.9009E-02	3.4295E-05	2.435
Gravity_X_10N_Z	0.3327	3.0230E-02	2.9102E-05	2.0663
Gravity_Y	0.3327	3.5610E-03	3.5356E-06	0.25103
Gravity_Y_10N_X	0.3327	3.5700E-03	5.4991E-06	0.39043
Gravity_Y_10N_Y	0.3327	3.2570E-02	3.7440E-05	2.6582
Gravity_Y_10N_Z	0.3327	3.0518E-02	2.9472E-05	2.0925
Gravity_Z	0.3327	3.7665E-03	3.8679E-06	0.27462
Gravity_Z_10N_X	0.3327	3.7782E-03	4.5615E-06	0.32386
Gravity_Z_10N_Y	0.3327	2.9334E-02	3.5587E-05	2.5267
Gravity_Z_10N_Z	0.3327	3.3999E-02	3.3062E-05	2.3474

Table 5.11 Gravity and loading effect on modular link

Type	Mass	Key Deformation	Key Strain	Key Stress
Gravity_X	0.3327	1.2722E-05	7.7729E-08	5.52E-03
Gravity_X_10N_X	0.3327	8.2807E-05	4.8560E-07	3.45E-02
Gravity_X_10N_Y	0.3327	9.4550E-03	2.0047E-05	1.4233
Gravity_X_10N_Z	0.3327	1.0173E-02	3.4812E-06	0.24716
Gravity_Y	0.3327	1.2646E-03	2.6998E-06	0.19169
Gravity_Y_10N_X	0.3327	1.2779E-03	2.9831E-06	0.2118
Gravity_Y_10N_Y	0.3327	1.0719E-02	2.2703E-05	1.6119
Gravity_Y_10N_Z	0.3327	1.0287E-02	4.2703E-06	0.30319
Gravity_Z	0.3327	1.3788E-03	4.0942E-07	2.91E-02
Gravity_Z_10N_X	0.3327	1.3890E-03	6.9330E-07	4.92E-02
Gravity_Z_10N_Y	0.3327	9.5914E-03	2.0021E-05	1.4215
Gravity_Z_10N_Z	0.3327	1.1553E-02	3.8938E-06	0.27646

Table 5.12 Gravity and loading effect on keys in modular link

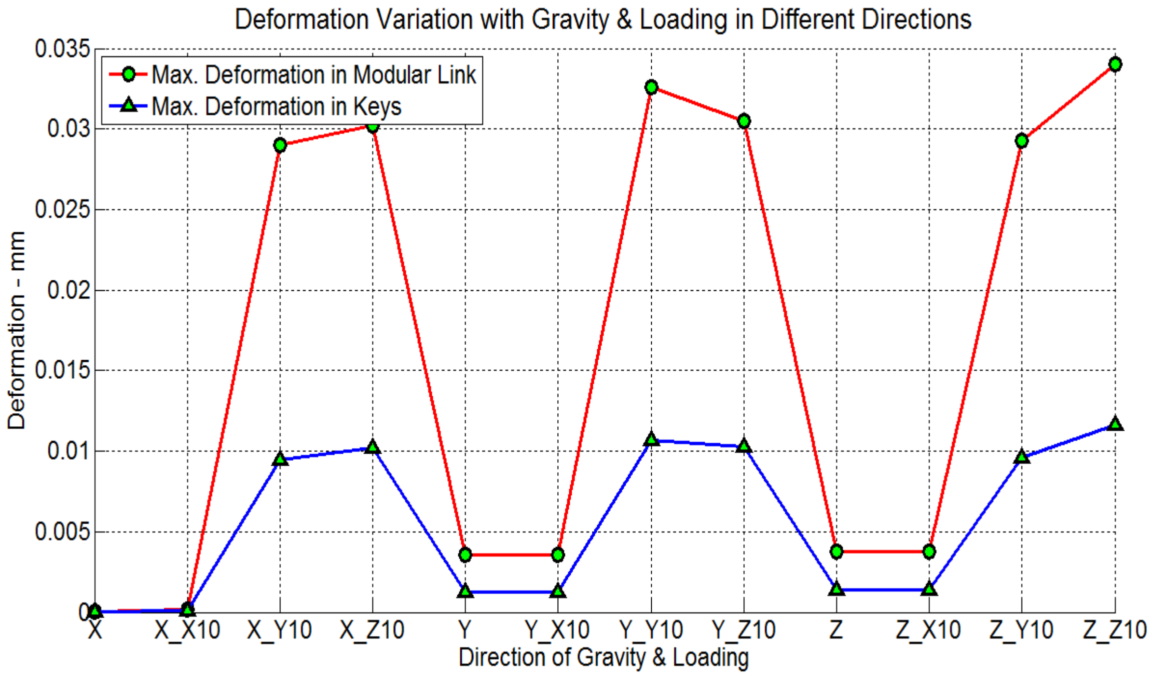


Figure 5.31 Comparative Graph for Deformation

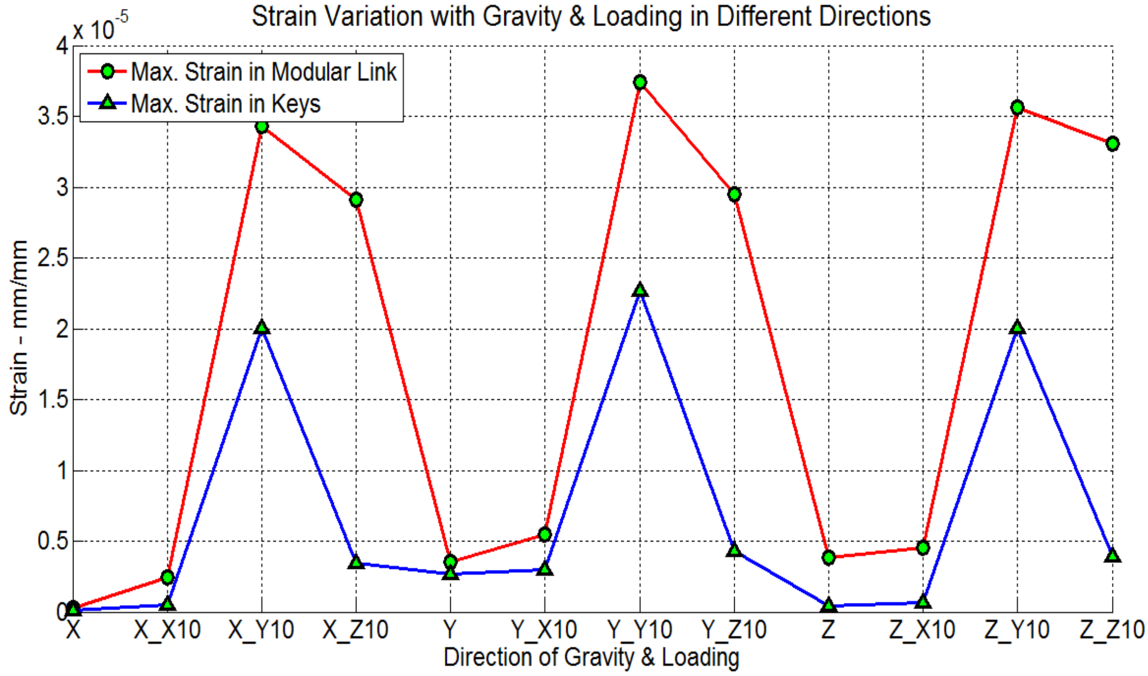


Figure 5.32 Comparative Graph for Strain

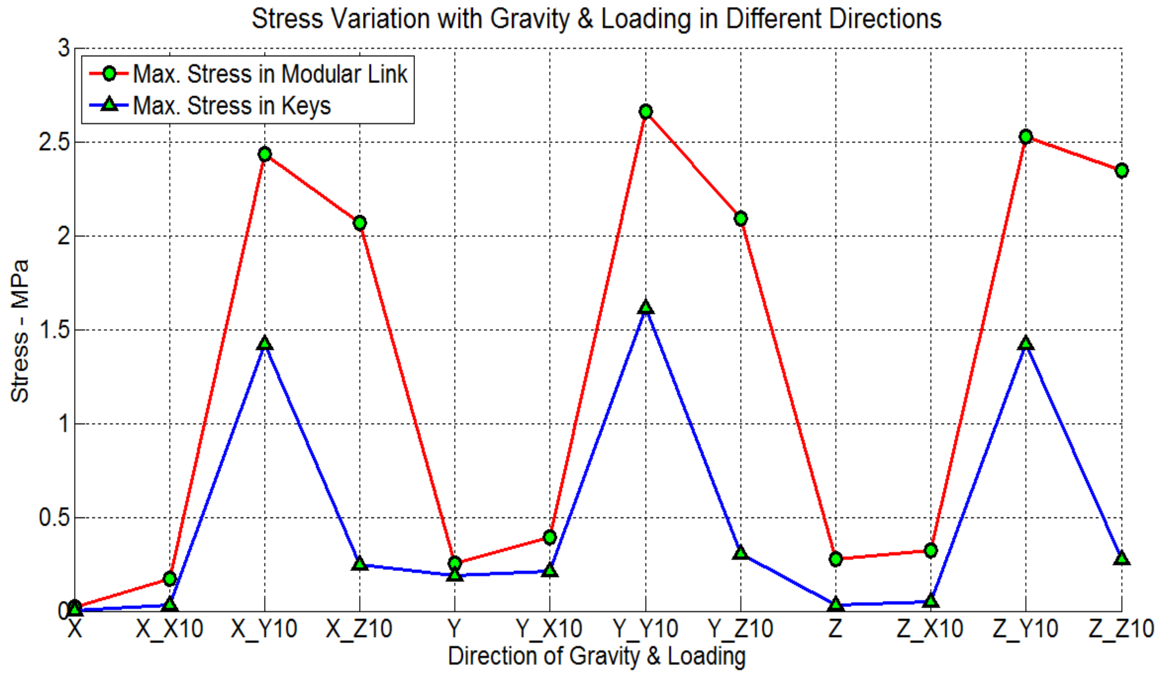


Figure 5.33 Comparative Graph for Stress

From the analyses, studied in this chapter, it is concluded that maximum stresses developed in modular link are more than keys that are used in modular link due to loss of material in modular link because of number of holes. But all values of stresses developed in modular link are under the value of yield stress in each case. Hence, the modular link developed is safe under the applied loading conditions as in above analyses.

CHAPTER-6

CONCLUSION AND SCOPE FOR FURTHER STUDY

6.1 CONCLUSION

There is a great complexity in industry to fabricate the robotic link to handle any real values of DH Parameters. There is no much work has been done in this area to handle them for their fabrication. This concept of modular link given in the present work will be very useful to fabricate the modular link in parts at low cost. Moreover, the values of link length and twist angle can be obtained as per requirement using the provided design.

6.2 SCOPE FOR FURTHER STUDY

The current work is an initiative to develop such type of modules. There exist a wide range of possibilities for extensions of such modules and several interesting openings for future research and development. Study of motors and their attachments used for the modular arm needed to be explored and finalized. During this stage, attachments of other important components required for transmission (i.e., gears etc.) and for control method are needed to be worked upon.

Software can be developed for virtual simulation of such module. The work done up to now for variation in link length and twist angle is to vary the parameter in discrete form. It implies that change in link length and twist angle is limited to some specified value. No values other than these can be obtained. The work can be extended to obtain the results for continuous variation in parameters.

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