DESIGN AND FABRICATION OF MULTIMATERIAL FLEXIBLE MECHANISMS WITH EMBEDDED COMPONENTS

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Motohide Hatanaka
June 2005

© Copyright by Motohide Hatanaka 2005
All Rights Reserved

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

Mark R. Cutkosky
(Principal Adviser)

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

Friedrich B. Prinz

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

Larry J. Leifer

I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

Yotaro Hatamura
(Professor Emeritus, University of Tokyo, Japan)

Approved for the University Committee on Graduate Studies.

Abstract

Modern day technology has produced countless artifacts containing advanced functionality. However, unfortunately, it is often the case that these high-tech equipments are fragile. Robustness is often provided by increased size and rigidity, but another viable solution is to introduce compliance.

Shape deposition manufacturing (SDM) is an already proven method for producing compliant mechanisms with advanced functionality. This rapid prototyping method, which is a hybrid of machining and molding, is well suited for producing robust, simple, and integrated mechatronic systems. The special capabilities of SDM that help the production of such systems include its abilities to mold different materials together and to embed components inside cast material. The technical feasibility has been well demonstrated in a series of biomimetic robots that were produced using SDM. Two areas of further improvements in SDM are presented in this dissertation. One is the general organization and exploration of methods of embedding flexible components across material boundaries. The other is stiffness modification of flexural hinges by fiber reinforcement.

The cross-boundary embedding technology enables local improvements in mechanical properties such as stiffness and strength or it can introduce other functionalities such as electrical or thermal conductivity or fluid channeling. Fabrication methods were organized and explored first by defining the objective of cross-boundary embedding and then searching for solutions. Each of the SDM process steps involves either a part material, which will remain in the final product, or a sacrificial material, which is temporary and will be removed before product completion. Such materials are added or removed either selectively, i.e. with precise geometric control,

or in bulk. Consideration of fabrication processes according to the aforementioned $2 \times 2 \times 2$ classification reveals that one selective process is required for a successful cross-boundary embedding. As a result, four fabrication processes were identified. In addition, two alternative methods for indirect cross-boundary embedding are indicated to simplify fabrication or to overcome fabrication difficulties while maintaining similar functionality.

Stiffness modification of flexures by fiber reinforcement helps overcome some of the shortcomings of flexures such as low torsional stiffness. It can also realize complex deformation patterns in simple geometries. The design approach is presented along with analysis and experimental results and fabrication method. The design strategy is to hinder undesired deformation by adding fibers along the lines of major tensile strain for unwanted deformations while avoiding that for desirable deformations. Finite element analysis (FEA) was employed for identifying such locations of strain and also for predicting performance of fiber-reinforced structures. Analysis and experimental results were compared and the two matched reasonably well. It showed the feasibility of simple FEA as a qualitative performance prediction tool.

Acknowledgments

I would like to thank the following people, groups, and organizations for their support during my studies at Stanford:

Professor Mark Cutkosky, my advisor, and all of my colleagues at the Stanford Biomimetics and Dextrous Manipulation Lab, especially Jorge, Wes, Sean, Jonathan C., Will, Trey, and Jonathan K. with whom I spent a significant amount of time in the lab. Professor Fritz Prinz and collaborators at Stanford Rapid Prototyping Laboratory, especially Tom, Yu-Chi, Won, Sangkyun, and Byongho. Professor Larry Leifer and members of the Stanford Center for Design Research. Professor Yotaro Hatamura, my undergraduate thesis advisor and mentor, who is responsible for my addiction with design. Research collaborators in and out of Stanford, especially Professor Bob Twiggs in Stanford AA department. Friends from Ecole Internationale de Genève, International Christian University High School, and the University of Tokyo... especially Shuya, Yuki, Reiko, Kensuke, Hiraku and Kinya with whom I shared similar goals in engineering, design, and/or post-graduate studies. Friends from Stanford: Bon, KiHong, Fendi from my early Stanford days. Surf buddies Georg, Flo, Howe, Christian, Thuy. Friends at Stanford CCRMA, especially Hiroko and YiWen. Friends from Summerschool 2002 in Mexico and from project TANE in München, especially Fozzy and Ingo. My housemates over the years, especially Sakiko, Ida, and Karen for providing a nice home when completing this dissertation. The Ericksons, my host family, for being my family in this country. My father, Takazumi, for always giving me the freedom to do what I wanted to do. My mother, Yuiko, for always encouraging me when I faced difficulties. My brother, Taro, for being an excellent motivation as a tough rival all my life. My sister, Kayo, for keeping

my parents busy at home while I've been away.

I would also like to thank ONR, NRO, DARPA, and NASA for research funds that supported my work over the years.

Contents

Abstract **iv**

Acknowledgments **vi**

1 Introduction **1**

1.1 Shape deposition manufacturing as a unique fabrication method . . . 2

1.1.1 Conventional fabrication . . . 3

1.1.2 Rapid prototyping . . . 3

1.1.3 Photo lithography . . . 4

1.1.4 SDM . . . 4

1.2 SDM specialties . . . 5

1.2.1 Multimaterial component fabrication via SDM . . . 5

1.2.2 Component embedding in SDM . . . 7

1.2.3 Other related works on SDM . . . 8

1.3 Motivation . . . 8

1.3.1 Cross-boundary embedding . . . 9

1.3.2 Flexure stiffness modification by fiber reinforcement . . . 9

1.4 Contributions . . . 9

2 Previous work **11**

2.1 Previous work on component embedding . . . 11

2.1.1 Previous component embedding work : non-SDM . . . 11

2.1.2 Previous component embedding work: SDM . . . 13

2.2 Previous work in fiber-reinforced elastomers . . . 13

2.2.1 Application, modeling, and theories . . . 13
2.2.2 Anisotropic property modification for kinematic functionality 14
2.3 Modeling and analysis for design . . . 15
2.4 Fibrous material selection for elastomer reinforcement . . . 16

3 Cross-boundary embedding of flexible components 18
3.1 Introduction . . . 19
3.2 Fabrication method and nomenclature . . . 20
3.2.1 Materials and manufacturing methods . . . 21
3.2.2 Nomenclature . . . 21
3.3 Partial and cross-boundary embedding challenges . . . 23
3.3.1 Fixturing challenges for flexible components . . . 23
3.3.2 Material deposition and removal challenges . . . 23
3.3.3 Stress concentration considerations . . . 25
3.4 solutions . . . 25
3.4.1 Flexible component fixturing solutions . . . 26
3.4.2 Material deposition and removal solutions . . . 29
3.4.3 Alternative solutions . . . 44
3.4.4 Process selection guideline . . . 50
3.5 Conclusions . . . 50
3.6 Future directions . . . 53
3.6.1 Vertical cross-boundary embedding . . . 53
3.6.2 Suspending fixture for embedding rigid components . . . 54

4 Stiffness modification of flexures by fiber reinforcement 55
4.1 Motivation . . . 55
4.2 Design guideline . . . 58
4.3 Finite element analysis for design . . . 60
4.3.1 FEA method . . . 60
4.3.2 Analysis configurations and results . . . 67
4.3.3 Analysis conclusion . . . 88
4.4 Fabrication method . . . 92

4.5 Stiffness testing . . . 94
4.5.1 Test method . . . 94
4.5.2 Test results . . . 98
4.5.3 Error quantification . . . 104
4.5.4 Stiffness test conclusion . . . 110
4.6 Strength testing . . . 110
4.7 Chapter conclusion . . . 115
4.8 Future directions . . . 116
4.8.1 Improving the state of the art . . . 116
4.8.2 Discovering the unknown . . . 116
4.8.3 Further applications . . . 117

5 Conclusion **119**
5.1 Summary . . . 119
5.1.1 Developments in fabrication . . . 119
5.1.2 Developments in design . . . 120
5.1.3 Application . . . 120
5.2 Beyond SDM . . . 121

Bibliography **121**

List of Tables

3.1 Design and material guidelines for cross boundary embedding 41
3.2 Pros and cons of alternative methods 49
3.3 Process favorability assessment table 50

4.1 Strength test results 111

List of Figures

1.1 SDM process cycle 6
1.2 SDM robot 7
1.3 SDM leg with embedded components 8

3.1 Crossboundary embedding objective 20
3.2 Nomenclature 22
3.3 Pre-encapsulation process example illustration 28
3.4 Suspending fixture method 30
3.5 Process flowchart for the four main methods for partial and cross-boundary embedding 32
3.6 Selective material deposition 34
3.7 Selective sacrificial material deposition 35
3.8 String gimbal fabrication process 36
3.9 String gimbal photo 37
3.10 Selective sacrificial material removal 38
3.11 Spring joint fabrication process 40
3.12 Spring joint photo 41
3.13 Photolithographical cross-boundary embedding process 42
3.14 Photolithographed product photo 43
3.15 Pre-encapsulation 45
3.16 Three types of linkages 46
3.17 Pseudo-boundary formation 48
3.18 Process selection flowchart 51
3.19 Process selection flowchart for direct cross-boundary embedding . . . 52

4.1 Coordinate system definition 56
4.2 Load, deformation, major strain, and fiber location 61
4.3 Principal X strain 62
4.4 Principal Y strain 63
4.5 Principal Z strain 64
4.6 FEA setup 66
4.7 control FEA results 70
4.8 a01 FEA results 71
4.9 a02 FEA results 72
4.10 a03 FEA results 73
4.11 a04 FEA results 75
4.12 a05 FEA results 76
4.13 a06 FEA results 77
4.14 a09 FEA results 79
4.15 a11 FEA results 80
4.16 a12 FEA results 81
4.17 a16 FEA results 82
4.18 a19 FEA results 84
4.19 a21 FEA results 85
4.20 a22 FEA results 86
4.21 a23 FEA results 87
4.22 a24 FEA results 89
4.23 a25 FEA results 90
4.24 b05 FEA results 91
4.25 Relative stiffenings in Y bending and Z torsion 93
4.26 Fabrication sequence 95
4.27 Prototype photo 96
4.28 Comparison of FEA and test results for the control piece 100
4.29 Comparison of FEA and test results for a01 101
4.30 Comparison of FEA and test results for a02 103
4.31 Comparison of FEA and test results for a05 105

4.32 Comparison of FEA and test results for a12 106
4.33 Comparison of FEA and test results for a19 107
4.34 Comparison of FEA and test results for a21 108
4.35 Photo broken control piece 112
4.36 Photo broken a01 112
4.37 Photo broken a02 113
4.38 Photo broken a05 113
4.39 Photo broken a06 114

Chapter 1

Introduction

Juu yoku gou wo seisu (flexibility overcomes sturdiness).

-Japanese proverb.

Laptop computers, digital cameras, and robots are just some of the gadgets that represent the latest advancement in mechatronics. They are equipped with the fastest processors, the highest resolution imaging, or the smartest learning capabilities and hence share the glorious image of cutting edge technology. However, they also share a common negative property... fragility. The finest mechatronic systems have always been fragile. You may remember the yellow rugged sports-line Sony Walkmans from the 1980's or the bulky shock-resistant Casio G-shock wristwatches from the 1990's. Robustness, or its imagery, have often been provided by strengthening structures by enlargement or addition of protective gear. Now think of the monstrous sport utility vehicles that are nothing but harmful both for humans and for the environment.

The other option for providing robustness to complex systems is to simplify, integrate, and introduce flexibility. There are literally countless examples of such elegant solutions in nature, including sometimes not-so-favored animals like cockroaches and geckoes, to which human technology has long long ways to go. However impossible they may be to reproduce artificially, they still serve as excellent inspirations.

Shape deposition manufacturing (SDM) has already proven to be a valid method

for realizing such simplicity, integrity, and flexibility in advanced mechatronic systems. It is a rapid prototyping method, originally developed at Carnegie Mellon University (Merz, 1994) (Merz et al., 1994) (Prinz and Weiss, 1994), that can produce complex geometries with multiple materials and embedded components. The process consists of repetitive cycles of molding and machining. Its multimaterial molding and shaping capability enables complex functionality to be realized in simple and robust integrated flexible mechanisms. There are two key technologies involved here. One is the ability to deposit or remove varying materials selectively to produce complex multimaterial geometries (Weiss et al., 1997). The other is the ability to embed premanufactured discrete elements such as small parts and fibers during the fabrication process. This provides local improvements in properties such as tensile strength, stiffness, and thermal or electrical conductivity or enables fluid channeling. Both of these features are further explored in this thesis, focusing on the manufacturing process planning needed to achieve multimaterial prototypes and on the design method for stiffness modification of flexures.

1.1 Shape deposition manufacturing as a unique fabrication method

Hardware fabrication typically consists of material deposition, deformation, and/or removal and assembly. Let us leave deformation and assembly aside and focus the discussion on material deposition and removal. Conventional fabrication primarily involve selective (=controlled) material removal and bulk (=uncontrolled) deposition. On the other hand, rapid prototyping is primarily selective material deposition. Shape deposition manufacturing is closer to conventional fabrication methods in that it primarily involves selective material removal and bulk deposition. However, it is more like rapid prototyping in that complex artifacts can be produced relatively easily and quickly.

1.1.1 Conventional fabrication

One may think of several different processes for conventional fabrication. Let us consider machining and molding, which represent selective material removal and bulk material deposition. There are other processes like stamping, rolling, welding, and fastening, but these are deformation and assembly methods which we have decided to set aside for this research.

There are four elements to a machining setup. The work piece, tool, fixture, and source of power. You can think of an analogy of peeling an apple with a knife. The apple is the work piece, knife is your tool, the hand holding the apple is the fixture, and your upper body as a whole provides power. The human hand is a very versatile fixturing device which allows the person to peel other vegetables and fruits with the same setup. However, in industrial machining, the lack of versatile fixturing has kept machining from becoming a major method of rapid prototyping (Bloomenthal et al., 2001). Instead, machining in mass production often rely on custom fixtures. While it is not versatile geometrically, machining is applicable to a wide variety of materials. Another benefit of machining is its high precision.

Molding is almost the exact opposite of machining in that it is a bulk (=uncontrolled) deposition process. A molding specialist may argue that the process is very much controlled in terms of how fast and where the material flows. However, the deposition is largely uncontrolled in that the final geometry of the deposited material is determined by the mold geometry rather than the deposition process. A wide variety of materials can be molded including those that cannot be machined because of, for example, low stiffness. Mold fabrication can often be too costly for small volume production, but the cost benefit is significant when it comes to large volume fabrication in which the custom mold can be used repetitively. The dimensional precision is relatively poor.

1.1.2 Rapid prototyping

There are numerous rapid-prototyping methods available. These include stereo lithography (Jacobs, 1992), selective sintering (Deckard, 1988) (Nutt, 1991), fuse deposition

modeling (Stratasys, 1991), 3D printing (Sachs et al., 1992) and laminated object manufacturing (Feygin and Hsieh, 1991). These methods all share a common property. They are all categorized as layered manufacturing in which materials are added in layers selectively in locations where needed. This approach eliminates the need for custom fixturing or custom mold fabrication as desired in conventional machining and that provides the high geometric versatility. However, each of the methods often require process-specific materials and hence the available material options are usually limited. These processes can usually produce prototypes with reasonably high precision at a reasonable speed and cost, but the economic benefits quickly decline for mass production. For these reasons, rapid prototyping processes are often used to create non-functional geometrical models or they are post-processed with conventional machining to produce functional prototypes.

1.1.3 Photo lithography

Micro fabrication techniques exemplified by photolithographic MEMS/IC fabrication processes involve bulk deposition and bulk removal procedures as well as bulk chemical and thermal reactions that are interfered by masks that are created via photochemical reactions. The mask interferences make the bulk processes effectively selective in their outcome. Photolithography is another kind of layered manufacturing which is relatively versatile but has material constraints and is also costly and time consuming especially when producing thick objects. Geometric resolution can be very high if thickness is limited. This process is in fact very similar to SDM in terms of process planning although the specific methods involved are different. (Madou, 2002) is a good reference on micro fabrication.

1.1.4 Shape deposition manufacturing (SDM)

SDM is basically a combination of machining and molding which takes place in repetitive cycles. (Please see figure 1.1.) The mold and the part material are machined using the same method, typically a CNC mill. Both the part and mold material, also

referred to as sacrificial material, can be deposited as needed. During part machining, the mold serves as a custom fixture for the work piece. This provides geometric versatility unmet in conventional machining processes while providing the same dimensional precision and also accommodating soft unmachinable materials that need to be molded. It is sometimes considered a layered manufacturing process but it is fundamentally different from previously mentioned rapid prototyping methods. While the rapid prototyping methods build parts strictly in planar layers with even thickness, SDM-built layers generally vary in thickness and often intersect with each other. These properties specific to SDM allow the process to produce intricate functional parts with complex geometry and material combination. The main drawback to this process is its time-consuming serial process which is mainly attributed to material deposition.

1.2 SDM specialties

The very nature of SDM as a hybrid fabrication method allows it to do things that are otherwise difficult or impossible. These include multimaterial part fabrication and component embedding. Such specialties have helped establish design of mechanisms and systems that are distinctive to SDM.

1.2.1 Multimaterial component fabrication via SDM

One of the properties that make SDM interesting is the repetitive material addition. Different materials can be deposited to compose monolithic multimaterial components which are functionally much more versatile than single material hardware. One of the best proven applications of multimaterial SDM components is that in biomimetic robot legs as seen in figure 1.2 (Clark et al., 2001a) (Cham et al., 2002). Compliant multimaterial monolithic legs consisting of rigid and soft polyurethane are a simple and robust solution to realize desired kinematic, stiffness, and damping properties all in one. Consequently, mechanisms with custom designed compliant joints, e.g.

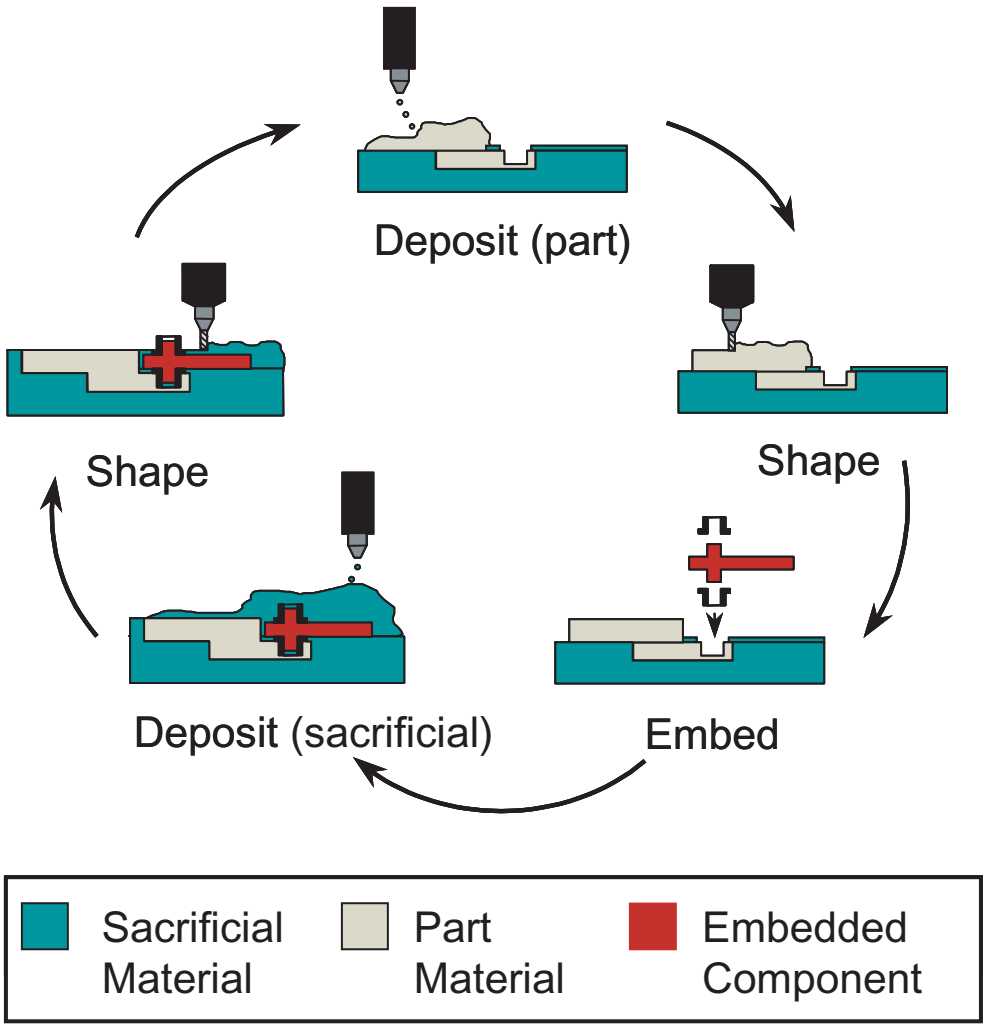


Figure 1.1: SDM process cycle involving material addition and removal and component embedding

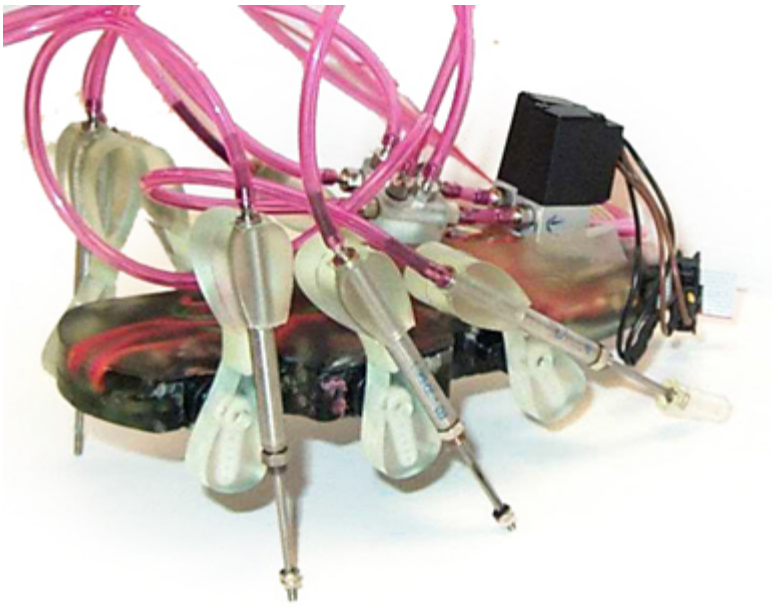


Figure 1.2: SDM robot featuring embedded components and multimaterial legs

flexures, have been identified as a specialty of SDM for its functional versatility supported by relative ease of design and manufacture. Naturally, further exploration of SDM capabilities around compliant joints became an obvious area of challenge.

1.2.2 Component embedding in SDM

Another SDM specialty is component embedding. When cavities are machined for material deposition, other things can also be placed inside. Since materials are added in several discrete steps, unlike the usually uninterrupted addition in other rapid prototyping, the process interruption also provides a good opportunity for components to be inserted in the cavities. One application of component embedding is structural stiffening or strengthening. Another is the embedding of functional components that cannot or rather not be produced by SDM. These include mechanical components like joints and electric or electronic components ranging from circuitry, actuators, to sensors as seen in figures 1.2 and 1.3 (Cham et al., 1999) (Bailey et al., 2000) (Li et al., 2000) (Park, 2002)(Park et al., 2003). The research presented in this dissertation deals

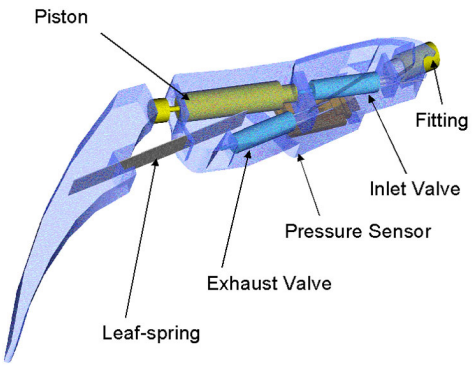


Figure 1.3: SDM leg with embedded components

with both of the SDM specialty areas of compliant joints and component embedding.

1.2.3 Other related works on SDM

There are several variations of SDM including those that use metals, polymers, and ceramics (Li et al., 1999) (Kietzman, 1998) (Cooper, 1999). Here, the discussion is primarily on polymer SDM. Multimaterial part design for SDM has been studied theoretically and so is the manufacturing process planning (Rajagopalan and Cutkosky, 1998) (Rajagopalan and Cutkosky, 1999) (Rajagopalan et al., 2000) (Binnard and Cutkosky, 1998) (Binnard, 1999) (Clark et al., 2001b). Discrete joints such as pin joints have been both fabricated via SDM and embedded (Cham et al., 1999) (Park et al., 2003) (Stefanini et al., 2003). Compliant materials dynamics have been modeled and used in dynamic simulation to design and tune SDM fabricated robots (Xu et al., 2000) (Clark et al., 2004).

1.3 Motivation

Application of SDM in mechatronic systems such as the previously mentioned robots has created desires and needs to further develop its special capabilities. One is cross-boundary embedding of components which enables fabrication of integrated systems. Another is fiber reinforcement of flexures which overcomes some of the strength and

stiffness limitations of flexures.

1.3.1 Cross-boundary embedding

SDM applications in robots and other mechatronic systems have inspired desires to embed components across material boundaries. Initial needs included exposure of electrical and pneumatic connectors and partial embedding of mechanical components such as joints and springs(Cham et al., 1999). Newer needs include wiring across multimaterial compliant joints for electrical power supply and signal transfer, similar needs in fluid systems for fluid channeling, and mechanical boundary crossing for structural improvement.

1.3.2 Flexure strength and stiffness modification by fiber reinforcement

As SDM robot designs were refined and simulation techniques were improved to determine flexure properties for better performance, design and fabrication technology had to keep up with the demand. The challenge began with strength and flexibility tradeoff when strength concerns arose as flexures were made thinner for increased flexibility. There had also always been a demand to increase a flexure's stiffnesses for secondary bending and twisting without compromising the primary bending flexibility. More advanced needs were identified in having direction-dependent stiffness specifications, for example in a robot leg hip joint that can bend easier backward than forward.

1.4 Contributions

The cross-boundary embedding work helps enable SDM fabrication of robust integrated mechanical systems. Fabrication process options were theoretically organized, explored and also experimented. The organized process options, along with some initial application examples, provide the starting point for further exploration and refinement of cross-boundary embedding techniques.

The flexure strength and stiffness modification work allows better realization of flexure design specifications within dimensional constraints and limited material choice while maintaining design and fabrication simplicity. It also broadened the potential application areas for flexures by overcoming their disadvantages. Furthermore, it provides a starting point for related applications such as flex sensor development and through-flexure wiring design.

Chapter 2

Previous Work

In order to prepare for cross-boundary embedding and fiber reinforcement of flexures, related works both in and outside SDM were studied. Component embedding work has been demonstrated mainly in mass production and SDM. On the other hand, there are difficulties encountered in other rapid prototyping methods. Fiber reinforcement has been long practiced by humans in various areas, mostly for structural strengthening. Some of the composite structures have also been modeled and studied. There have also been applications of anisotropic fiber stiffening for producing actuators. Finally, modeling and analysis methods for elastomer structures were studied to aid the design of fiber-reinforced flexures.

2.1 Previous work on component embedding

2.1.1 Previous component embedding work: Non-SDM

Although SDM is arguably the rapid prototyping process that most invites component insertion, due to its alternating additional and removal processes and comparatively small number of process layers, the problem of embedding components has also been addressed for other rapid prototyping processes. In discussing approaches for creating prototypes containing discrete parts of a dissimilar material, it is useful to distinguish

between component insertion and component embedding. In the former case components are inserted into a cavity inside part material after the surrounding part is built whereas the immediate surrounding part material is cast after component placement in component embedding. Kataria et al. have developed methods for inserting components in stereo lithographed structures (Kataria and Rosen, 2000). DeLaurentis et al. have produced a robotic vehicle with inserted components also using stereo lithography (Mavroidis et al., 2001) (DeLaurentis et al., 2002). These works mention limitations related to laser shadowing and obstruction of the material addition due to the strictly planar layered nature of the fabrication method. This poses numerous constraints on what can be inserted and when. Besides, the components are simply inserted into a cavity that is left out during fabrication. Hence, there will be no adhesion of the encasing polymer to the inserted components unlike with embedded components in which polymer is cast and cured directly around them. For this reason, inserted components may have limited support from the encasing polymer compared to embedded components.

Component embedding has been implemented earlier in mass production. Insert molding is common in large volume injection molding of thermoplastics and thermoplastic elastomers (Digiantonio, 1992) (Digiantonio, 2005). For example, many cable connectors for electronic appliances have molded insulation housing over the metal conductors. An in-line skate wheel consists of inserted rigid core material and molded higher-friction tire material. (Please note the difference in the use of the word insert in this paragraph and the one before. Insertion in the previous paragraph refers to that with respect to the polymeric part that is being produced. In this paragraph, it refers to the insertion of the component into the injection mold.) Since it is not a layered manufacturing, the part material can conform and bond to the inserted component surface as it is injected into the mold. Two-shot molding of different polymers, as often seen in toothbrushes with hard and soft material, is also a similar process. Large volume production also justifies greater time and monetary investment on creating customized equipment for insert molding or two-shot molding. That is yet another factor that enabled the implementation of component embedding in mass manufacturing.

2.1.2 Previous component embedding work: SDM

SDM's high compatibility with component embedding has led to numerous implementations up to date. Despite the fact that SDM is often categorized as layered manufacturing, it is notably different from other layered manufacturing methods. Ordinary layered manufacturing involves sequential stacking of fine strictly planar geometries which only grow in one direction. On the other hand, in SDM, material can also be added in levels lower than the top of the previously cast layer. The individual layer thickness can also be much larger. These differences provide adequate physical space and process planning freedom for component insertion. Furthermore, adding material immediately adjacent to inserted components is easy in SDM because materials are usually added in bulk and they naturally fill up any empty volume. This is often more challenging or even impossible for other layered manufacturing involving selective material addition because of process obstruction. These properties of thicker and sometimes intersecting material layers added in bulk facilitate component embedding in SDM. In effect, the process is much more like insert molding. (It indeed is insert molding. The difference is that SDM is open molding whereas insert molding is injection molding.) In addition, component insertion is also possible if desired. Examples of previous works are indicated in the previous chapter.

2.2 Previous work in fiber-reinforced elastomers

2.2.1 Application, modeling, and theories

Fiber reinforcement of materials has long been practiced in various fields. Wood is a naturally composite material. One of the very early human applications include reinforcement of earthen adobe with fibrous plant materials such as straw which dates back as far as 7000 B.C. (McHenry, 1988). More modern applications are in the fields of fiber-reinforced polymers as often seen in the aero-astro and racing industry for constructing lightweight structures. Applications in fiber-reinforced elastomers include rubber tires and hydraulic tubings with embedded strengthening cords. (Wake

and Wootton, 1982) covers the basics of textile-reinforcement of elastomers in practical manner. Tire properties have been studied actively since the 1960's by many investigators including (Clark, 1963b), (Clark, 1963a), (Clark, 1964), (Gough, 1968), (Akasaka, 1959), and (Biderman et al., 1963). Coated fabric properties have been studied by (Akasaka and Yoshida, 1972), (Alley and Fairslon, 1972), (Reinhardt, 1976), (Skelton, 1971), and (Stubbs and Thomas, 1984). Chou et al. have modeled flexible composites that undergo large deformations. (Chou and Takahashi, 1987) Luo and Mitra et al., along with Chou, have studied flexible composites experimentally (Luo and Mitra, 1995) (Mitra and Luo, 1995) (Mitra and Luo, 1994a) (Mitra and Luo, 1994b) (Luo and Chou, 1990). Peel and Jensen et al. have also worked on the modeling flexible composites and developed fabrication methods (Peel et al., 1998) (Peel and Jensen, 2000). (Chou, 1992) is a good background reading for the field of flexible composites.

Please note the various terminologies used for referring to the general area of fiber or fabric reinforced elastomers. Flexible composites, coated fabrics, cord-rubber composites, and cord-reinforced rubber are some of the useful keywords for searching for literature about the subject.

2.2.2 anisotropic property modification for kinematic functionality

Gaylord invented and patented the McKibben actuator in 1958, which is a composite structure of elastomer bladder contained within braided fibers (Gaylord, 1958). Here, the two materials are separate from each other. Suzumori et al. have produced near-cylindrical silicone rubber actuators with embedded fibers, circumferentially wrapped around, that are pressure-activated to bend in different directions incorporating its anisotropic material properties (Tanaka et al., 1991). Various mechanical systems such as walking robots, robotic hands and grippers have been produced using this actuator(Suzumori, 1996). However, the group has moved on to designing similar actuators from a single material due to the difficulty of miniaturization of the composite structure (Suzumori et al., 1996) (Takagi and Suzumori, 1996). Dohta et al.

have produced a very similar flexible bending actuator, composed of silicone rubber, circumferentially wrapped reinforcement fibers, and a sheet of plastic also for reinforcement (Dohta et al., 2000). Tanaka et al. have also produced a similar actuator with fibers used in circumferential wrapping and longitudinal reinforcement (Tanaka, 1993) (Tanaka et al., 1996). Here, the fibers are adhered to the rubber tube surface.

2.3 Modeling and analysis for design

In this thesis research, finite element analysis (FEA) was employed as the tool for analyzing design options for fiber-reinforced flexures. Popular FEA software for elastomers include ABAQUS, ANSYS, and MARC (ABAQUS, 2005) (ANSYS, 2005b) (MSCsoftware, 2005). The analysis involves the modeling of fibers and elastomer as analysis elements and integrating them into a single stiffness matrix. Fibers or string elements can be effectively modeled as linear elements which only resist tensile load. On the other hand, elastomer modeling is rather delicate and complex. Most research publications indicate that it is very difficult to simulate large deformation of elastomers (Lloyd-Lucas, 1999) (Ramsay, 1999) (Turner et al., 1999). Hyperelastic material properties are commonly represented using the Mooney-Rivlin model or the Ogden model (Rivlin and Saunders, 1951) (Adkins and Rivlin, 1952) (Adkins and Rivlin, 1955) (Ogden, 1982). These models are capable of handling large strains. For example, the Ogden model can handle strains of up to 700% (ANSYS, 2005a). There are other hyperelastic material models such as Arruda-Boyce and Gent which can handle strains of up to 300% and Neo-Hookean which is only applicable to small strains of up to $20-30\%$ (Arruda and Boyce, 1993). Some others such as the polynomial and Yeoh models have varying strain level applicability depending on the number of parameters employed, just like the Mooney-Rivlin and Ogden models (Yeoh, 1993). Both the Mooney-Rivlin and Ogden models require involved experimentation for accurately determining the material properties that would lead to reliable analysis results (Cadge and Prior, 1999) (Daley and Mays, 1999) (Gough et al., 1999) (Johannknecht et al., 1999). There have been efforts to simplify the material models but these methods are still not mature enough (Shariff and Stalker, 1999) (Williams

et al., 1999). On a side note, material testing is commercially available at costs from around $1500 for determining elastomer material properties(AxelProducts, 2000).

FEA of structure with linear reinforcing elements was first demonstrated by (Ngo and Scordelis, 1967) for steel reinforced concrete. Coupling of fibers and elastomers in FEA was first demonstrated in tire simulation by (Watanabe and Kaldjian, 1983). Multiple cords were represented as one cord in the FEA model. The coincident nodes of the elements were fixed with respect to each other to emulate the effect of interfacial bonding between the two. This approach of coupling coincident nodes was directly applicable for the analysis of fiber-stiffened flexures dealt in this dissertation, even better than for the application in the original publication, because there were only finite number of fibers in the structure and each one of them could be included in the model without simplification by unification of multiple fibers. An alternative method exists for facilitating modeling of composite structures with arbitrary location and orientation of reinforcing elements. (Helnwein et al., 1993) However, the fiber orientations of interest were relatively small in variety for this dissertation research such that the previously mentioned simpler method was adequate.

Lists of literature on the finite element analysis and simulation of rubber and rubber-like materials are available in (Mackerle, 1998) and (Mackerle, 2004).

2.4 Fibrous material selection for elastomer reinforcement

There are four major criteria for fiber material selection;

- lengthwise stiffness,
- flexibility in other directions,
- strain resistance,
- fatigue life,
- strength,

- bonding.

The material is largely responsible for the stiffness while geometry also takes significant role in the other properties. The finer the fibers are, the more flexible the bundle of fibers will be for equal total cross-sectional area because of slippage allowed between the fibers. This may also reduce maximum stress in fibers to improve strain resistance and fatigue life, especially in bending. Strength is also improved in a bundle of finer fibers by inhibiting crack propagation. Bonding strength is closely related to surface area, hence finer fibers also help improve this property. Polyester and cotton were the readily available materials that exhibited favorable properties. Cotton showed good bonding while moderate in stiffness and strength. Polyester proved to be better at stiffness and strength but had limitations in bonding. As a result, cotton or cotton/polyester blend were used. More information on this topic is available in (Wake and Wootton, 1982) (Gupta, 1998) (Gupta, 2001).

Chapter 3

Cross-boundary embedding of flexible components

As mentioned in Chapter 1 and 2, an important advantage of SDM with respect to other rapid prototyping processes is that it is relatively easy to embed components. In comparison with commercial layered manufacturing processes such as fused deposition modeling and stereo-lithography, SDM has a relatively small number of cycles, which generally correspond to transitions between upward- and downward facing part surfaces (with respect to the growth direction) or to changes in the part material. The breaks between cycles create a natural point at which discrete parts can be added. Many examples of multi-material parts, including parts with embedded components, have been created and the process planning for such parts has been described in previous work (Cham et al., 1999) (Binnard, 1999). However, a number of unsolved problems remain. Foremost among these are the problems associated with embedding components that traverse material boundaries, especially when embedding flexible components. The treatment of flexible elements that cross material boundaries in SDM is covered in this chapter.

3.1 Introduction

There are several common reasons for embedding flexible elements in multi-material parts. One common application of fibers is to alter the strength or stiffness of a part. Fiber-reinforced materials are common both in nature and in man-made products ranging from golf clubs to fiberglass boats to automobile tires. In these examples, fibers are used that have a considerably higher specific strength or stiffness than the surrounding material. In other applications, flexible elements such as wires or fiber optic strands may be embedded to transmit power and/or signal through the part. Similarly, hydraulic and pneumatic tubes may be embedded within a part. In each of these applications, it may be desired to have the fibers, tubes or wires continue uninterrupted across transitions from one material region to another. This would enable the production of a functionally integrated joint which can transfer not only force and displacement but also information, energy, and material. The work described in this chapter has led to four basic methods to accommodate such cross-boundary flexible embedded elements. In addition, two alterative methods are described that essentially emulate the functionality of cross-boundary embedding.

The challenges associated with cross-boundary embedding are primarily:

- Precisely defining the location and orientation of the embedded component during the fabrication process.
- Selectively adding, removing, or otherwise processing material around the embedded components without damaging them or being hindered by them.
- Preventing stress concentrations at material boundaries that could lead to early failure.

In the following section these issues are discussed in the context of a simple abstract example of an embedded flexible component that straddles the boundary between two different part materials as shown in Figure 3.1. The requirements for the finished product are as listed below. The criteria consist of geometric requirements, interfacial bonding requirements, and functional requirements.

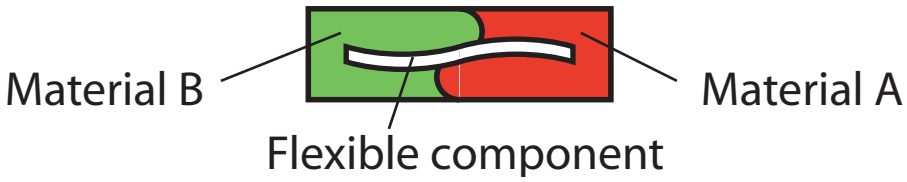


Figure 3.1: Crossboundary embedding objective

1. Embedded component crosses the material boundary.
2. Location and shape of the embedded component are precisely defined.
3. Inter-material boundary geometry is precisely defined.
4. Individual part material geometry is precisely defined.
5. Secure material bonding is established at all interfaces; between the embedded component and the part materials and between the two part materials.
6. The embedded component is functional, i.e. it meets functional requirements for strength and stiffness and fatigue life and maintains any additional functionalities such as the ability to transfer signal, energy, or material.
7. The encasing part materials are functional, i.e. their functionality is not compromised by the addition of the flexible component or by the processes used to create the part.

3.2 Fabrication method and nomenclature

The fabrication method and nomenclature are explained in this section as basic background information for the understanding of the work.

3.2.1 Materials and manufacturing methods

In Shape Deposition Manufacturing (SDM), various materials can be deposited, and also removed, to obtain the desired part. When materials are selected prioritizing their functionality in the finished product, they may not necessarily have desirable properties for fabrication. In order to overcome limitations in fabrication due to material selection, temporary materials that are better suited for fabrication are sometimes incorporated into the process to facilitate production. These materials, called sacrificial materials, only serve to facilitate the production and they do not remain in the finished product. On the other hand, the materials that remain in the finished product to help realize its functionality are referred to as part materials. In the examples that follow, combinations of stiff polymers and flexible elastomers are employed for creating the parts, and waxes or uncured polymers as the sacrificial support materials. Flexible components included fibers, fabrics, electrical wires and flexible printed circuits. CNC machining and a hot water jet were employed for selective removal of sacrificial materials; solvents were employed for bulk removal.

3.2.2 Nomenclature

In the following discussions and examples, a series of schematic diagrams are used for manufacturing process illustration. The diagrams are all overhead views of a part in process. In other words, machining tool access and material deposition both occur in the orientation normal to the plane of the page. Figure 3.2 is a diagram for color scheme explanation.

For generality we further assume that one of the part materials, B, is possibly a soft material for which controlled material addition or removal is impractical. Thus, material B can only be added or removed in bulk.

Glossary of components and materials:

- Flexible component: A highly deformable part that improves properties of or adds functionality to the product. It may contribute to structural improvements (e.g. strengthening or stiffening) and/or energy, motion, material, and/or signal

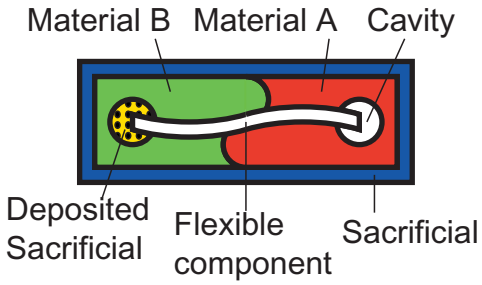


Figure 3.2: Generic in-process example with embedded flexible fibers

transfer. Typical examples include fibers, fabric, electric wire, and pneumatic tubing.

- Part material: Deposited material that constitutes the final product. Part materials are selected prioritizing their properties in the final form rather than their fabrication properties. Typical part materials include polymers and elastomers such as polyurethane, epoxy, and silicone with varying material properties. In the examples employed in this chapter, materials A and B are part materials. Of these two materials, material A is assumed to be a stiff polymer that is machinable and material B is a flexible elastomer that cannot be machined.

- Sacrificial material: Temporary materials used to aide fabrication. Part materials may have properties that are not ideal for fabrication since they are chosen based on their functionality in the finished product. Sacrificial materials that do not remain in the finished product are selected based on their properties that facilitate fabrication. These include the ability to be (1) deposited in controlled geometry, (2) removed in controlled geometry, (3) easily deposited without damaging the flexible component or part materials, and (4) easily and cleanly removed when no longer needed. Typical sacrificial materials include waxes with various melting temperatures and stiffnesses as well as solid soap.

3.3 Partial and cross-boundary embedding challenges

As previously mentioned, the three main difficulties associated with creating parts with embedded flexible components were fixturing the flexible members, achieving good control of the geometry of part materials in the vicinity of the flexible elements, and avoiding stress concentrations. These difficulties are explained in the remainder of this section.

3.3.1 Fixturing challenges for flexible components

Components need to be properly located inside the mold upon embedding. Sometimes, parts are directly placed inside an empty mold. Component location can be defined using matching features on the mold. At other times, components are placed in a partially filled cavity. The bottom of the cavity would already be filled with part material with machined features that matched the component to be embedded. Another method is to fabricate a custom harnessing fixture for the component to use as a support when placing it inside a mold, either empty or partially filled. In all of the above cases, the component can obtain additional fixturing support by using adhesives often in the form of, but not limited to, fluids. These methods are generally effective for rigid components. However, flexible components such as electrical wires or reinforcement fibers and fabrics often require other means of fixturing to achieve desired locating accuracy. In addition, flexible components, which cannot support their own shapes require some means for defining the shape. Several alternate methods have been developed.

3.3.2 Material deposition and removal challenges

To satisfy the previously defined requirements, any combination of controlled material deposition and removal may be used. For example, in the case of fused deposition modeling (FDM) the part materials are deployed precisely to the desired shape; in the case of shape deposition manufacturing (SDM) controlled material removal or

shaping is used to create the desired shape. These processes will be referred to as selective material addition and removal, respectively, in the following discussion. The challenge in each case is (1) not to be hindered by the flexible material (i.e. to have access to all regions desired) and (2) to avoid damaging the flexible elements as a side-effect of the material deposition, removal or curing process.

A typical problem is to prevent castable materials (i.e., bulk material addition) from infiltrating regions where they are not desired. When flexible fibers pass through the boundary of a region, sealing can be especially difficult. On the other hand, removing material around a flexible component can lead to problems because the flexible element is unable to support itself as it becomes released and this may hinder precise material removal or increase the risk of component damage.

Where selective material addition or removal is impractical in the vicinity of flexible elements, the alternatives are bulk material addition or removal. For example, these include casting a liquid polymer into a cavity or removing an entire region of sacrificial material by melting it or washing it away with solvent. A variation on this process is to combine SDM with photolithography in which a mask and UV light are used to define a geometric pattern, followed by bulk material removal with solvent. Examples of these methods are presented in the next section. However, in this case there is the problem that the fibers may shield or shadow the material underneath. Similar interference problems have been identified by other researchers (Kataria and Rosen, 2000) (DeLaurentis et al., 2002).

Glossary of processes:

- Selective deposition: Controlled material addition such that the material is deposited only to designated locations to form a defined geometry. Fused deposition manufacturing (FDM) is an example of selective deposition.

- Bulk deposition: Uncontrolled material addition such that the material is free to fill all available volume. Molding is an example of bulk deposition.

- Selective removal: Controlled material removal such that the material is removed only from designated locations to leave behind a defined geometry. Machining is an example of selective removal.

- Bulk removal: Uncontrolled material removal such that all of the material of the same kind will be removed. Chemical etching and melting are examples of bulk removal.

3.3.3 Stress concentration considerations

Stress concentration is one of the most important factors to be considered when designing structures that deform or bear cyclic loads. A stiff material may crack; a soft material may tear; delamination may occur at a material interface. An embedded component may also break when the surrounding matrix deforms.

Sharp-edged concave geometries are generally undesirable, both on the exterior of the part and on interior boundaries between dissimilar materials. Stress concentrations also occur where there is an abrupt change in the Young's moduli. The obvious countermeasure is to avoid having material boundaries at locations where high stresses are expected. In a smaller scale, inter-material bonding strength can also be strengthened by selecting materials or material combinations with appropriate chemical properties and by adding geometric interlocking features or simply by increasing the interfacial surface area. In addition, microscopic defects on material surfaces - especially for soft materials that undergo large strains - should be avoided. For example, it is known that selective material removal for soft materials will lead to surface cracks and poor fatigue life (Kietzman, 1998). However, by modifying the process plan, the soft material (generic material B) can be cast into a smooth cavity that establishes its shape, hence eliminating the need for material removal. Examples of linkages with flexures that have survived over 1 million cycles are presented in the next section.

3.4 Solutions

Solutions for the fixturing problem are mentioned followed by solutions for the general process planning. The process planning solutions include both real cross-boundary

embedding solutions and alternative solutions that can provide similar effects. Selection guidelines for the various methods are also provided.

3.4.1 Flexible component fixturing solutions

Two new methods have been developed for fixturing flexible components. Here, the objective was to locate flexible components with high accuracy in a defined shape for embedding in cast material. The flexible components are generally not stiff enough to hold themselves in proper position when they are left without support. Hence, previous methods of direct placement inside empty or partially filled mold cavities are not applicable. Another problem, which is also encountered in direct placement of flexible components, is displacement by floating. Light flexible components such as threads and fabrics may easily float out of the mold cavity, especially during the degassing process for air bubble removal immediately after the material casting because of the vigorous bubbling. Generally, it would also not be appropriate to use a permanent rigid harness for supporting the component since it would hinder the flexibility of the component and the finished product. In some initial attempts, fluid adhesives were used to temporarily fixture reinforcing fabric to the bottom of the mold. Relatively thick cyanoacrylate adhesive was employed so as to localize adhesive infiltration in the fabric which would lead to its stiffening. This is a simple and valid method when the positioning accuracy requirement is not very tight and the fabric does not need to be in tension. However, it is a rather unreliable skill-dependent method and hence performance consistency cannot be expected. The two methods to follow are intended to overcome these problems and limitations.

Pre-encapsulation

One method is to pre-encapsulate (pre-embed) the flexible component in a polymer. It is a preparatory procedure for the flexible component which is otherwise unfit for cross-boundary embedding processes. By having a layer of another material encasing it, it can have sufficient rigidity for keeping its shape and also enough density to prevent displacement by flotation. Even then, some sort of fixation is still required

for the pre-encapsulation process. However, the advantage in performing the pre-encapsulation off-line as opposed to direct in-situ embedding is that more elaborate fixtures can be used because of less spatial limitations during the process and also because the fixture can be removed from the component before its incorporation into the mechanism in production.

The best way to define the geometry of a flexible component is to apply tension. Naturally, straight forms are the simplest to produce when tension is used. For example, fiber-reinforced elastomer strips can be produced by holding fibers in tension in a shallow mold cavity supported by anchors at both ends and then casting the material into the mold. The process is shown schematically in figure 3.3. Molding provides a significantly better dimensional accuracy compared to polymer impregnation in open space or vacuum bagging, and this is helpful in the component handling when integrating it to the final mechanism. The increased size, rigidity, and better defined geometry would also make the component easier to fixture.

Curved geometries can also be produced in a similar fashion by running fibers in tension in a curved cavity and relying on the cavity inner walls for the curves. Another way to fixture fibers in a curved geometry is to first prepare a straight strip as previously mentioned and to fixture it in curved geometry in later stages of fabrication. When the pre-encapsulated component is to be re-embedded as in this case, rib-like features either on the flexible material or the rigid surrounding are useful for positioning and supporting. The ribs behave like the custom harnesses used for rigid component embedding. One can also pre-embed a flexible component without fixture by using a tightly made mold that will fit the component inside with sufficient locating accuracy.

The surrounding material can also serve as a protective layer for preventing undesired material infiltration or chemical reactions that influence functionality or bonding properties. Examples of these applications will be discussed later along with detailed description of the process options. The extra layer can also be a bonding agent interlinking the flexible component and the surrounding part material if the two cannot bond well directly. In short, the benefits of pre-encapsulation extend beyond solving fixturing problems.

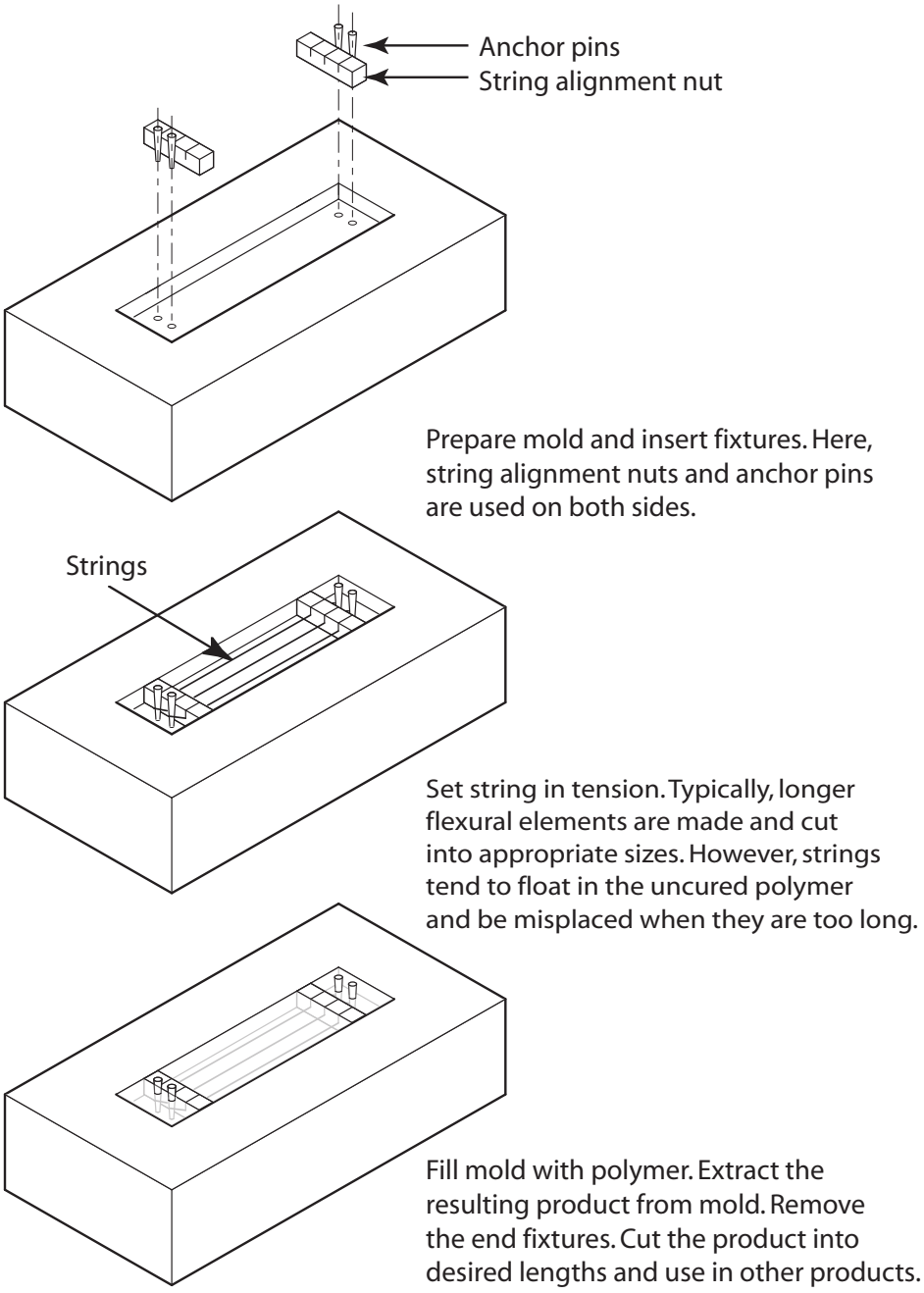


Figure 3.3: Pre-encapsulation process example illustration

Suspending fixture method

Another method is to create a custom harness for the flexible component and suspend it into the mold cavity. The process cartoon is shown in figure 3.4. The harness would typically secure the flexible component in two or more locations. These multiple securing parts would be in one rigid piece until the component is fully embedded. And then they would be separated, for example by machining the top part off, to allow relative motion of the pieces. Initially, the securing parts are held together to facilitate preparation of the geometry. For example, preparing fabrics or fibers to be embedded in tension is much easier when the securing anchor pieces are fixed with respect to each other instead of being free. In addition, positioning one structure in a mold is much simpler and often reliable than having to position multiple securing pieces. An example of this method is shown in the following chapter.

The first method of pre-encapsulation is useful for relatively simple geometries and it can be applied in small sizes as well. The second method of fixture suspension is able to achieve more complex geometries, but fixture design and preparation may be troublesome. The first method would generally be recommended whenever possible, especially for large volume manufacturing, because of the complexity involved in performing the second method.

3.4.2 Material deposition and removal solutions

This section describes several process options for creating multi-material parts with embedded flexible components that overcome difficulties described in the previous section. The options are illustrated with examples of mechanisms actually created and their accompanying process plans.

The process options consist of combinations of material deposition and removal, both of which can be either selective (=controlled) or bulk (=uncontrolled). Selective material deposition is the process of depositing material specifically at designated locations. Fused deposition manufacturing is an example of selective material deposition. Bulk material deposition, on the other hand, allows the material to fill any empty volume without geometric control and it is exemplified by molding processes.

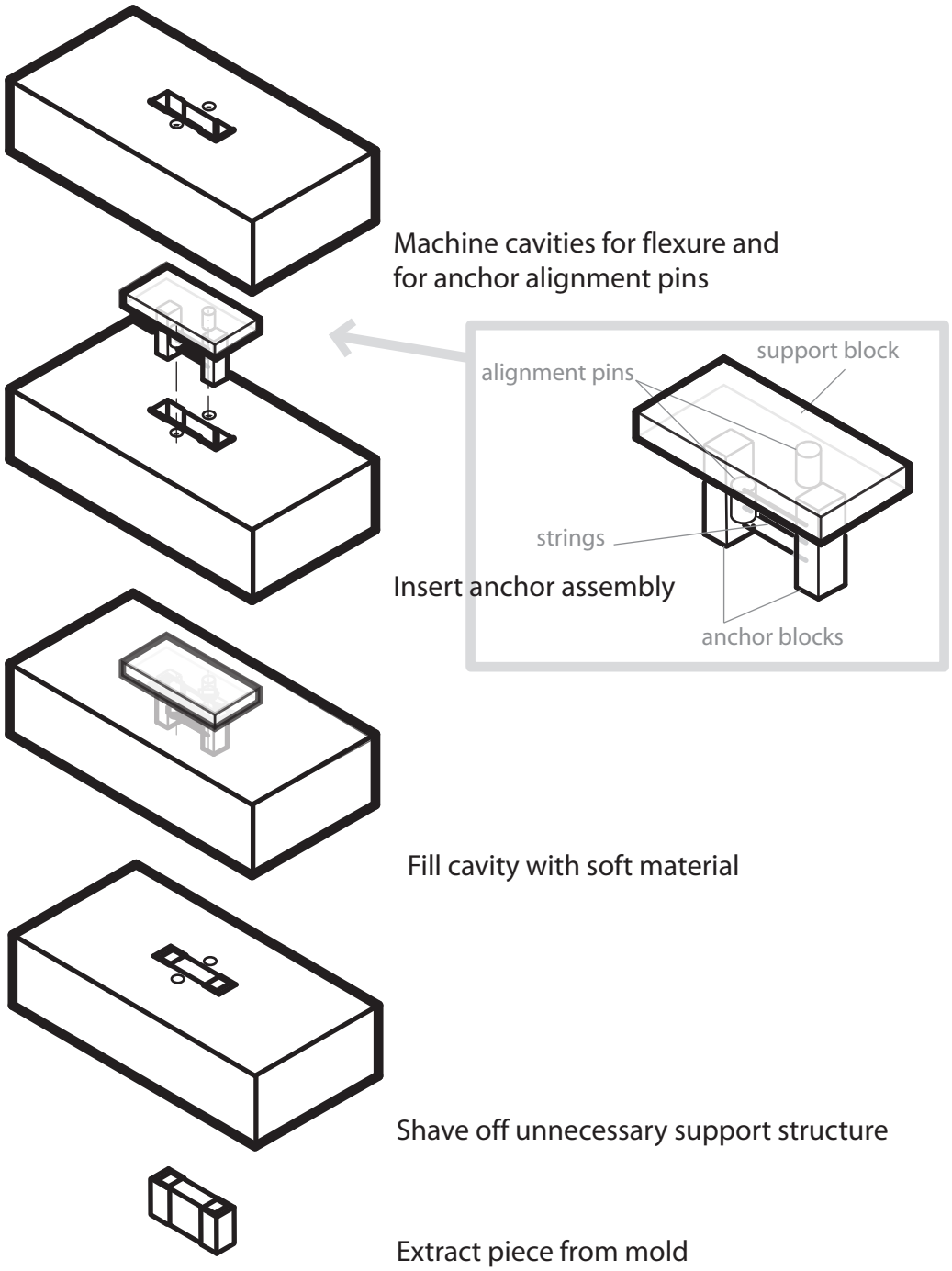


Figure 3.4: Suspending fixture method

Selective material removal takes material away specifically from designated locations. Machining is an example of selective material removal. In contrast, bulk material removal takes away all materials for which the process is applicable without geometric control. Chemical etching and melting by heat are examples of bulk material removal.

Each of the process options involves one step of selective material addition or selective material removal. The various process sequences are illustrated schematically in Figure 3.5 and are understood to represent partial process plans or plan fragments. In each case, it is assumed that the process starts with creating temporary or sacrificial fixtures and inserting the flexible material into them. In the documentation to follow, processes are named after the selective process employed.

Selective material deposition

The most straightforward approach to achieving the configuration in Figure 3.1 is to selectively deposit either material A or material B so as to create a defined boundary between them while encapsulating the flexible component. This approach is labeled as sequence I in Figure 3.5 and the manufacturing steps are depicted in Figure 3.6.

Let us go through the process step by step following Figure 3.6. (1) The mold defines the outer geometry of the product. The fixtures define the location and shape of the embedded flexible component. They have to remain there until the flexible component is securely embedded. (2) The flexible component is held in place by the fixtures. The fixture must be able to hold the flexible component securely. Securing options include press fit, tying, bolt fastening, and adhesive application among others. When the component's limited size, strength or stiffness inhibits secure fixturing, it can be pre-encapsulated in a material that can improve these properties without hindering the functionality. Depending on the fixture design, it may be more appropriate to set the flexible component in the fixturing structure before inserting them in the mold. (I-3) Material A is selectively deposited into its designated location. This process defines the inter-material boundary geometry and is also responsible for establishing material bonding with the flexible component. Selective material deposition like FDM and stereo lithography usually require access in the proximity of the deposition location, physical or optical, and that can result in interference problems

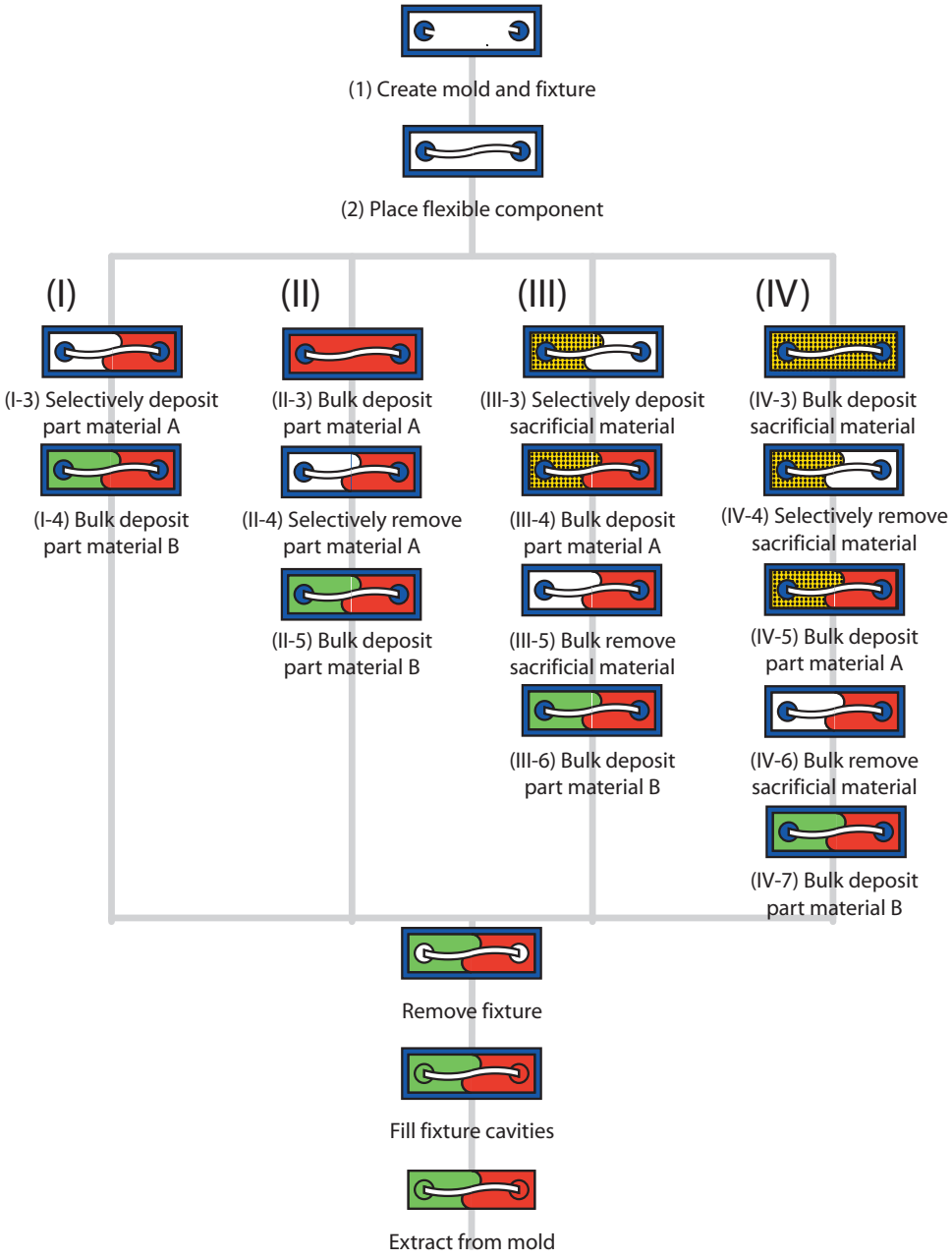


Figure 3.5: Process chart for the four main methods for partial and cross-boundary embedding: (I) selective material deposition, (II) selective material removal, (III) selective deposition of sacrificial material, (IV) selective removal of sacrificial material.

in which components may obstruct the deposition process and also risk damaging of or being damaged by the deposition system. If these problems cannot be avoided, another process would have to be employed. If the material quality obtainable from the selective deposition process is not satisfactory, there is an option to create a fine 3D mesh with the imperfect material and then infiltrate the material with another material to improve the material property. In this case, the infiltration material cannot be selectively deposited in open volume. However, it can be selectively deposited about the 3D mesh because of capillary action. For example, FDM often uses porous polycarbonate which is brittle and has weak bonding capability. This can be complemented by infiltration with materials such as epoxy or urethane which have better wetting capabilities and hence good bonding but are difficult to deposit selectively. The capillary action can also be harmful at times. For example, some flexible components, especially fabrics, may have the problem of being infiltrated by the deposited material even past the designated material boundary and changing its functional property (e.g. flexibility). This can usually be prevented by pre-encapsulation or pre-infiltration. (I-4) Material B is bulk deposited in the remaining cavity. Inter-material bonding at the boundary and with the flexible component is established in this step. (Finish) Fixtures are removed to free the component motion and the resulting cavities are filled with part materials by bulk deposition process. These two steps can be avoided by making the fixtures with appropriate part materials that can remain in the product. However, in this case, the fixtures must be detachable from the base mold. (Release) The finished product is extracted from the mold.

An alternative is to selectively deposit a sacrificial material that is subsequently removed to create a shaped cavity for adding part material in bulk. The corresponding sequence is labeled III in Figure 3.5 and the modified steps are illustrated in Figure 3.7. Steps (III-3) and (III-4) follow immediately after step (2) in figure 3.6 and are very similar to steps (I-3) and (I-4) in the previous example except that the materials deposited are sacrificial material and material A as opposed to materials A and B, respectively. Hence, the required considerations are also similar except for the choice of the sacrificial material which needs to be removable. The sacrificial material has to be removed completely in step (III-5) such that there is no residual material

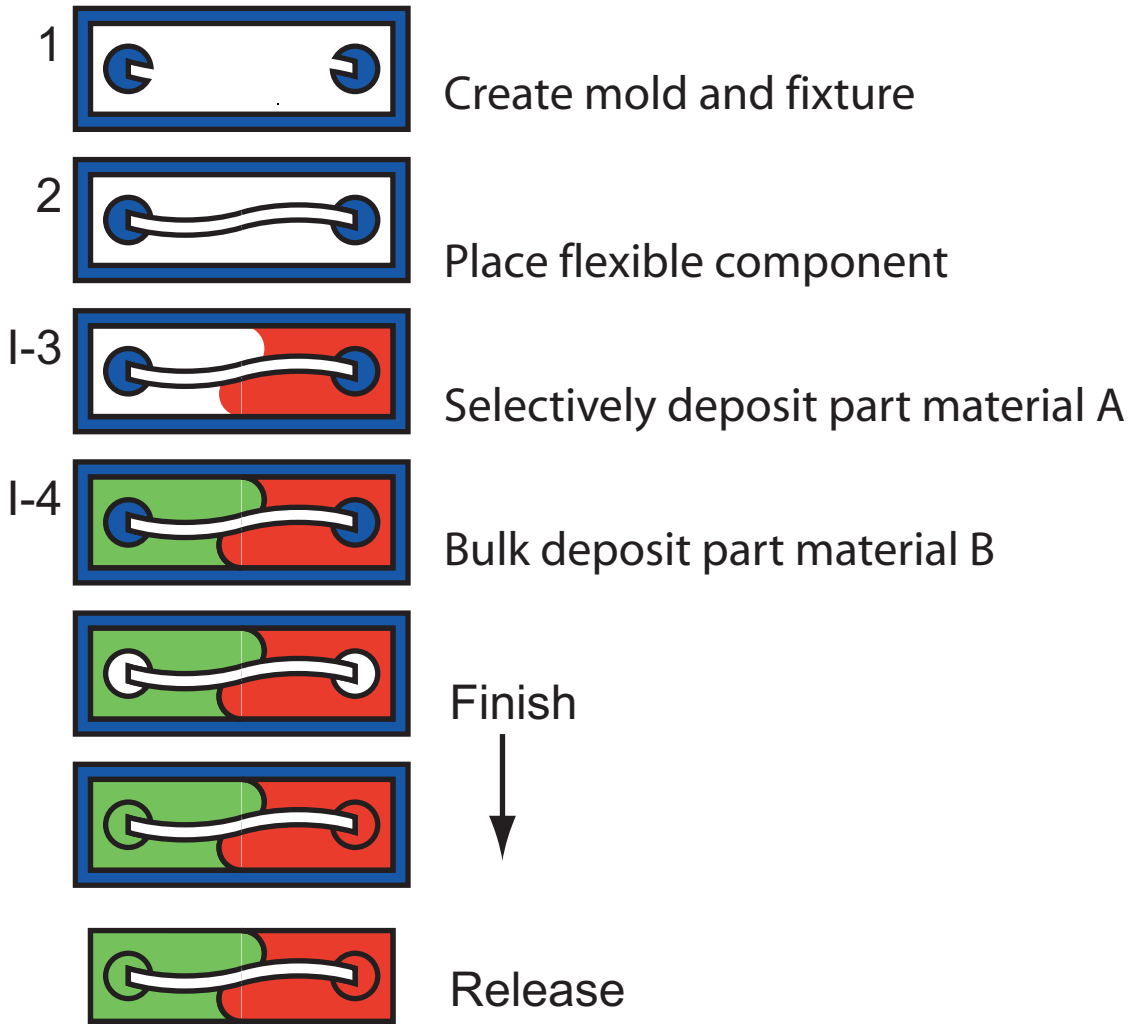


Figure 3.6: Selective material deposition (Process I, Fig.3.5) for creating a two-material part with embedded flexible elements.

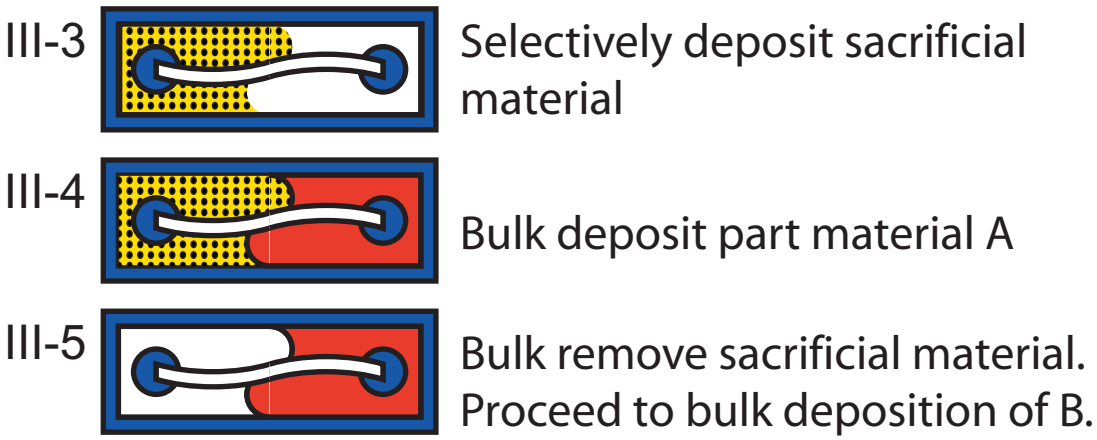
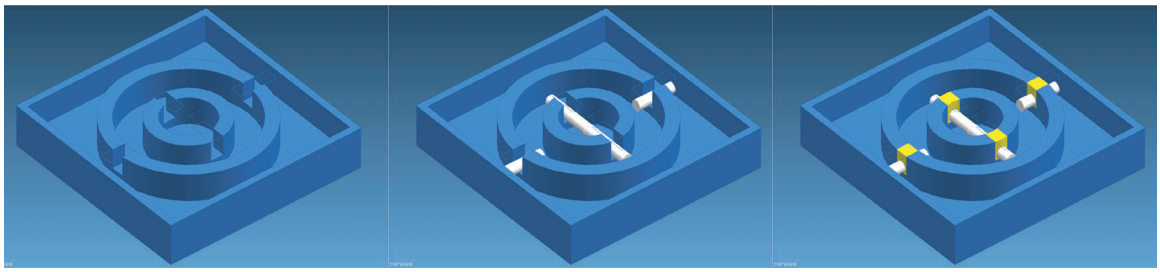


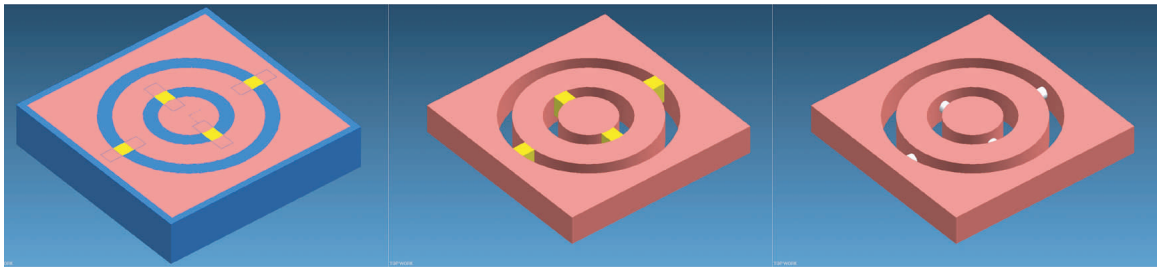
Figure 3.7: Selective sacrificial material deposition (Process III, Fig. 3.5)

remaining on the flexible component which might degrade the bonding properties or the component functionality. This is especially challenging for fibrous components which wick the sacrificial material, and a valid solution is, again, to pre-encapsulate the component before depositing the sacrificial material. The removal process can usually be a bulk removal process that takes away all of the selectively deposited sacrificial material by geometrically uncontrolled means such as melting and dissolving. However, the fixture must either remain or be replaceable to locate and shape the liberated portion of the flexible component. The bulk removal process is often facilitated by temporarily extracting the entire part from the base mold. However, one needs a reliable means of placing the part back into a mold with reliable positioning accuracy.

A technique that can be used to enhance the control with which either part or sacrificial material is added, is to temporarily create narrow shapes such as channels so that added material is kept in place by capillary action while still in the liquid state. This is the approach used for the string-suspended gimbals as shown in Figure 3.8and Figure 3.9. The flexible fibers in this case are $\phi 1.0[mm]$ diameter strings of cotton yarn. A mold is first created in sacrificial material (wax) and the fibers are stretched and held in place. Small amounts of additional sacrificial material are



Prepare mold and fixtures by selective removal (machining) of wax support and place the flexible elements (strings). Selectively deposit sacrificial material in thin grooves.



Bulk-deposit part material in remaining cavities. Extract part from mold. Bulk-remove protective wax with hot water jet.

Figure 3.8: An example of using selective addition and removal of sacrificial material: process steps for creating 2DOF gimbals with fiber flexures.

then added to encapsulate the fibers at narrow gaps in the mold. Part material (castable urethane in this example) is then poured into place. After removal of the wax, the complete gimbals are as shown in Figure 3.9. Note that there is no second part material. Related techniques include creating temporary "dams" or spacers of sacrificial material to create a boundary for the part material.

Selective material removal

When selective addition of part or sacrificial material does not give adequate control of the local geometry or surface finish, an alternative is selective material removal. The removal can be via CNC machining (Merz et al., 1994) (Liou, 2001) or can use methods such as laser melting or vaporization or a water jet. Selective removal of

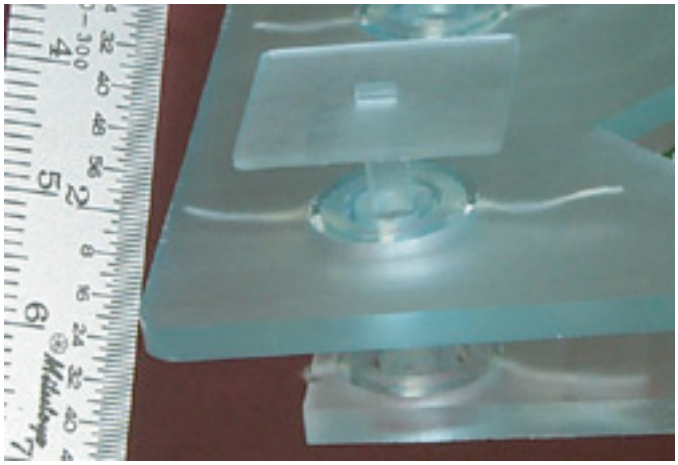


Figure 3.9: Finished mechanism with string-suspended gimbals supporting upper and lower plates.

part material is illustrated as process II in Figure 3.5. When working with embedded flexible components, however, selective removal of sacrificial material was more commonly employed (process IV in Figure 3.5, modified steps in Figure 3.10.) to create a shaped cavity into which part material can be introduced by bulk deposition without damaging flexible materials. The required considerations for the two processes are very similar. When the first material is added in bulk in step (II-3) or (IV-3), the material must be chosen such that they can be cleanly removed by the selective removal process to follow so that neither the bonding properties or the functionality are influenced. Again, a fibrous component would be challenging and pre-encapsulation is a good solution to overcome the problem. In figure 3.10, process (IV-4) is separated into two parts. The first step represents a rough selective removal process which may be fast but have the risk of damaging the inserted component. The second step represents a possibly slower but also gentler removal process for the safety of the flexible component. An example would be the combination of machining and focused hot water jet used to remove wax.

Selective removal of sacrificial material was employed in building the spring-loaded flexural hinge shown in Figure 3.11. The flexible insert in this example is a coil spring

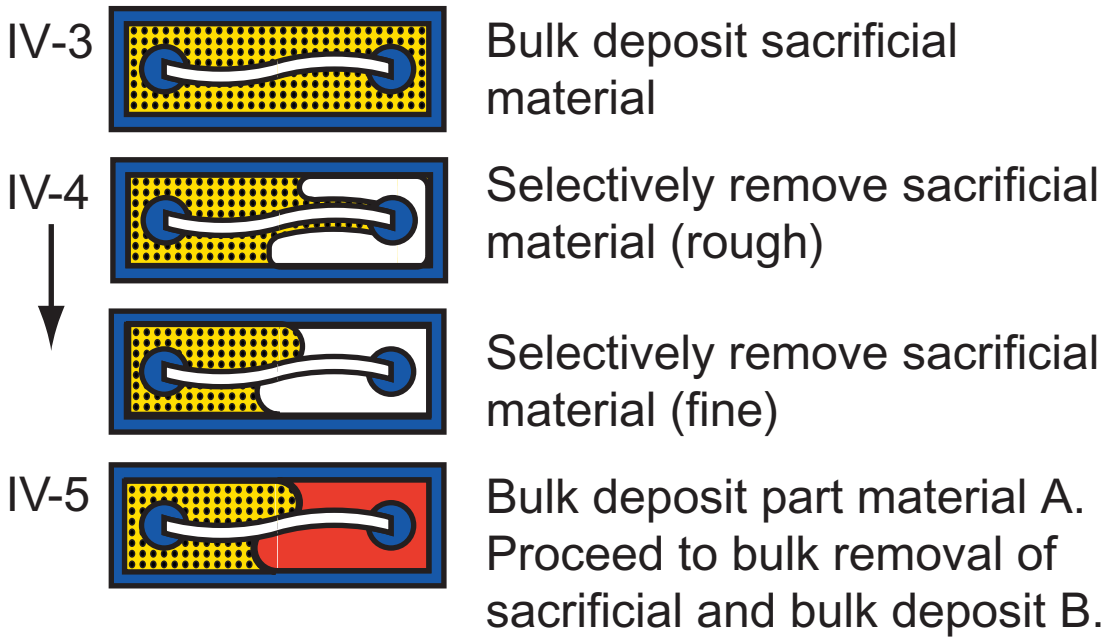


Figure 3.10: Selective sacrificial material removal (Process IV, Fig. 3.5) : initial selective removal with a conventional process such as CNC machining provides a smooth surface finish over most of the interface region; residual sacrificial material on the flexible elements is removed with a hot water jet or other process that does not affect fibers.

that is anchored in solid polymer at each end. The spring was first completely encased in sacrificial wax and then its ends were exposed by selectively removing wax. The remaining wax in the center protected the spring when solid polymer (material A) was cast around it. The completed product is shown in Figure 3.12.

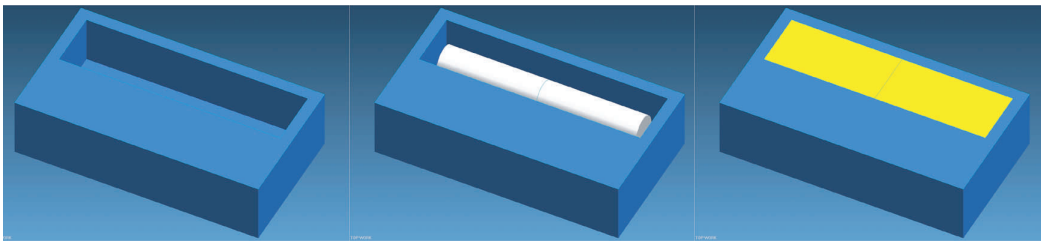
Photolithography

For delicate fibers, it may be difficult to remove sacrificial materials selectively without causing damage. A useful variation in such cases is to employ a photosensitive material that is selectively exposed and then removed chemically. This method was used to create another flexural hinge with embedded fibers and fine electrical wires, following the process shown in Figure 3.13. This is a variation of the selective removal of part material in which the selective removal process is decomposed into two steps of (1) a non-physical photo-chemical selective material property change and (2) bulk removal of the photo-chemically unaltered material.

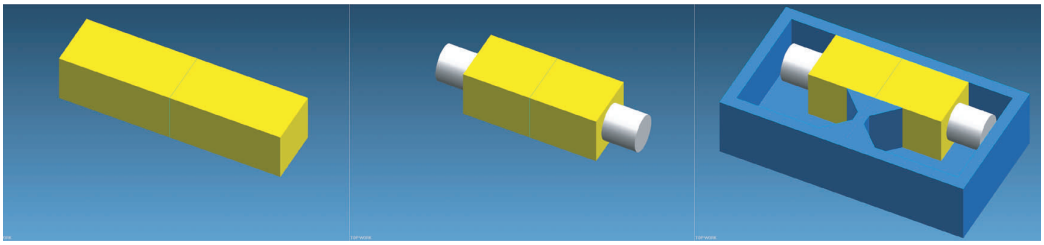
A photo-curable epoxy, SU-8 was employed as the rigid part material. Bundles of threads and wires were placed in a sacrificial mold, encapsulated in SU-8 and baked at low temperature to drive off the solvents, following the standard procedure for thick layers of SU-8 (SU-8, 2001). A mask was then positioned to block UV light from the region of the flexure. The sample was exposed to UV light and a solvent was applied to remove the unexposed SU-8. A soft solicone was then cast into the flexure region. After curing, the part was released from the sacrificial mold. An early finished prototype is shown in Figure 3.14. Subsequent steps for a part using this approach would be to machine the upper surface of the hard SU-8 material and then continue with additional SDM cycles to create more features

Summary of design and material selection guidelines

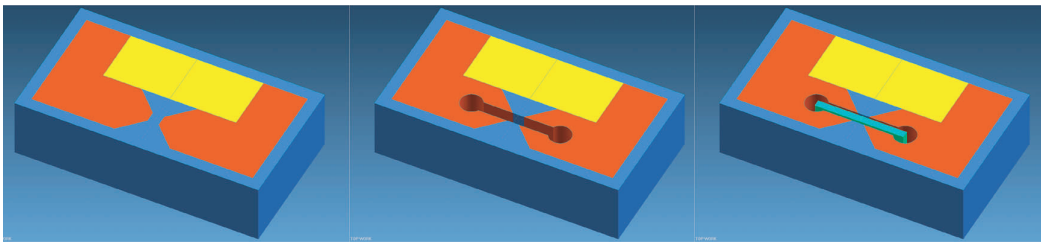
The design and material selection guidelines for the four major methods of cross-boundary embedding are summarized in table 3.1.



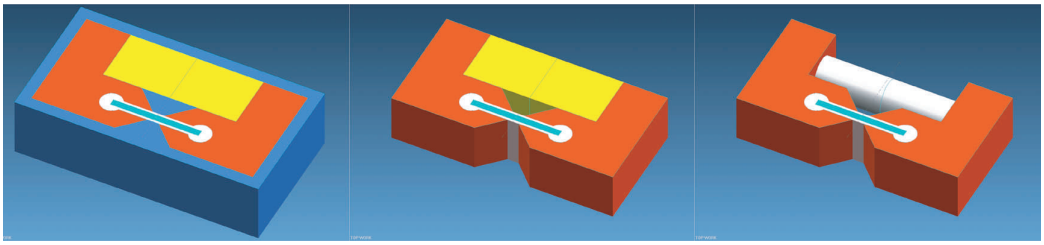
Machine mold in support material and place coil spring inside . Then bulk-deposit wax to protect the spring from being embedded in plastic.



Release the wax-encased spring from the mold and selectively remove wax from its ends to expose sections to be embedded in plastic. Replace in new mold.



Bulk-deposit part material A in mold cavity and machine mold cavity for the flexure in the part material and mold. Insert reinforcement fabric in slot.



Bulk-deposit soft material B to encapsulate fabric. Extract part from mold and bulk-remove protective wax from coil spring by melting.

Figure 3.11: Process steps for creating a durable spring-loaded hinge with a combination of hard and soft polymers and a fabric-reinforced flexure

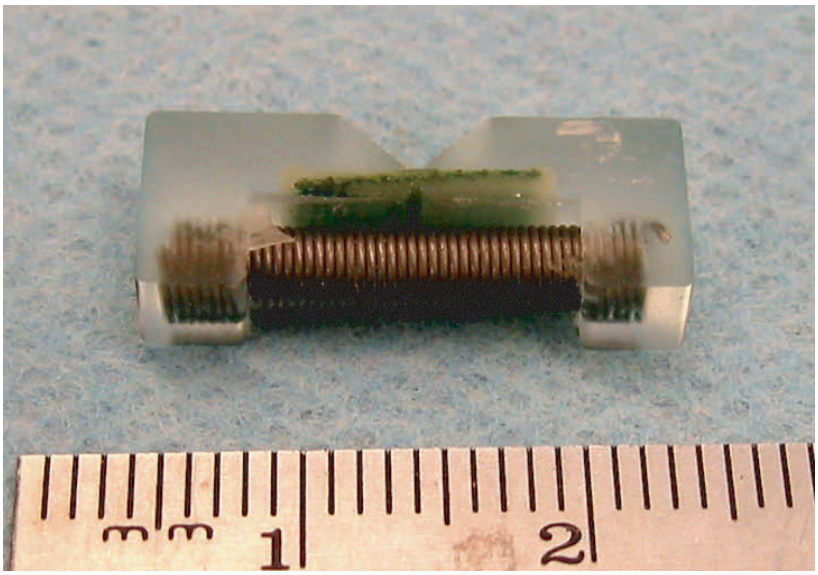
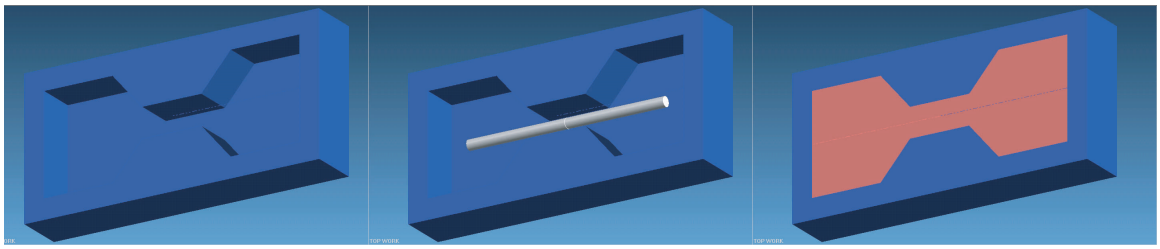


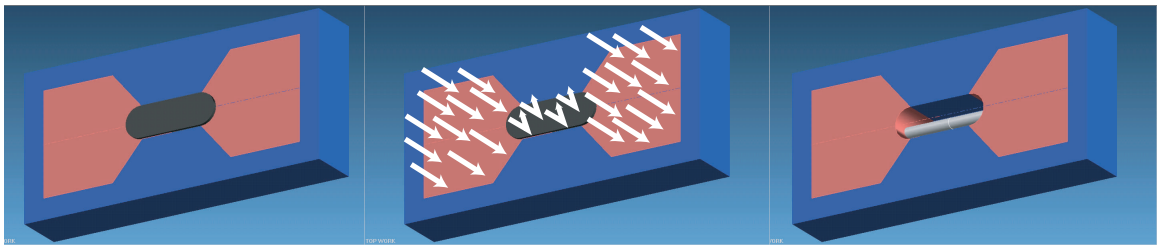
Figure 3.12: Photograph of the finished spring-loaded hinge with fabric-reinforced flexure

Selective Deposition
Design: Create geometry to provide clear access for deposition tool. Create mold features to facilitate control of material (e.g. by capillary action).
Material: Use mold/part material combination with good wetting in corners and narrow passages. Deposit material with moderate viscosity and fast solidification to minimize reflow.
Selective Removal
Design: Create geometry to provide clear access for removal tool. Provide space and routes for waste material removal.
Material: Use mold/part material combination with large difference in melting temperature or resistance to chemical, solvent or abrasive removal.

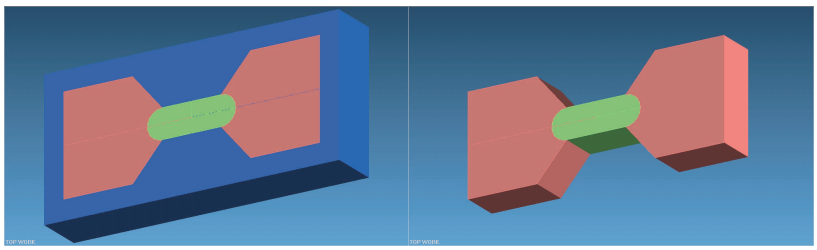
Table 3.1: Design and material guidelines for cross boundary embedding



Machine mold in support material and place flexible insert.
Bulk add photocurable polymer (SU-8)



Position photomask over flexure region and expose in collimated UV light.
Bake and use solvent to remove the unexposed polymer.



Bulk-add flexible polymer (material B)
and extract component from support material.

Figure 3.13: Process steps for creating a fiber-reinforced flexure with hard (SU-8) and soft (silicone) materials.

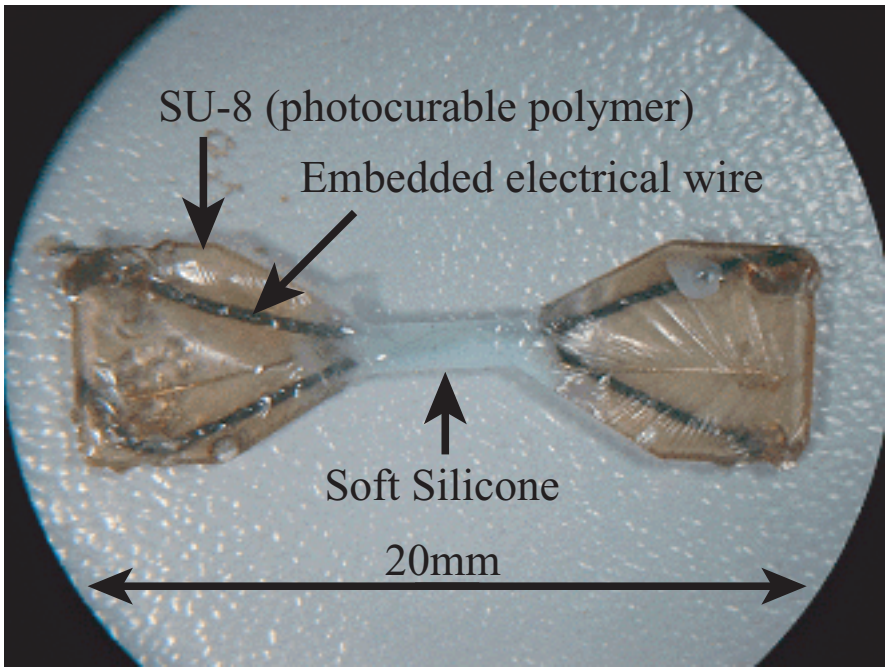


Figure 3.14: Finished flexure fabricated from SU-8 and flexible silicone. (Source: S. Bailey, Stanford CDR)

3.4.3 Alternative solutions

The alternative solutions are methods that emulate the effects of cross-boundary embedding without actually doing so. The solutions help overcome manufacturing constraints that unable the implementation of the four methods previously discussed. They can also simplify the fabrication process by reducing the number of steps and by eliminating high-risk processes. There are two methods; pre-encapsulation and pseudo-boundary formation.

Pre-encapsulation

We have already seen pre-encapsulation mentioned as a solution for various problems identified above and in fixturing. Just to refresh your memory, it is a preparatory procedure so that a flexible component incapable of direct exposure to the cross-boundary embedding methods can go through the processes. The main purposes of pre-encapsulation are (1) to add sufficient rigidity, size, strength, density, and or geometric definition to the flexible component to enable secure fixturing, (2) to pre-infiltrate fibrous materials to prevent unwanted part or sacrificial material infiltration that would degrade its bonding or functional properties, and (3) to coat and treat material surface to improve bonding. Another significant advantage about this method is that the material can provide a buffer zone to prevent damage to the embedded component during selective removal of adjacent part material, for example by machining. The prepared component can be put through any one of the four previously-mentioned methods of cross-boundary embedding. An example of the procedure is shown schematically in Figure 3.15 for the case of implementing selective removal of part material after pre-encapsulation.

Pseudo-boundary formation

Another option is to make a structure such that there is a thin layer of one of the part materials between the flexible component and the other part material. The flexible component is encased within one material but the functional performance of

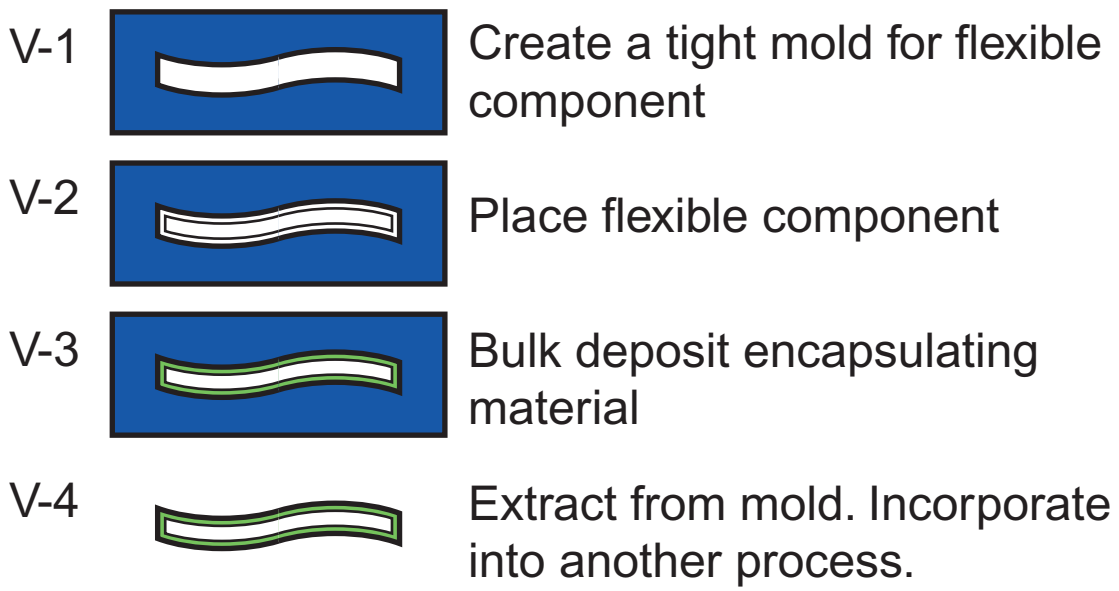


Figure 3.15: Pre-encapsulation of the flexible insert in a thin shell of soft part material, followed by selective removal of part material. This facilitates the fixation of highly flexible material with low geometrical definition. Basically, pre-encapsulation is to be used only when the flexible insert is too difficult to fixture or too sensitive to some of the selective processes. It is a preparation step for such delicate inserts which is to be avoided if possible in order to reduce work.

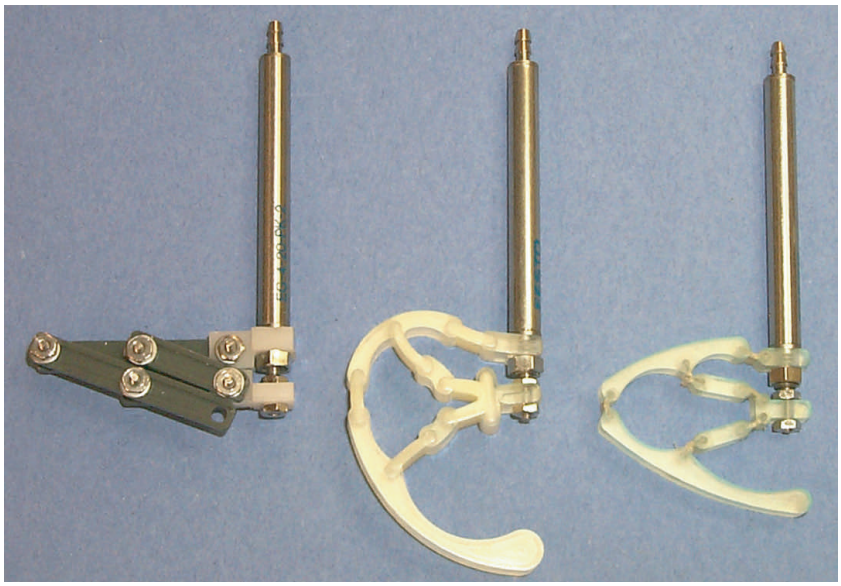


Figure 3.16: Linkages for extending piston stroke length in a legged robot. Left: original version with fasteners, pins and bearings has thirty one components in addition to the piston. Middle: an early fabricated protoype with hard links and thick flexures of soft material. Right: improved linkage with hard links and thin but tough fabric-reinforced flexures encased in soft material.

the product can be very similar to that made with cross-boundary embedding of pre-encapsulated component. Since the embedded component does not really go across a material boundary, we refer to this as the pseudo-boundary formation method. An example of a product of this method is shown in figure 3.16.

The rightmost linkage in Figure 3.16 consists of fabric-reinforced flexures that connect links of hard material. The linkage is a single element that replaces a pantograph with 31 assembled components, shown at left. Versions of the fabric-reinforced linkage have undergone a million actuation cycles without failure.

This method is applicable when one of the two part materials is appropriate as the pre-encapsulation material. Then, you would want to simplify the fabrication process of cross-boundary embedding of pre-encapsulated component by unifying the two material casting processes of the same material. The benefits of the pseudo-boundary formation method include process simplification, as was just mentioned,

and risk elimination of flexible component damage. It also helps overcome problems of undesired material infiltration concern and weak bonding between the flexible component and one of the part materials. These effects are very similar to those of pre-encapsulation. However, unlike pre-encapsulation, this process requires the flexible component to capable of being fixtured. When fixturing is not possible, one may simply resort to the combination of pre-encapsulation and one of the four cross-boundary embedding methods or else apply pseudo-boundary formation for embedding the pre-encapsulated component.

The approach is illustrated in Figure 3.17, and it follows the same sequence as used to create the fabric-reinforced hinge in Figure 3.11. The fabric is encased entirely in soft material, including where it is nominally surrounded by hard material. This approach also helps to avoid failure of the flexible member at the original hard material/soft material interface because the soft material helps to distribute loads. Functionally, the modified design in Figure 3.17 is very similar to the original specification in Figure 3.1. The stiffness of the hard material region is not seriously compromised if the thin inclusion of soft material is hydrostatically incompressible (e.g. silicone rubber or polyurethane with a Poisson's ratio of 0.5) because it cannot bulge or contract laterally, being restrained by the hard material above and below.

Why choose these alternative methods?

The two alternative methods of embedding flexible components offer advantages and disadvantages as indicated in table 3.2. Pseudo-boundary formation is easier and safer than real cross-boundary embedding. It also reduces stress concentration on the flexible insert and helps overcome infiltration and bonding issues as previously mentioned. Hence, this process is the most favorable as long as the potential reduction in anchoring strength is acceptable. Pre-encapsulation, on the other hand, is a preparatory process which adds extra labor prior to performing one of the four methods of cross-boundary embedding. Therefore, you would generally want to avoid this process if it is not required. Most of the benefits of pre-encapsulation can also be gained by pseudo-boundary formation except for the preparation of flexible components that cannot be fixtured. Hence, in essence, pre-encapsulation is to be employed only when

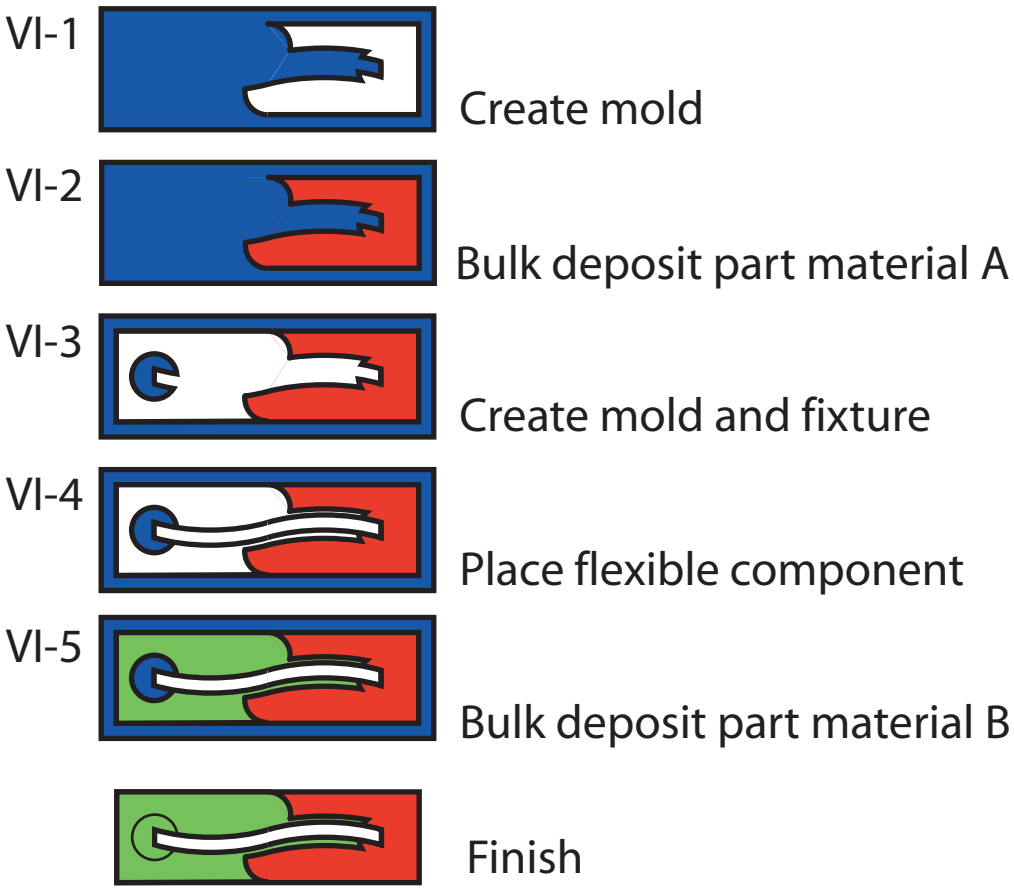


Figure 3.17: Pseudo-boundary formation. The insert is placed only after the first material is cast.

	Pseudo-boundary formation	Pre-encapsulation
Advantages	o Requires no selective additive or removal processes -Is easy to perform -No risk of insert damage o Relatively low number of steps o Reduces stress concentration on insert o Controlled geometry	o Eases fixturing by: -increasing stiffness -providing predefined geometry. o Lowers risk of insert damage o Reduces stress concentration on insert
Disadvantages	o No direct anchoring, hence possibly weaker anchoring strength of insert.	o Weaker anchoring strength of insert o Relatively large number of steps o Requires selective removal or deposition process

Table 3.2: Advantages and disadvantages of alternative methods compared to direct cross-boundary embedding.

the flexible component cannot be fixtured. However, pre-encapsulation might be less labor-intensive when the pre-encapsulation can be carried out with relative ease. For example, if it is possible to prepare a long strip of the flexible component which can be cut into segments and used in multiple products, then this might be more efficient in terms of fabrication compared to pseudo-boundary formation which requires the flexible component to be fixtured for each and every one of the products.

An exceptional case is when the second casting of part material can be eliminated because the pre-encapsulating material from step V-3 in Figure 3.15 serves as the second part material. Then this process becomes virtually equivalent to pseudo-boundary formation, also in advantages and disadvantages with the added benefit of overcoming fixturing difficulties, except that the material casting order is reversed.

	Selective Deposit of Part Material (I)	Selective Removal of Part Material (II)	Selective Deposit of Sacrificial Material (III)	Selective Removal of Sacrificial Material (IV)
Number of process steps	☆☆☆☆	☆☆☆	☆☆	☆
Time for tooling + curing	☆☆☆☆	☆☆☆	☆☆☆	☆
Insert damage risk	☆☆☆☆	☆☆	☆☆☆	☆

☆☆☆☆ =most favorable , ☆ =least favorable

Table 3.3: Process favorability

3.4.4 Process selection guideline

The decision making procedure for process selection is depicted as a flowchart in figure 3.18.

The selection process for specifying a direct cross-boundary embedding method is shown in figure 3.19.

This particular flowchart is made with process preference order (I)Selective deposition of part material, (II)Selective removal of part material, (III)Selective deposition of sacrificial material, (IV)Selective removal of sacrificial material. The order of preference can differ depending on what is important. Preference rating for three different criteria are shown as an example in table 3.3.

3.5 Conclusions

Several methods of cross-boundary embedding were developed and tested. Three major difficulties were identified: fixturing the insert, selectively adding, removing or otherwise processing material around the flexible insert without damaging or being

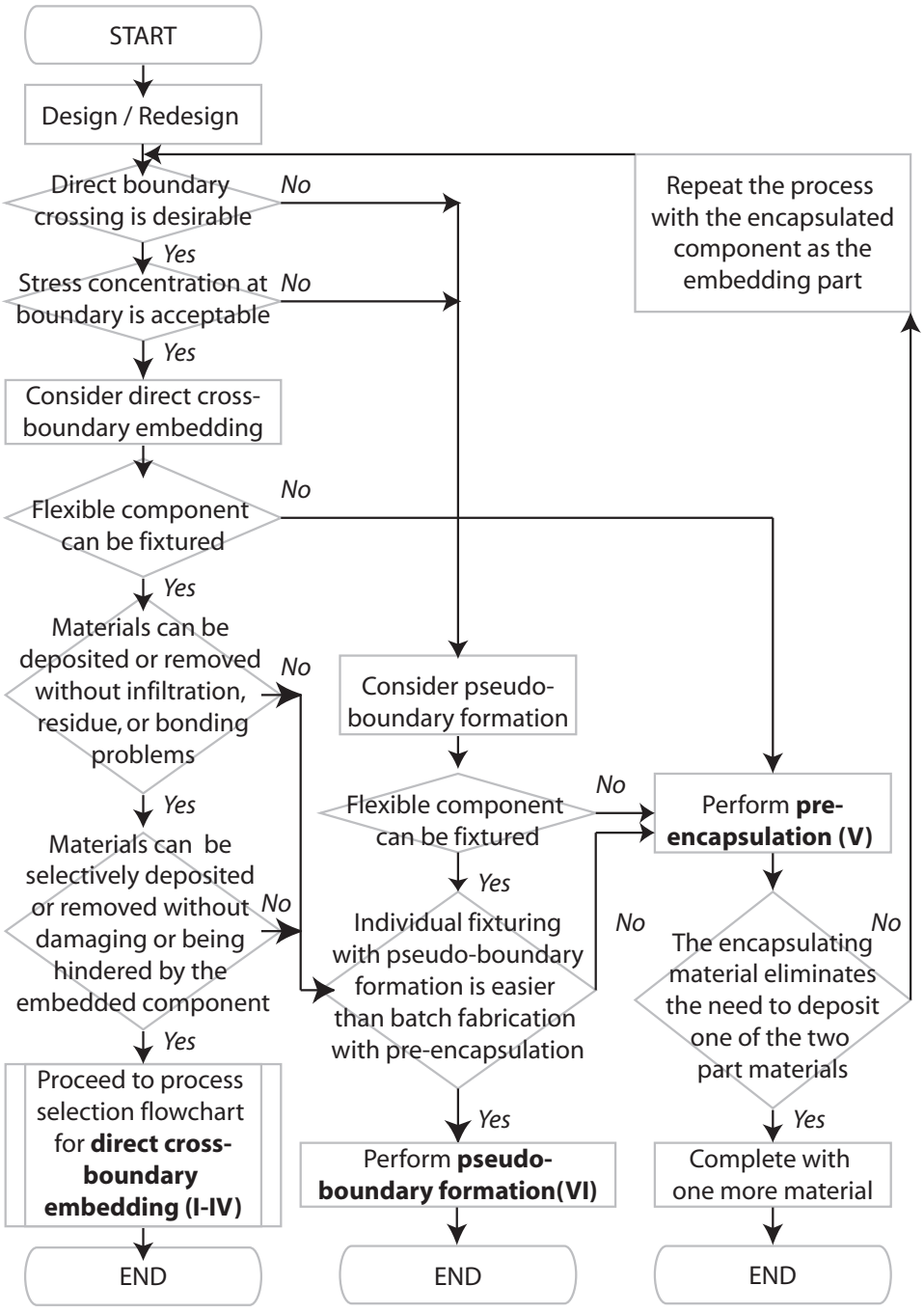


Figure 3.18: Process selection flowchart

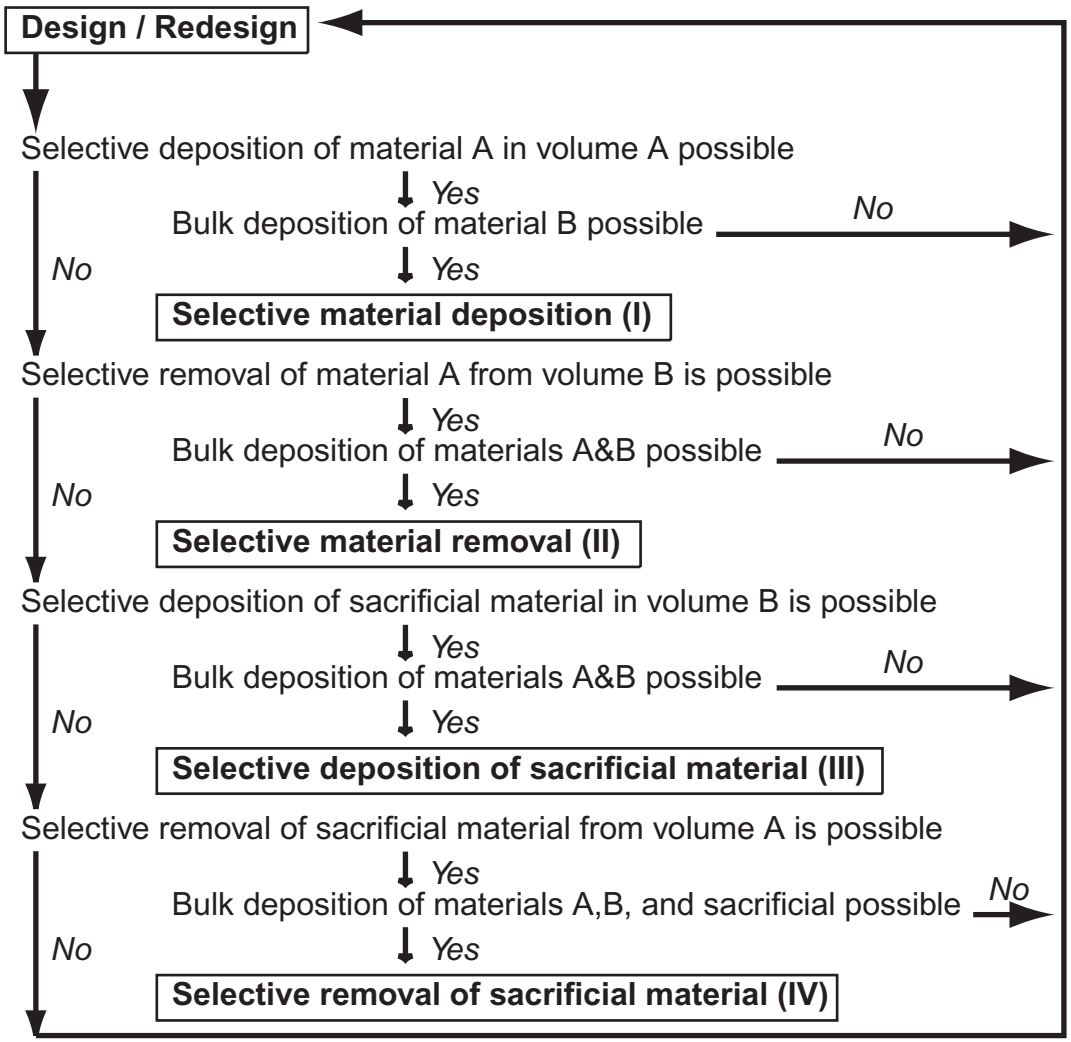


Figure 3.19: Process selection flowchart for direct cross-boundary embedding

obstructed by it, and avoiding stress concentration, especially at the material boundary. Accordingly, pre-encapsulation and suspending fixture methods were developed for insert fixturing. Methods of selective addition and removal of part material and sacrificial material were identified in terms of general process planning. Where conventional material addition or removal cannot prevent damage to embedded flexible components, an alternative is to combine photolithography with bulk material removal. In other cases, some alteration of the original specification can greatly simplify the process plan without significantly affecting functional properties, sometimes even improving them. Guidelines for design and process selection have also been established to help designers.

The variety of methods allows us to perform cross-boundary embedding of flexible components in multi-material parts. However, some of the processes still require refinement. Reduction of manual labor in fixturing the components is a major area of future work.

3.6 Future directions

The developed techniques lead to further developments and applications. One is the vertical cross-boundary embedding. Another is the application of the suspending fixture method for rigid component embedding.

3.6.1 Vertical cross-boundary embedding

Though the embedded components crossed boundaries sideways in the examples, it is also possible to apply the methods so that components can cross boundaries vertically in the part growth direction. Such work has already been demonstrated for rigid components. For example, shrink wrap tubing and pneumatic tubing have been used as sacrificial material that can be selectively removed from partially embedded screws and pneumatic tube fittings.

Vertical cross-boundary embedding of flexible components would be more challenging especially in terms of fixturing. One option would be to use a custom sacrificial fixture as in the suspending fixture method but in a different orientation. That would also have to be successfully combined with one of the cross-boundary embedding methods.

3.6.2 Suspending fixture for embedding rigid components

Use of suspending fixture for embedding rigid components may reduce labor, time, and material use by simplifying the process. Other fixturing options are bottom support with mold material, bottom support with part material, and non-suspending custom fixture. The first option requires no further simplification. The second method requires the part material to be cast in two separate steps, requiring more time and labor, and it also consumes extra time and material by having to machine the cavity for component placement. Both the suspending and non-suspending custom fixturing methods can be simpler than the previous method since it only requires single material casting. Of course, extra effort is needed for creating the fixtures, so the tradeoffs in labor, time, and material consumption must be evaluated and compared. There would be differences even between the suspending and the non-suspending fixtures and they must be well considered. For example, it might be better to use a suspending fixture if the component is to be embedded far above the bottom of the mold. Conversely, the non-suspending fixture might be better when the component is to be located far below the top of the mold.

Chapter 4

Stiffness modification of flexures by fiber reinforcement

4.1 Motivation

As indicated in the previous chapter, flexural joint strength can be improved by embedding fabrics. In other words, anisotropic material strength modification was successfully demonstrated. This naturally leads to the idea of anisotropic stiffness modification.

When designing a flexural hinge that is primarily intended for a single degree of freedom bending, the designer may often wrongly assume that the hinge would not deflect in other directions. However, such joints almost always contain extra degrees of freedom in unwanted directions unless properly constrained. One option is to add mechanical stops that would prevent such motions. Another is to stiffen up those degrees of freedom by modifying flexure geometry, for example by widening. Unfortunately, these options increase the joint mass and dimensions relative to the original flexure and are often undesirable. Moreover, torsional stiffness is closely coupled with the major bending stiffness and there is a tight limitation as to how much stiffer it can be made without influencing it. Theoretical bending and torsional stiffnesses of a beam with width=b and height=h ($b > h$) for small deflections are proportional to their respective moments of sections; $I_{xx} = \frac{bh^3}{12}$ for pitch or the primary

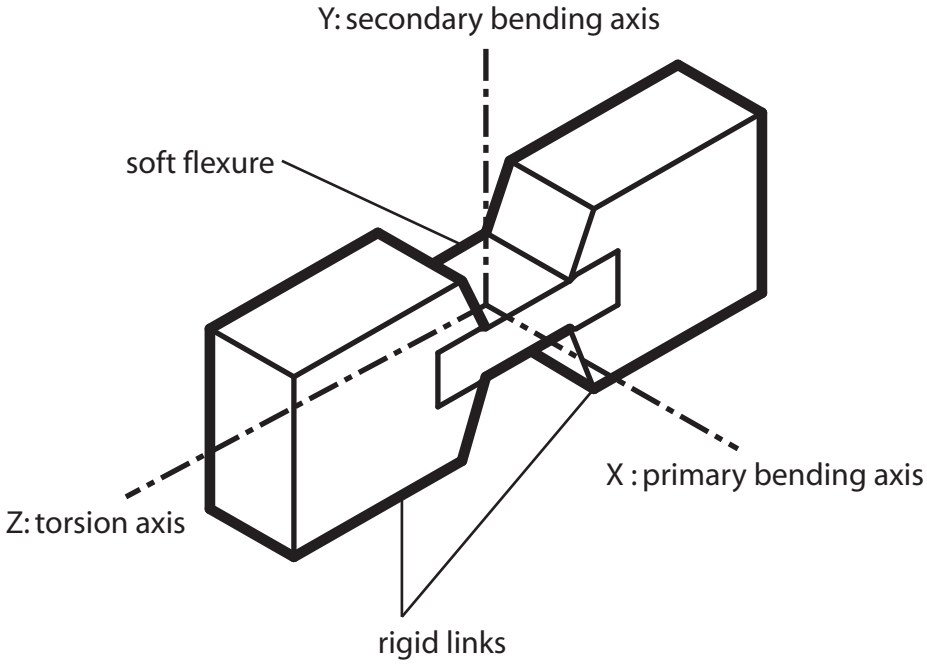


Figure 4.1: Coordinate system definition for the flexural joint.

bending axis, $I_{yy} = \frac{b^3 h}{12}$ for yaw or the secondary bending axis, and $K = \frac{bh^3}{3}(1-0.58\frac{h}{b})$ for torsion. (Please refer to (Ashby, 1999) or (Roark, 1989) for the theoretical stiffness formulae.) According to these formulae, for example, a flexure that is originally twice as wide as the thickness can only increase its torsional stiffness by about 40% by changing its dimensions while keeping the major bending stiffness constant. Hence, another solution that would enable flexure property modification without size or weight change was sought.

For the sake of argument, let us first define a coordinate system for a flexural hinge as indicated in Figure 4.1. (X-axis: width, Y-axis: thickness, Z-axis: length) The primary degree of freedom for the joint is bending about the X-axis, i.e. pitch. The common unwanted but often experienced degrees of freedom are bending and torsion about the Y- and Z-axes, i.e. yaw and roll, respectively.

Let us assume the flexure to have a simple rectangular block shape. This simple geometry, sometimes also referred to as 2.5D geometry because of its extruded shape, is the simplest to produce using SDM. When designing a flexure for a particular application, there would be functional specifications of bending or torsional stiffnesses about each of the three axes. Strength and durability are also important and damping for motion in the primary degree of freedom may also be specified in some applications. In order to satisfy these numerous specifications (seven in this example), a designer basically has only four parameters; width, thickness, length, and material choice. Although materials are available in various stiffnesses, strength, durability, and damping properties, they are not independent of each other and the number of design parameters is still limited to fulfill the functional needs. (Relationships among material properties are studied and visually organized by Ashby (Ashby, 1999).) Furthermore, realistic size limitations often pose additional constraints. Therefore more design parameters need to be introduced for meeting the functional specifications and implementation of another material is an effective solution. Here, fibers are highly effective as an alternative for overcoming this problem because they exhibit highly anisotropic mechanical properties, stiff and strong in tension and highly compliant in all other directions. Material properties of a flexure can be selectively modified using fibers to satisfy functional specifications which could otherwise not be met.

Prevention of non-primary bending and torsion are not the only motivations for this work. The technology can be applied to producing mechanisms that exhibit complex kinematics with simple construction. For example, one may want the knee joint of a robot to be flexible in one direction and stiff in the other (Kim et al., 2004), (Clark et al., 2004). A thumb joint that both bends and twists when loaded in one direction may be ideal for a robotic hand. Such asymmetric or complex properties can also be realized by adding extra features or by modifying the flexure geometry. However, such solutions often add to the complexities of both the fabrication process and the finished product which are to be avoided whenever possible. Again, flexures with fiber-modified anisotropic properties would provide a simple and elegant solution.

Such flexural joints with ideal properties may also replace conventional discrete

joints where contamination due to debris or lubrication is undesirable. The contamination problem is common in space and surgical applications. Any contamination in space may affect the performance of sensitive equipment such as cameras and solar cells on satellites and robots. Microscopic debris from artificial knee or hip joints can induce self-destruction of the surrounding bone known as osteolysis posing limitations to long-term use. Conventional flexures had strength and/or stiffness limitations that prevented replacement of discrete joints. However, the fiber reinforcement technology may enable flexures to be employed for these applications.

4.2 Design process

The basic design process is as follows:

1. Define desirable and undesirable modes of deformation in relation with loading.
2. Identify location and orientation of major extensive strain for each of the deformation patterns.
3. Place fibers along the lines of major extensive strain of undesirable mode(s) of deformation to stiffen, while avoiding them for the desirable mode(s) of strain to maintain flexibility.
4. (Optional) Use finite element analysis to verify the behavior.

Figure 4.2 shows the force application and deformation patterns for bending about the X- and Y-axes and torsion about the Z-axis (pitch, yaw, and roll). The principal extensive strain vectors are also represented as cones accompanied below by the fiber locations which would be most effective for stiffening up the structure against each loading pattern. Figures 4.3, 4.4, and 4.5 are larger images of the strain vector plots shown with typical deformation. The deformation plot on the second row of figure 4.2 and the data for strain vector plots were obtained from finite element analysis results of a flexure model without fiber reinforcement. The details of the analysis setup are described in the following section.

The suggested fiber configurations shown in the bottom row of figure 4.2 are not neutral, that is, they will also influence deformations under other loading patterns. In fact, they even induce bending or twisting which would otherwise not have been there. They are also direction dependent in that they would not have the same influence on loading in the opposite direction.

Symmetric fiber configurations lead to symmetric properties. In order to eliminate direction dependency, fibers are to be located symmetrically about the plane of symmetry of the two opposing loading patterns. In case of bending about the X-axis (pitching) for which the loads are parallel to the Y-axis, the XZ plane is the plane of symmetry. In case of bending about the Y-axis (yaw) for which the loads are parallel to the X-axis, the YZ plane is the plane of symmetry. In case of torsion about the Z-axis (roll) for which the loads are parallel to the Y-axis, the XZ plane is the plane of symmetry. The torque can also be applied as loads parallel to the X-axis and hence the YZ plane is also valid as the plane of symmetry.

Similarly, introduction of unintended bending or torsion due to asymmetric fiber placement can be relieved as follows. For loading intended for bending about the X-axis (pitching) to result in deformation in no other directions, the fibers are to be placed symmetrically about the YZ plane. Likewise, the fiber configuration must be symmetric about the XZ plane for loading intended for bending about the Y-axis (yaw) to exhibit no secondary bending or twisting. In order to eliminate secondary bending when applying torque about the Z-axis (roll), the fiber configuration must be symmetric about the Z-axis.

On the other hand, asymmetric fiber configuration would be useful for constructing mechanisms that exhibit asymmetric or complex kinematics. For example, the robotic applications of directional knee joint and thumb joint that bends and twists under single loading would be achievable using this technique. Such kinematics would be achievable by intentionally introducing asymmetry into the fiber configuration.

Again, the basic ideas in design is to inhibit unwanted extensive strain by embedding fibers along the lines of major stretching while allowing desirable extension. Symmetry or asymmetry in fiber configurations leads to symmetry or asymmetry, respectively, in the performance properties. These guidelines are employed collectively

for the generation of fiber configurations analyzed in FEA.

4.3 Finite Element Analysis for design

Finite element analysis (FEA) setup is described and then results are shown for seventeen different fiber configurations. Each of the results are presented with fiber configuration diagram, stiffness plots, and graphics. The analysis results are compared across the configurations for further understanding.

4.3.1 FEA method

FEA was carried out to examine various fiber configurations for design optimization. The flexure was modeled with dimensions 6[mm] width, 3[mm] thickness, and 6[mm] length and was meshed into $8 \times 8 \times 8$ evenly divided elements. The elastomer was represented as a simple linear elastic material with a Young's modulus of 6[MPa] and Poisson's ratio 0.499. The Young's modulus was measured by performing a linear elongation test on a $3[mm] \times 3[mm] \times 120[mm]$ polyurethane test specimen. The material used was IE 90A from Innovative Polymers. The Poisson's ratio was initially chosen to represent material incompressibility typical in elastomers, and this was later verified by experimentation.

Because the primary purpose for using FEA was in identifying locations for fiber reinforcement, accurate prediction of stress and strain was of lower priority. Consequently, the elastomer was approximated with simple linear elastic elements rather than with non-linear hyper-elastic elements using the Mooney-Rivlin or Ogden material models to avoid the cost and trouble involved in employing the complex models. The main shortcoming of this approach is the inaccuracy in the prediction of deformed geometry and associated stress and strain. As a result, quantitative prediction of stiffness would be inaccurate and errors in predicting stress distribution would influence, for example, design optimization efforts to improve stress-induced failures. However, the simplified model can still provide information needed for determining fiber configuration and verify performance qualitatively. The fiber configuration is determined

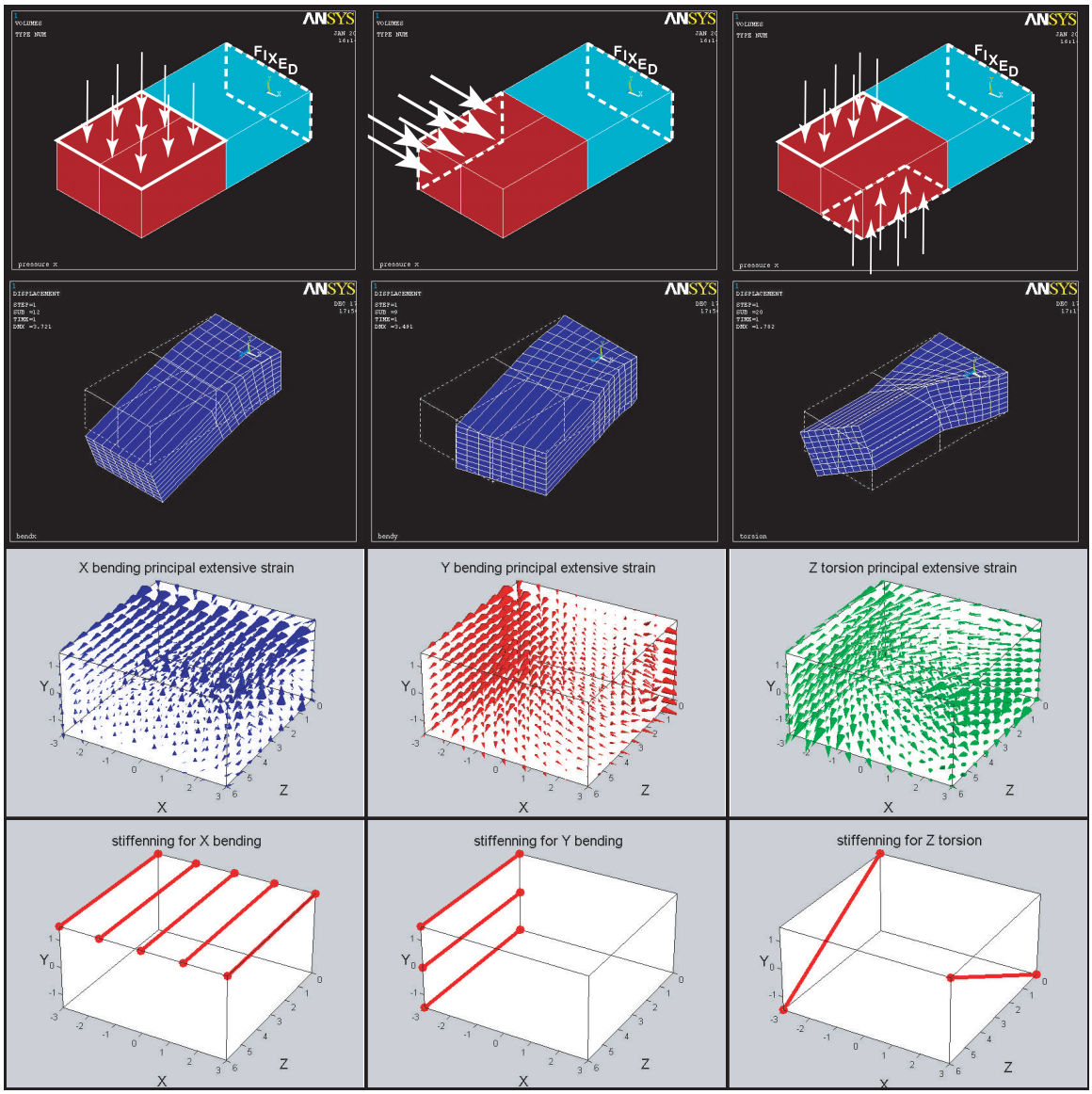


Figure 4.2: Each column illustrates the force application, typical deformation, principal extensive strain, and fiber location for stiffening for bending about the X- and Y-axes and torsion about the Z-axis(pitch, yaw, and roll).

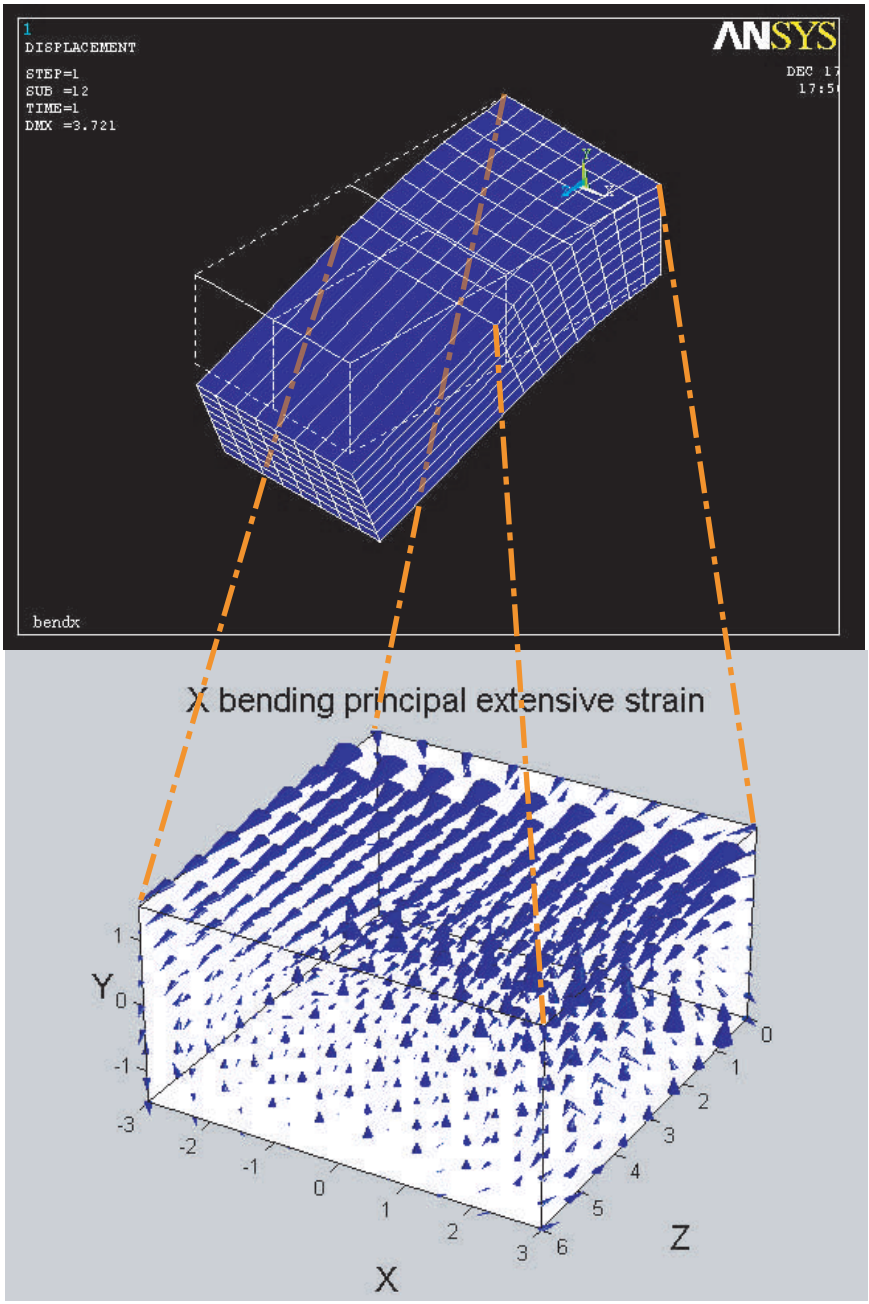


Figure 4.3: The cones in the lower plot indicate the orientation and size of the local first principal extensive strain in the flexure when bent about the X-axis as shown in the upper plot

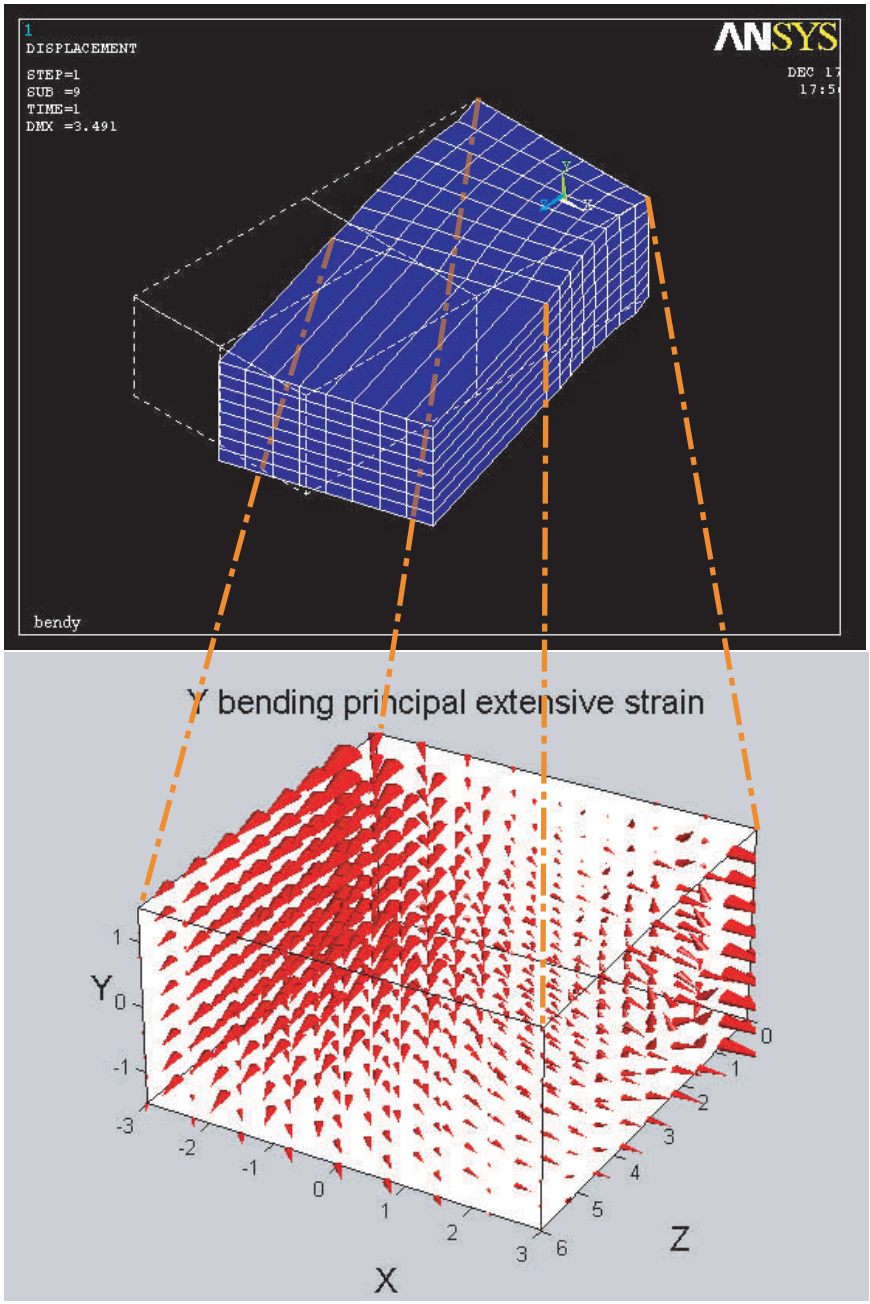


Figure 4.4: The cones in the lower plot indicate the orientation and size of the local first principal extensive strain in the flexure when bent about the Y-axis as shown in the upper plot

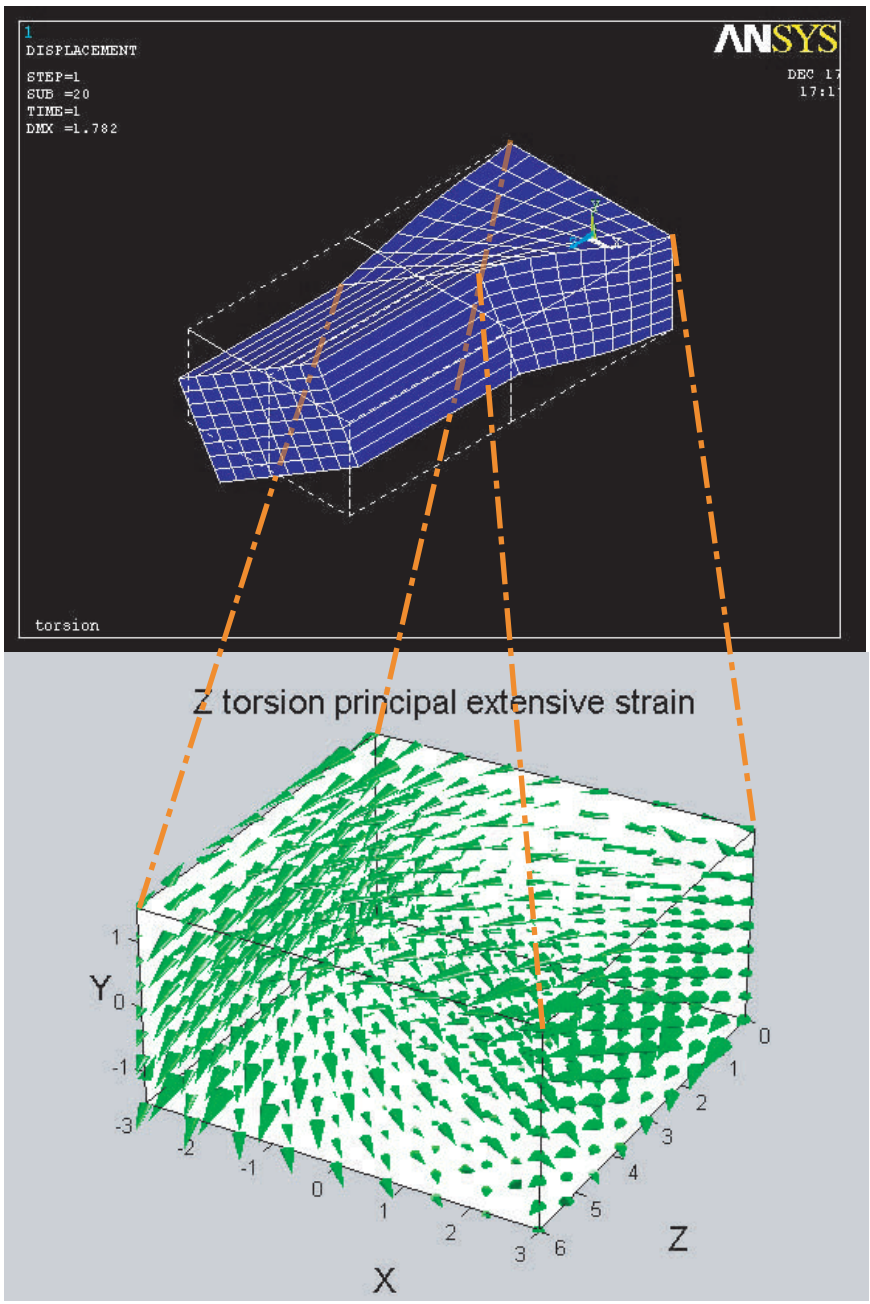


Figure 4.5: The cones in the lower plot indicate the orientation and size of the local first principal extensive strain in the flexure when twisted about the Z-axis as shown in the upper plot

based on the strain condition at the very beginning of deformation because the fibers are to be placed to prevent the deformation from the beginning, and the analysis results are quite accurate for small deformations even with the simplified model, as is indicated later in section 4.5.3 Error quantification. Consequently, strain information for large deformation is not needed for initial conceptual design purposes. The simplified model cannot accurately predict resulting large deformations for plain or fiber-reinforced flexures, but qualitative influence of fiber reinforcement can still be clearly observed in the results.

Fibers were represented as tension-only elements with Young's modulus of 3700[MPa] and cross sectional area $0.1[mm^2]$, effectively representing the polyester-cotton blend thread employed in prototyping (Singer button-carpet thread. 70% Polyester, 30% cotton blend). Reasoning for choosing a polyester-cotton blend is to combine the stiffness and strength of polyester with good material bonding of cotton. The stiffness was obtained by performing tensile test on the fiber. (There is one exception to this stiffness setting in which it is doubled in configuration b05.) Fiber elements stretched from one end of the flexure to the other, and they were divided into eight equal segments. Any coincident nodes of the elastomer and fibers were coupled so that there would be no relative motion between them. This emulates the effect of interfacial bonding between the two materials.

One end plane of the flexure was fixed in all degrees of freedom. The other end was attached to a rigid block with same dimensions but a much higher Young's modulus of 200[GPa] and Poisson's ratio of 0.3. The rigid block was incorporated to constrain the geometry of the end of the flexure and also to serve as force application medium for the structure.

Flexure deformations under three or six loads in different orientations were analyzed for symmetric and asymmetric structures, respectively, containing different fiber configurations. Please see Figure 4.6 for the illustration of the FEA setup.

For bending about the X-axis (pitch), 1/36[MPa] pressure was applied evenly on the top (+Y) surface of the force application block to effectively produce 6[Nmm] of torque about the center of the flexure. For bending about the Y-axis (yaw), 1/6[MPa] pressure was applied evenly on the -X side surface of the force application block to

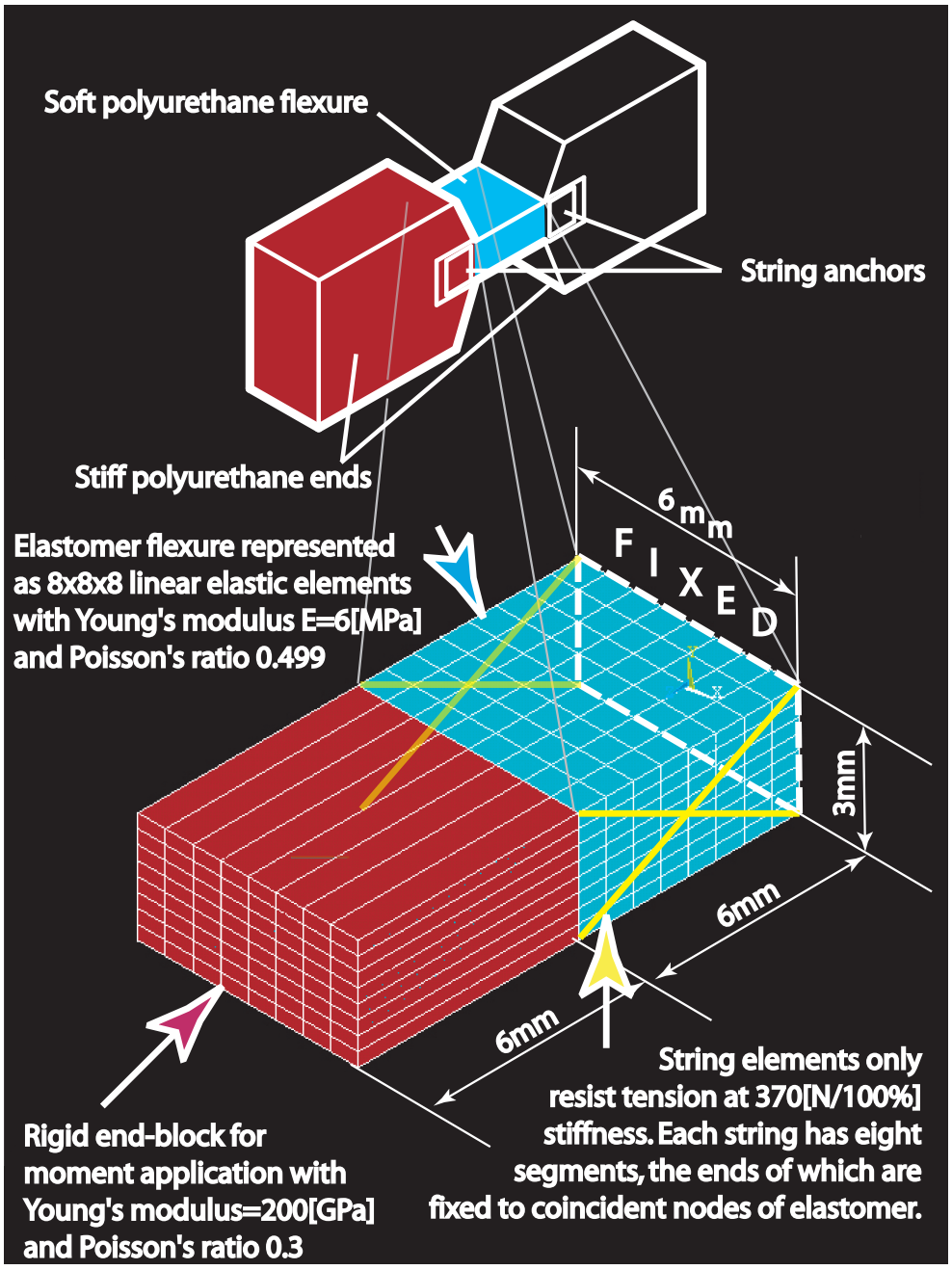


Figure 4.6: Finite element analysis setup. The top diagram illustrates the flexure geometry. The respective FEA model is shown below.

effectively produce 18[Nmm] of torque about the center of the flexure. For torsion about the Z-axis (roll), 1/6[MPa] pressure was applied evenly on the -X half of the top surface and the +X half of the bottom surface of the force application block to effectively produce 9[Nmm] of torque about the center of the flexure. Negative loads were applied similarly in respective symmetry for each of the three types. The load sizes were chosen to be small enough to enable reasonable analysis with the linear elastic element models in FEA, which are not so capable of performing large deformations, yet large enough to observe differences visually from resulting plots. The loads were applied gradually in multiple steps, typically around ten, automatically divided by the analysis software to account for the geometric nonlinearity due to large deformation.

Angular displacements of the FEA models were defined as follows. Angular displacement about the X-axis (pitch) was defined as the angle between the horizontal plane (XZ plane) and the vector normal to the deflecting end face. Similarly, angular displacement about the Y-axis (yaw) was defined as the angle between the vertical plane (YZ plane) and the vector normal to the deflecting end face. Roll was defined as the angular displacement of the end face about an axis normal to itself measured from the orientation in which its bottom edge would be horizontal with same pitch and yaw angles. In each case, clockwise rotation about the respective axis, looking away from the origin to its positive direction, is considered positive.

The software used for the analysis is ANSYS 7.0.

4.3.2 Analysis configurations and results

Design intentions and analysis results for various configurations are indicated one by one. The figures include a diagram to show the fiber configuration, plots of absolute stiffnesses and relative stiffnesses with respect to the control piece which has no fibers, and graphics of deformed shapes in isometric view.

The stiffness plots contain either three or six axes, depending on the symmetry or asymmetry of fiber configuration. They are labeled rotX(pitch), rotY(yaw),

rotZ(roll), rot-X(pitch), rot-Y(yaw), and rot-Z(roll) to represent the rotational stiffnesses about the respective axes. The plot axes are ordered to agree with those in the isometric view. The stiffness data for the control piece is plotted in the middle with dashed lines as reference. Naturally, the relative stiffness plot of the control piece forms an equilateral triangle. The absolute stiffness plot is especially informative for knowing the ratio of the rotational stiffnesses in different directions. In a triangular plot, the sharper a corner is, the stiffer the respective deformation is with respect to the others. Conversely, a blunt corner indicates relative flexibility. One must pay attention to the values and rather than the angles for interpreting similar information from the hexagonal plots. The relative stiffness plot is more informative for understanding the effects of fiber embedding. The numbers show the stiffening effect referenced on the control piece. In a triangular plot, if a corner is sharper than another the respective stiffness has been stiffened up more than the other, and vice versa. For example, for stiffening up the Y(yaw) and Z(roll) compliances without interfering with the X(pitch) compliance, the Y(yaw) and Z(roll) relative stiffness values must be large while leaving X(pitch) close to one as much as possible. The resulting triangle would have sharp corners for Y(yaw) and Z(roll) and blunt corner for X(roll). Again, one must pay attention to the values and not angles for hexagonal plots.

Please note that the configuration numbering has no particular meaning. They were numbered in order as different configuration ideas were generated. As some of them were never analyzed, these numbers are missing in the listing to follow. The main reasons for their omission are (i) close similarity with other configurations such that the performance could be reasonably foreseen or (ii) apparent insignificance or uselessness of functionality.

Control piece

Please see figure 4.7. The control piece has no fibers and is used as the reference for comparing the behavior of all other configurations. The analysis indicated X bending (pitch) stiffness and Z torsional (roll) stiffness to be approximately the same and Y bending (yaw) stiffness to be roughly four times larger than the other two.

The stiffness ratio between pitch and yaw is consistent with the theory of linear elastic beam bending in which the bending stiffness is proportional to the cube of the thickness and linearly proportional with the width.

a01

Please see figure 4.8. The a01 configuration has fibers running parallel along the length of the flexure in the mid horizontal plane, i.e. the XZ plane. This was intended to have no influence on the X bending (pitch) stiffness while adding significant stiffness for Y bending (yaw) as well as some for Z torsion (roll). This is a symmetrical configuration hence only three loads were analyzed. The fibers also strengthen the flexure for lengthwise stretch loading along the Z-axis.

a02

Please see figure 4.9. The a02 configuration is similar to that of a01 except that the fibers are placed in the top (+Y) face of the flexure. This makes the +X bending (pitching) stiffer while -X bending is kept just as flexible as it was in the control piece. Tendency to include some -X bending also show in deformations under Y bending (yaw) and Z torsion (roll) loads. (Please note that -X bending involves displacement toward the +Y direction. Bends and torsion are named according to the axis of angular displacement rather than the loading or displacement direction.)

a03

Please see figure 4.10. A03 contains two fibers running diagonally in the mid horizontal plane. It has hardly any influence on the X and Z stiffnesses. It has slight influence for the Y stiffness since the fiber orientation is close to that of the local first principal extensive strains. Please refer back to the strain vector plot in figure 4.4. However, the magnitudes of the strains are yet too small for the fibers to have a significant influence.

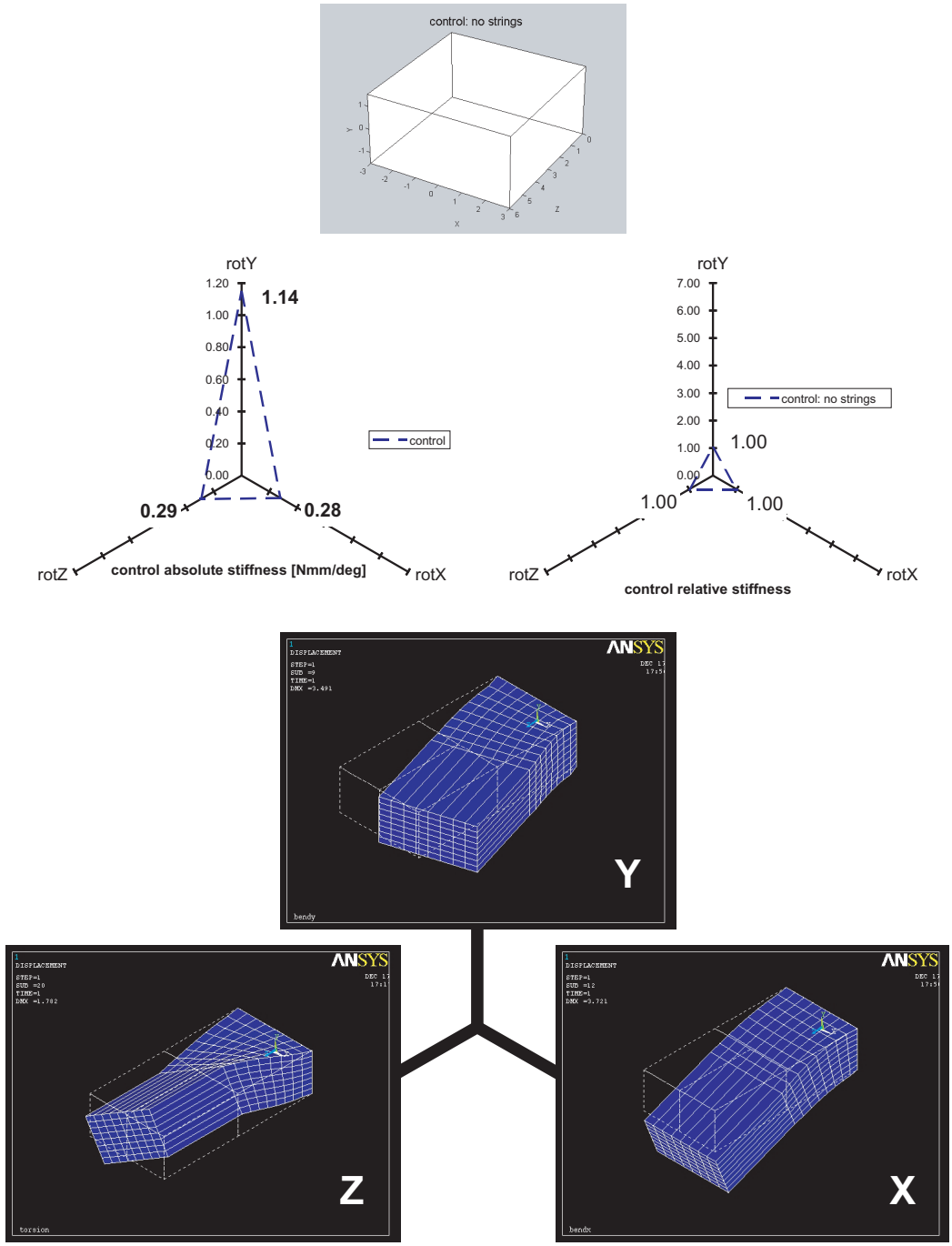


Figure 4.7: Control piece (no fibers) FEA results

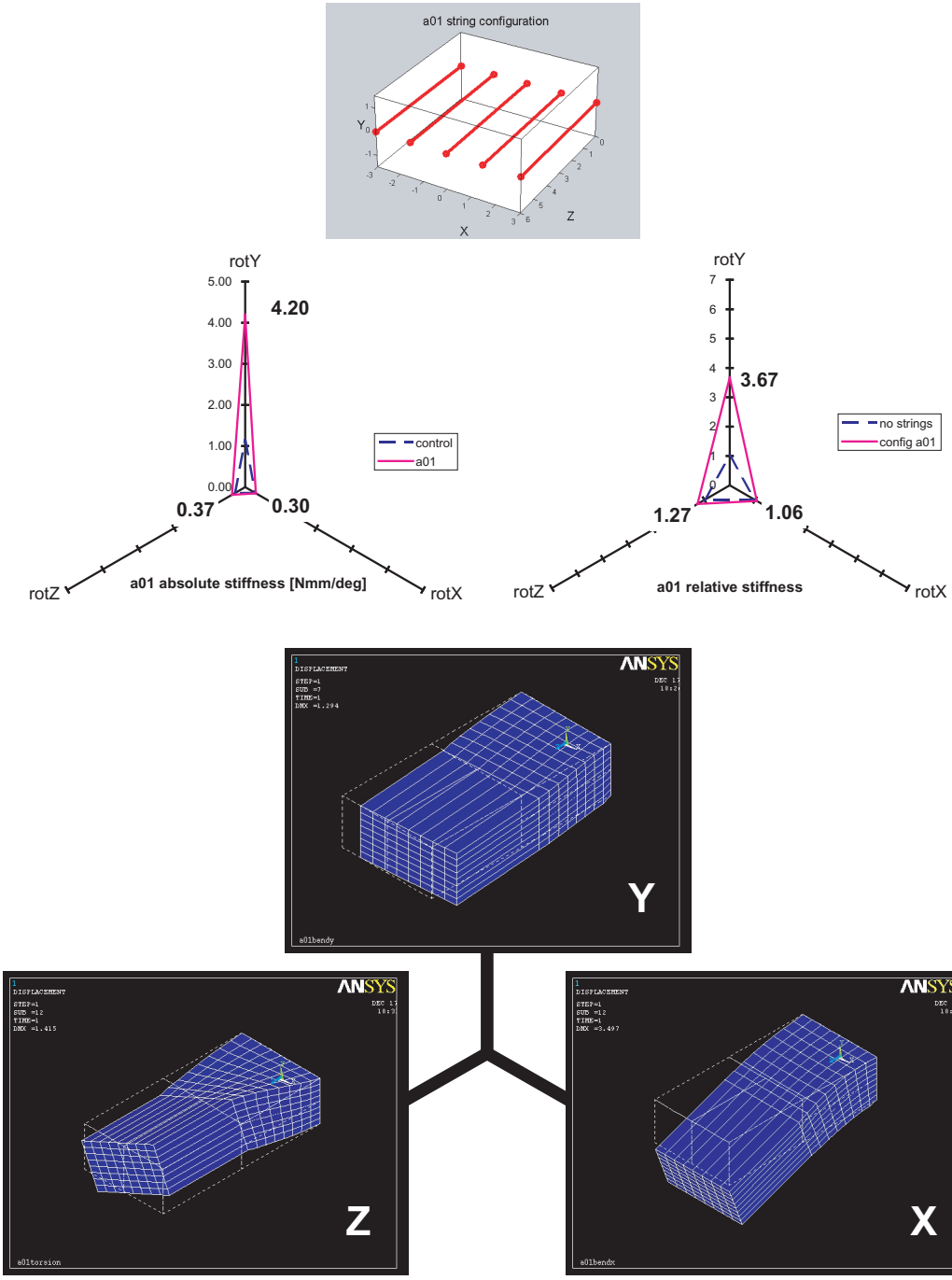


Figure 4.8: Configuration a01 FEA results

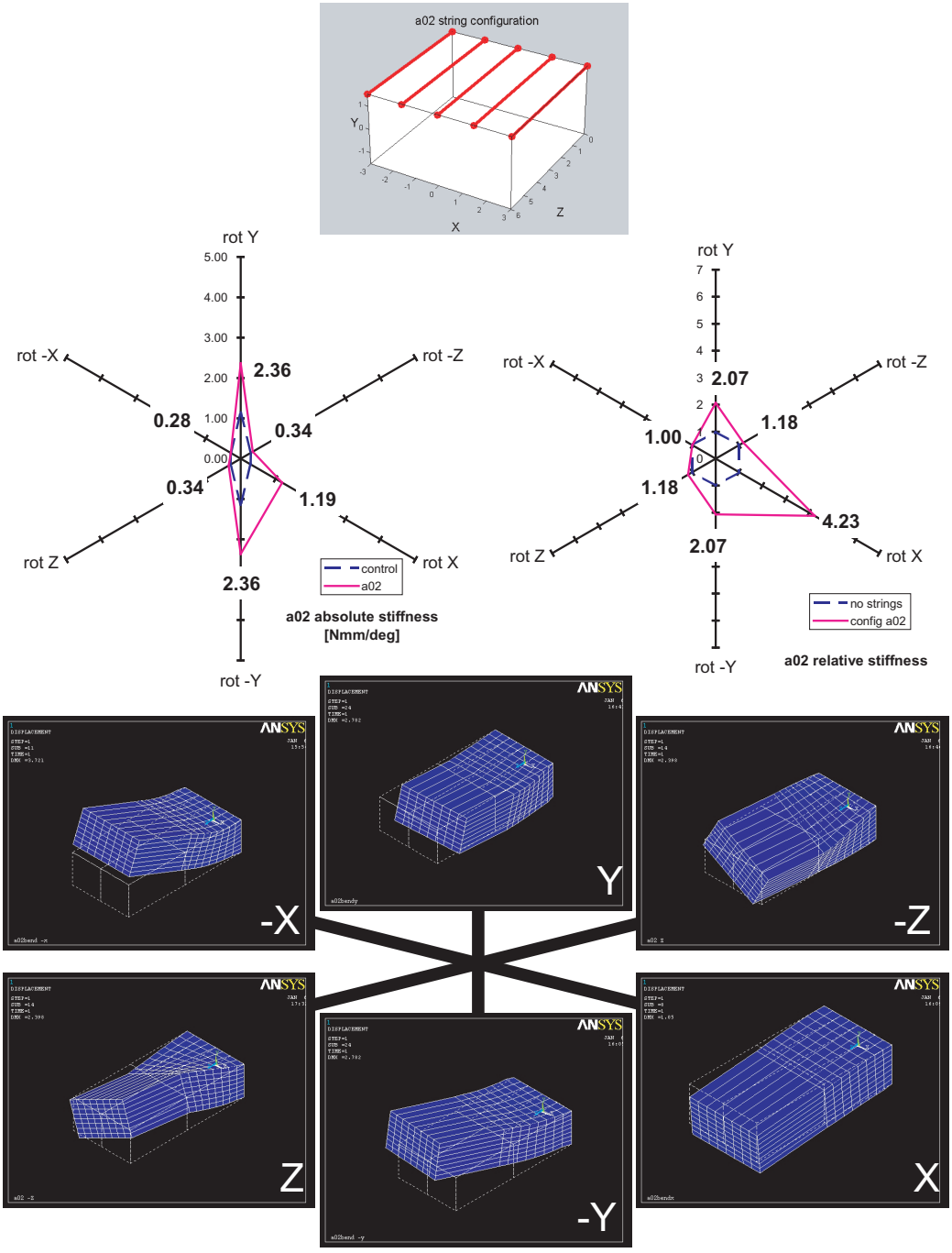


Figure 4.9: Configuration a02 FEA results

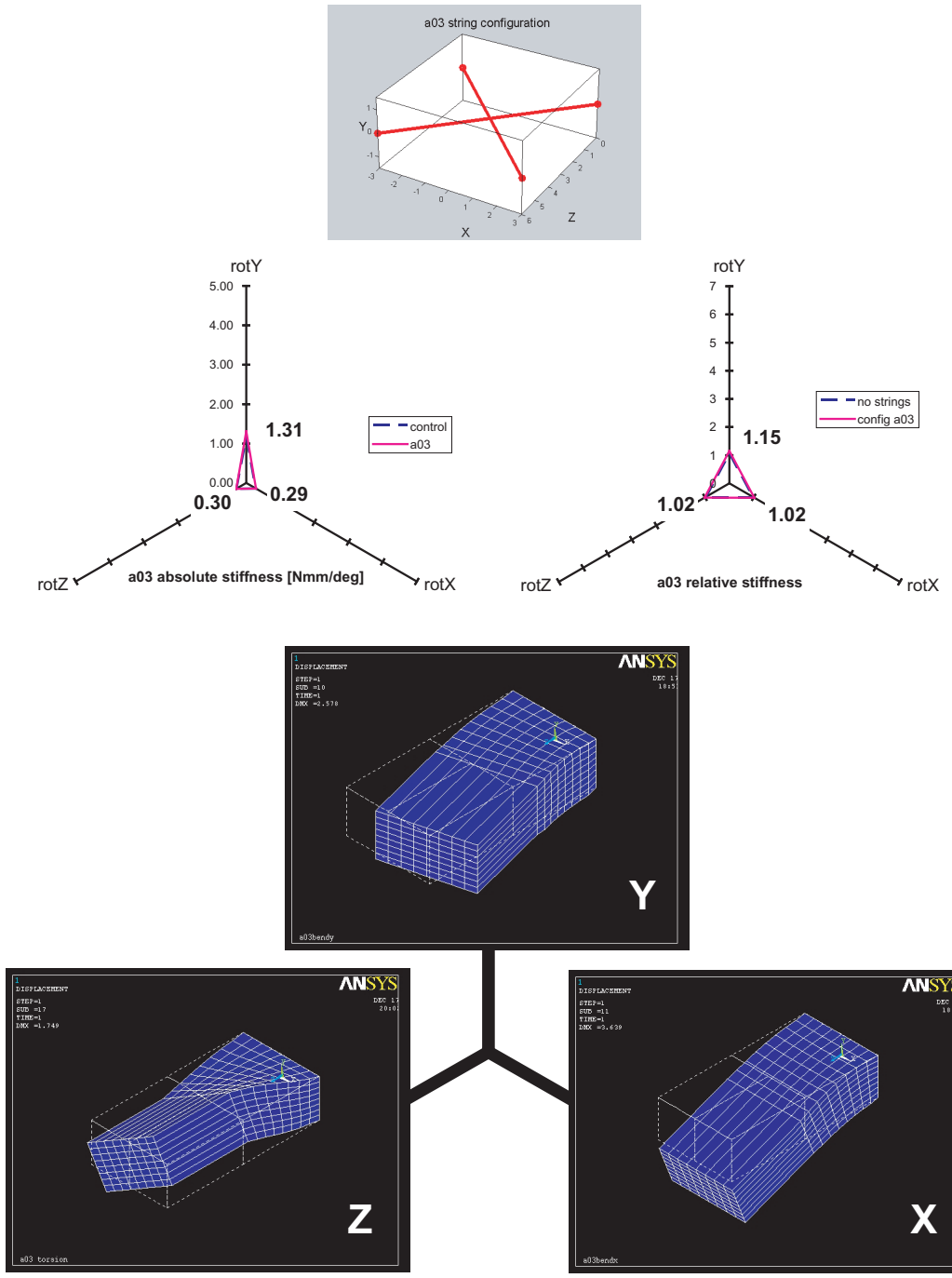


Figure 4.10: Configuration a03 FEA results

a04

Please see figure 4.11. A04 has diagonal fibers in the top and bottom horizontal planes. The influence on the Y bending stiffness is about the same as in a03. However, the influences on X bending and Z torsion are significant. For X bending, the fibers run at $45deg$ angle with respect to the direction of major extensive strain. For Z torsion, the fibers run along the direction of major strain on the top and bottom surfaces. However, the strains in these faces are not as large as the strains on the side faces. Consequently, diagonal reinforcement on the side faces as in a05 exhibit larger stiffening against Z torsion.

a05

Please see figure 4.12. A05 has the side faces reinforced diagonally. In essence, it is equivalent to swapping the X- and Y-axes in a04. Consequently, the relative stiffening pattern for a05 indicate similar tendency to a04 with X- and Y-axes interchanged. Relative stiffening is larger for both of the axes in a05. The reason for this might be that the fibers are oriented at a smaller angle with respect to the major strains in a05 compared to a04 (only 26.6° as opposed to 45°). As mentioned in the comments for a04, the Z torsion stiffening effect is more significant in a05.

a06

Please see figure 4.13. A06 has four fibers running diagonally through the center of the flexure block. Since they do not coincide with any of the major strain directions for any of the deformations, the stiffening effect is also generally small. As a result, this turns out to be a rather useless configuration from the applications standpoint.

a09

Please see figure 4.14. A09 is a configuration based on the a05, attempting to stiffen up the Y bending and Z torsion compliances further while maintaining X bending flexible. However, the reinforcements in the inner body do not help stiffen up the Y and Z since they undergo much less strain than the outer fibers. On the other hand,

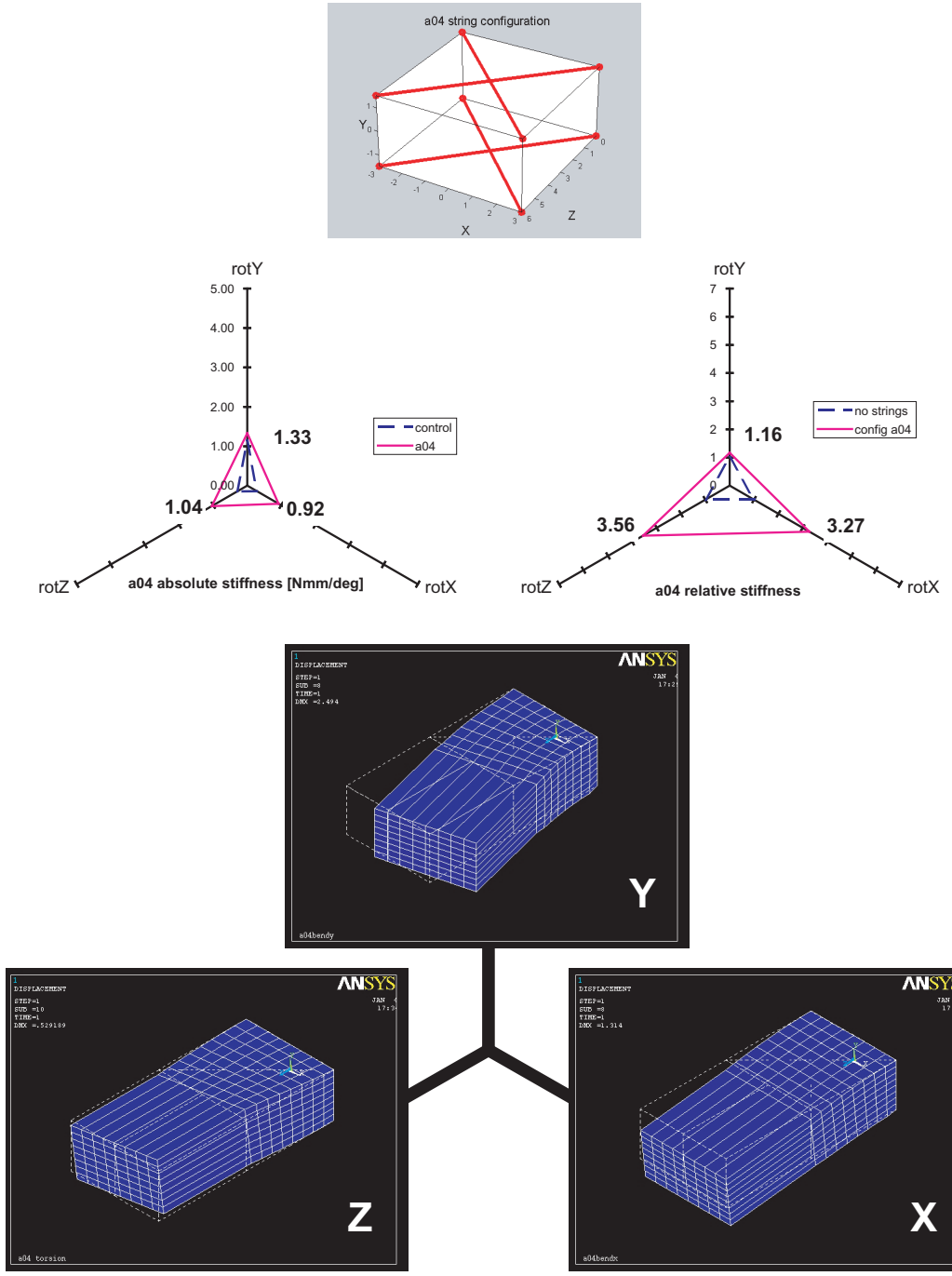


Figure 4.11: Configuration a04 FEA results

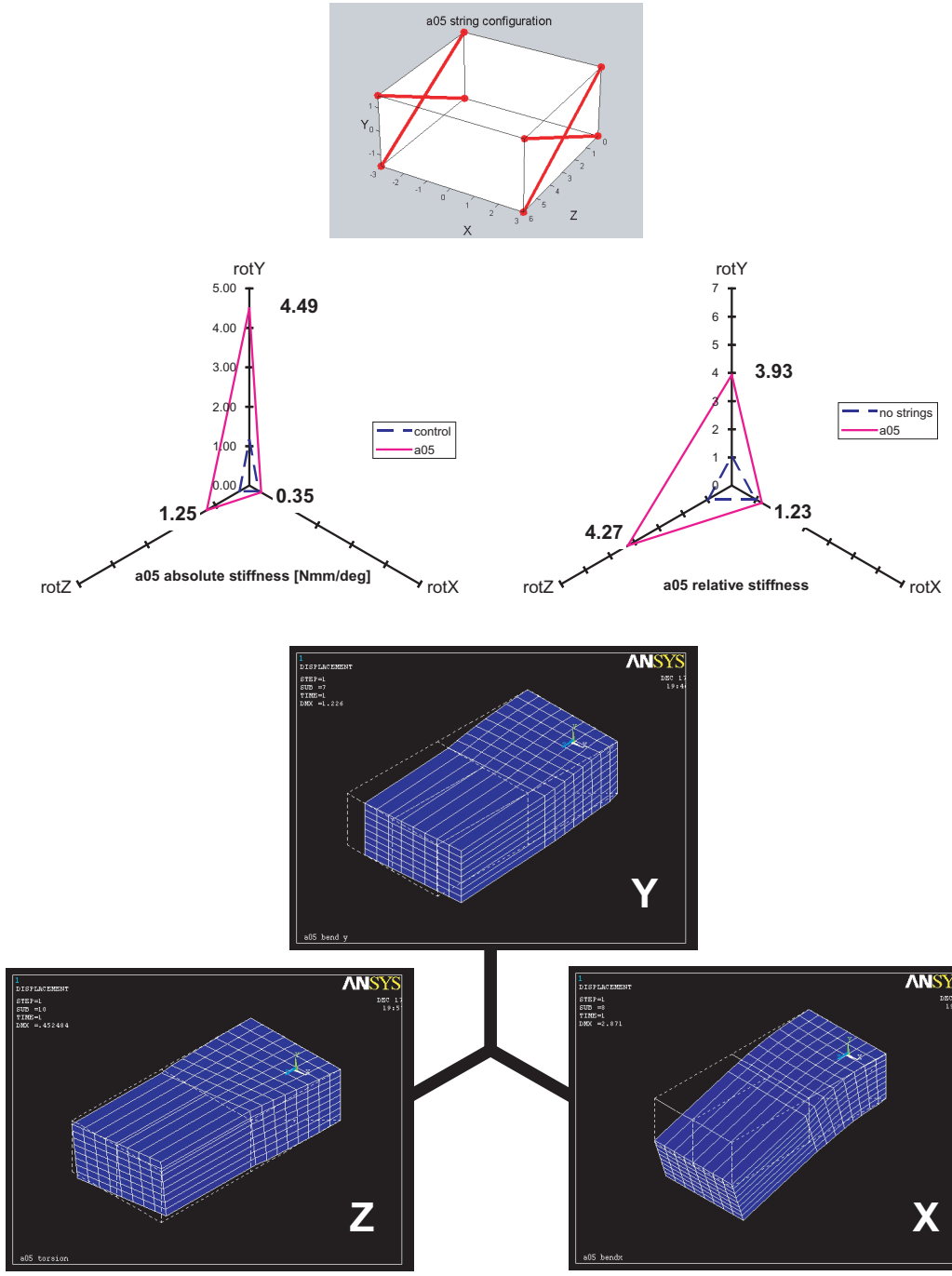


Figure 4.12: Configuration a05 FEA results

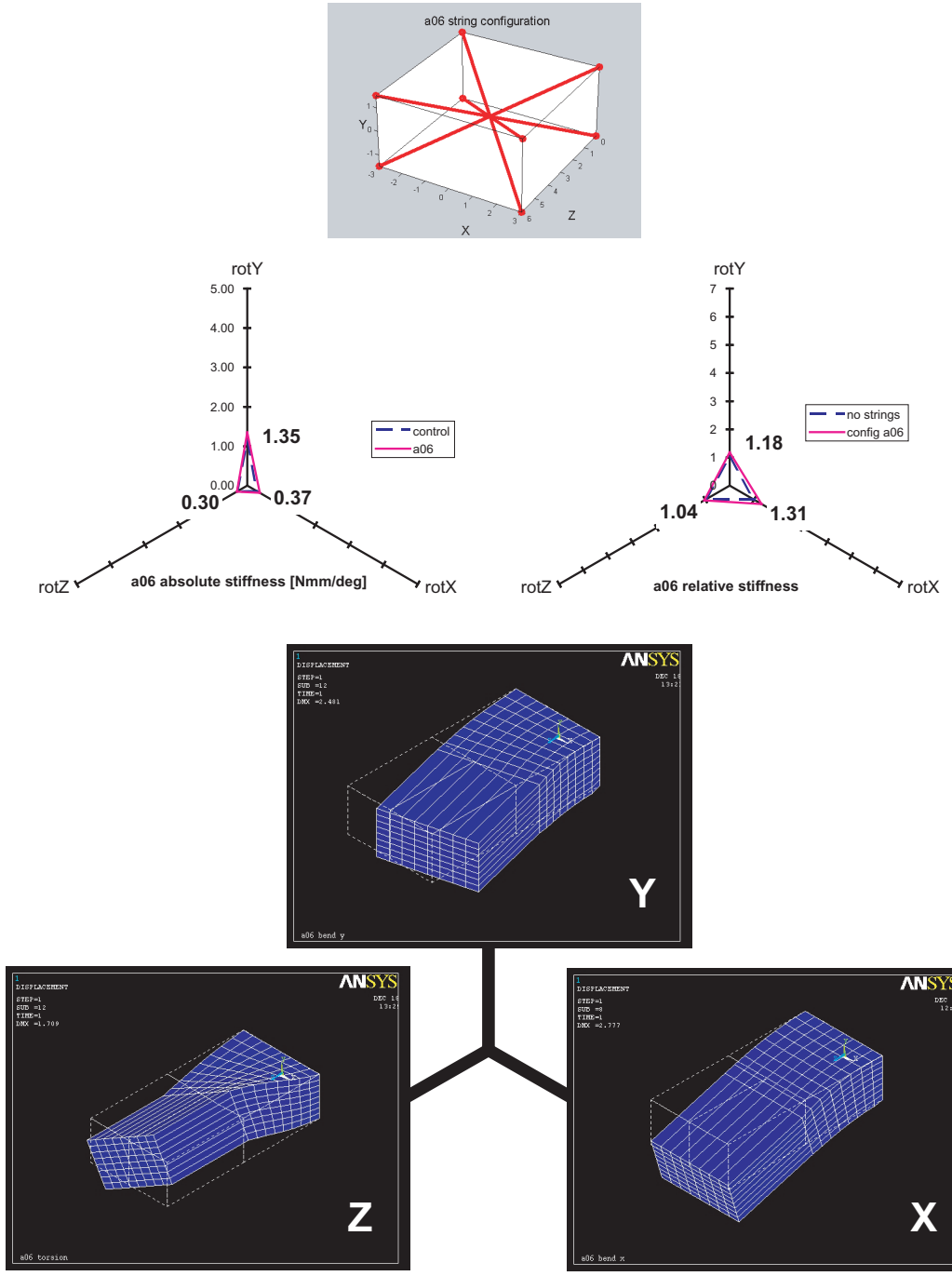


Figure 4.13: Configuration a06 FEA results

the fibers evenly shared load for X bending and stiffened up the structure for this deformation.

a11

Please see figure 4.15. A11 is a configuration to verify the insignificance of the inner fibers in a09 that made no contributions in stiffening up the Y bending and Z torsion compliances relative to a05. The stiffening effects are smaller in a11 than in a05 for both of the loading conditions. However, unexpectedly, the X bending is stiffened more in a11 than in a05 even though intuitively they would be expected to be approximately the same given the similar strain conditions of the planes in which the fibers are embedded. This would be an interesting subject for further investigation.

a12

Please see figure 4.16. A12 is a subset of a05 with directionality in Z torsion. It is stiff against +Z torsion and flexible for -Z torsion. For X and Y bending, it also exhibits some tendency to twist in the -Z direction. As was also seen in a02, directional preference between two opposing loads (-Z over +Z in this case) shows up in deformations under other loads to include the preferred.

a16

Please see figure 4.17. A16 has fibers running lengthwise along two corners which oppose each other diagonally across the flexure. This configuration exhibits moderate stiffening in all three directions. In addition, it shows some extra bending and torsion due to its asymmetry.

a19

Please see figure 4.18. A19 is an evolution of a05 by partial hybridization with a01, attempting to further stiffen the Y bending and Z torsion while keeping X bending flexible. The addition of horizontal side fibers increased Y bending stiffness with respect to a05 but left Z torsion stiffness unaffected. This is understandable considering

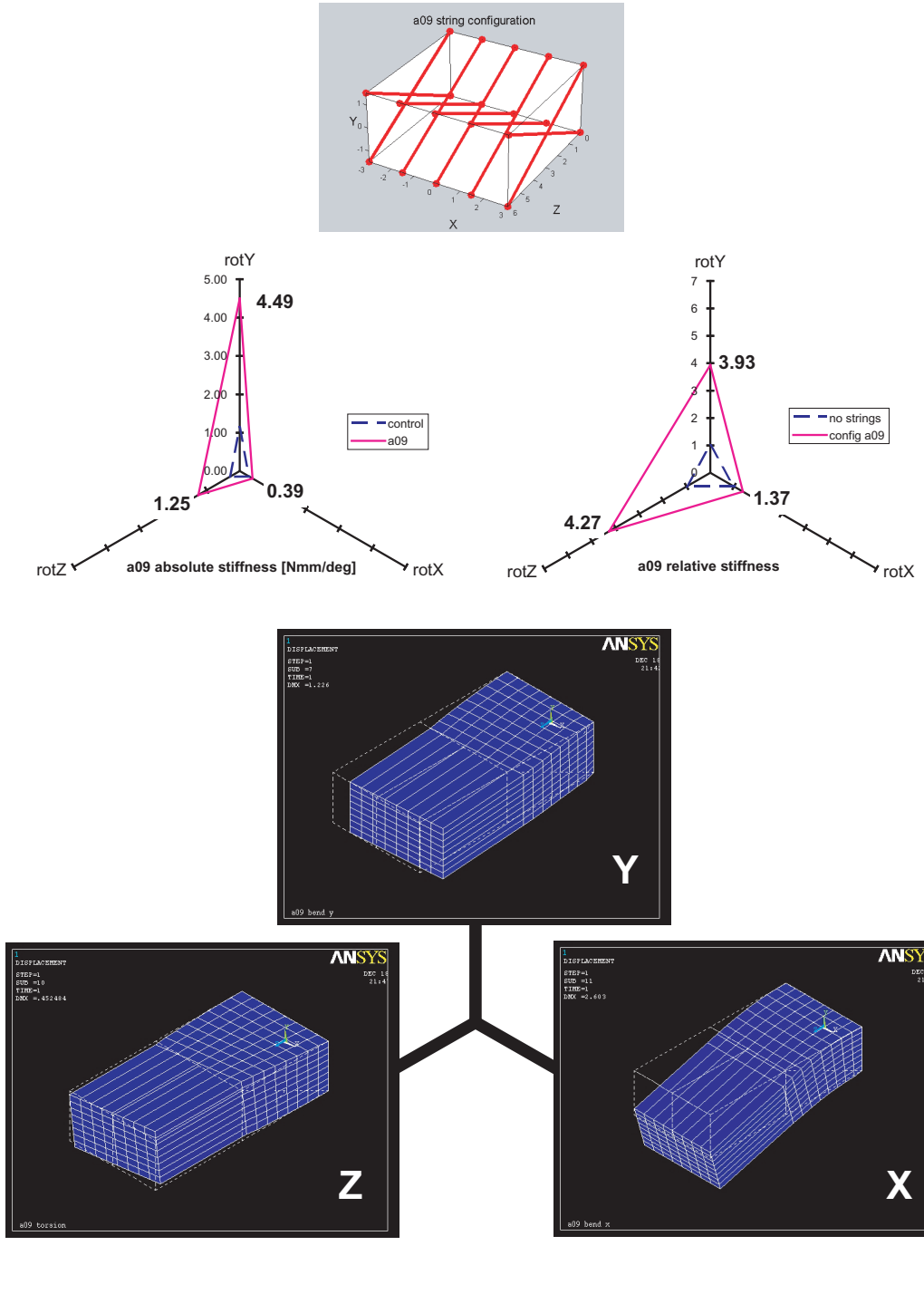


Figure 4.14: Configuration a09 FEA results

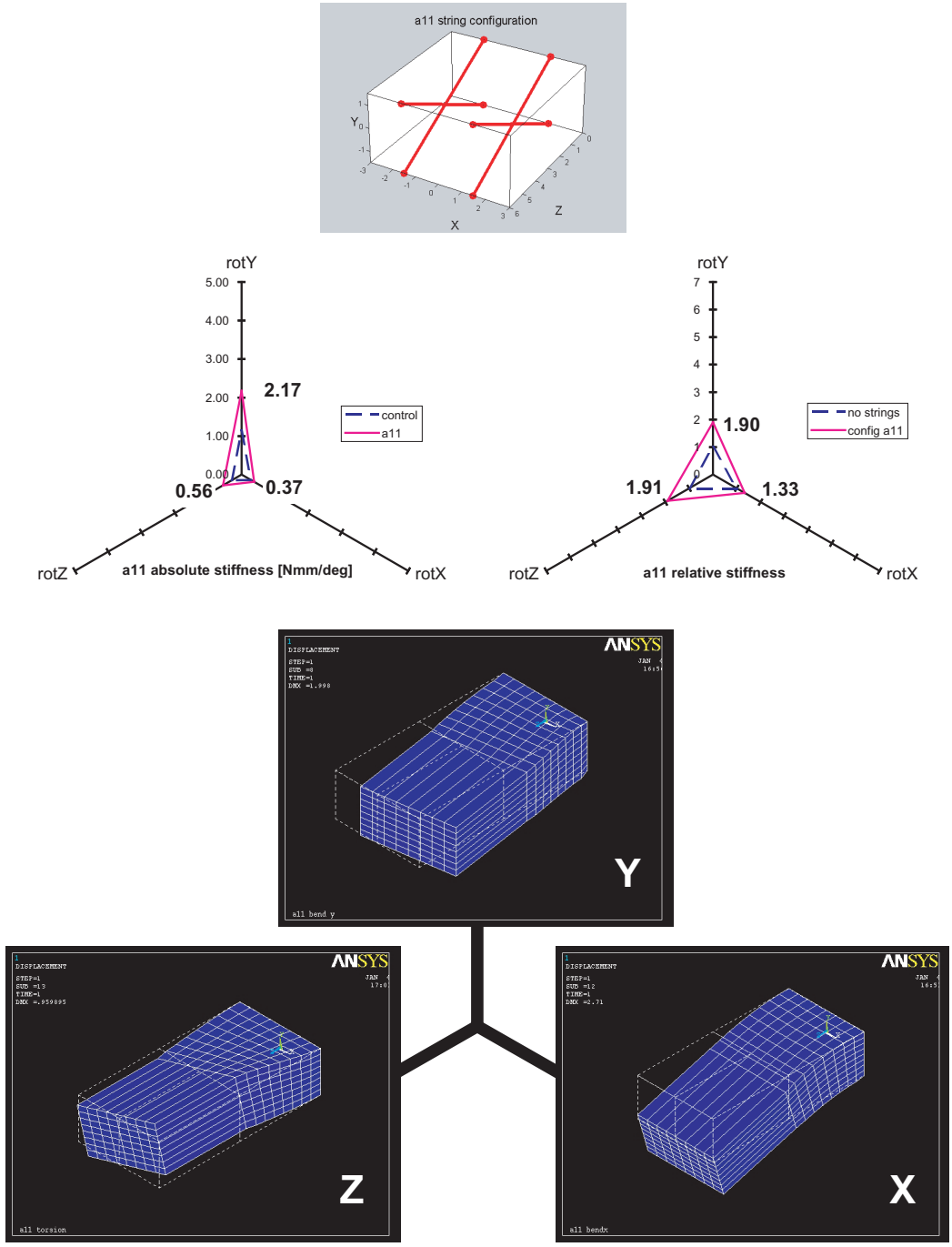


Figure 4.15: Configuration a11 FEA results

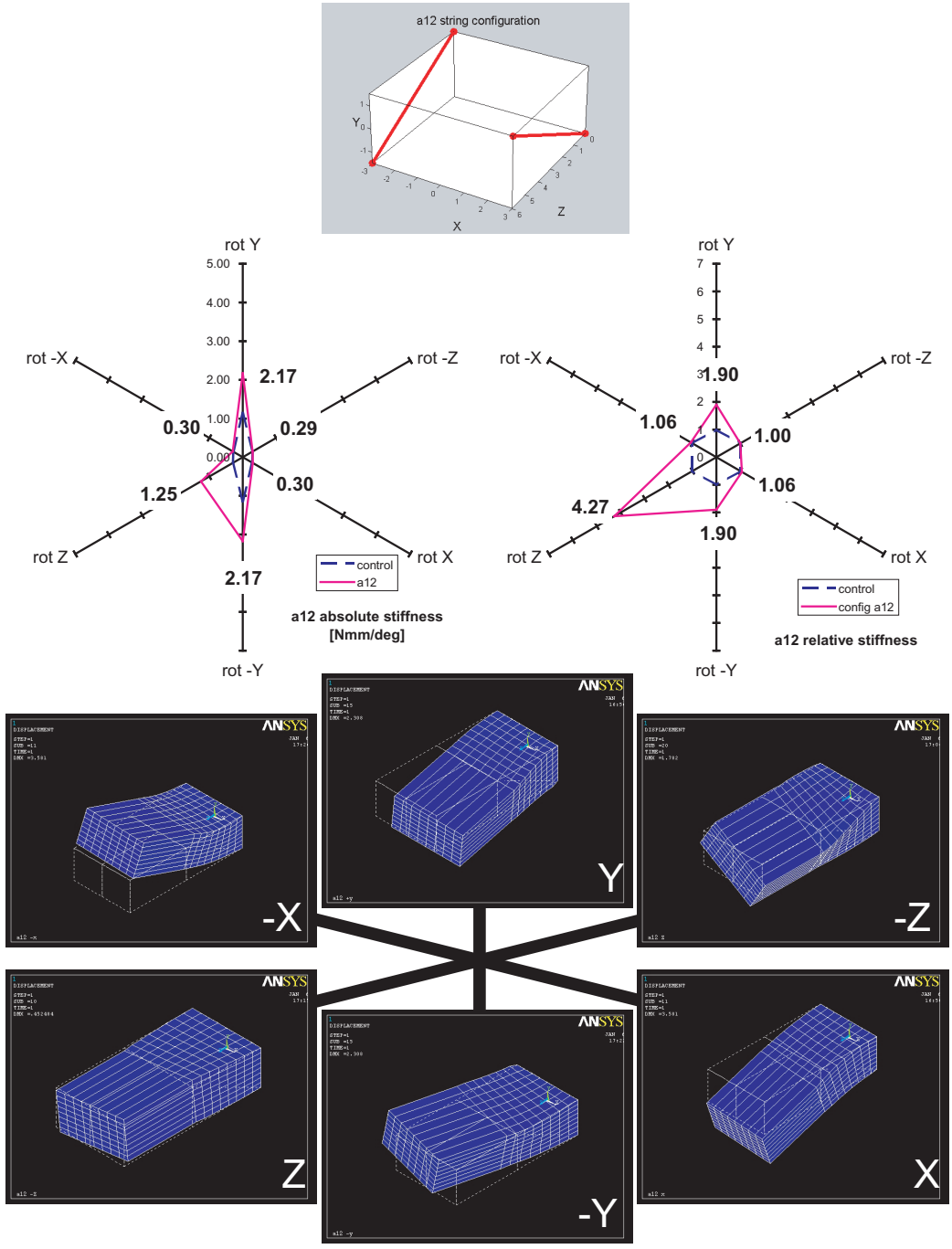


Figure 4.16: Configuration a12 FEA results

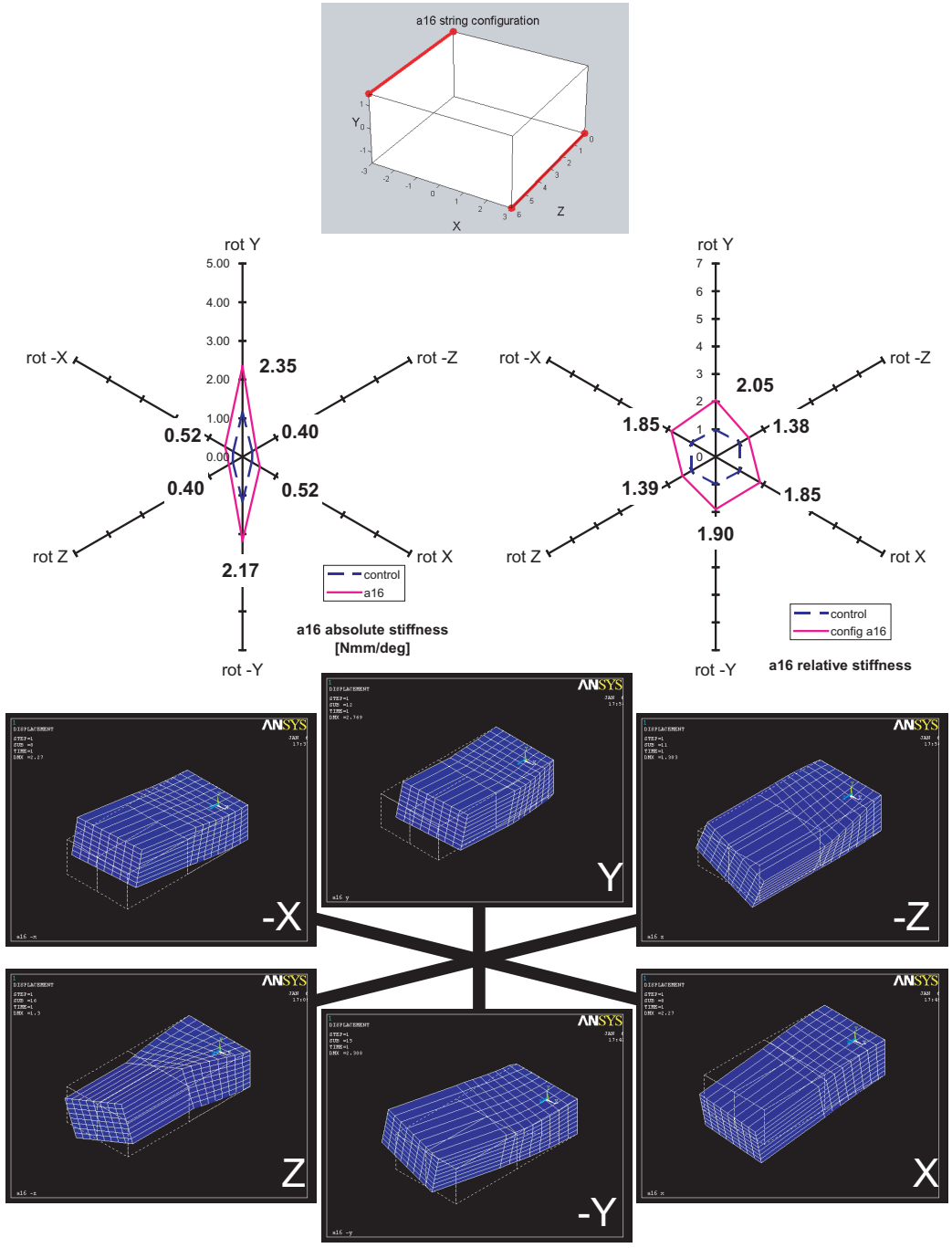


Figure 4.17: Configuration a16 FEA results

the significant Y stiffening and relatively small Z stiffening in a01. This configuration appears to be the best solution among all of the analyzed configurations for stiffening the Y and Z compliances while maintaining X flexible. When more tensile strengthening is desired, additional horizontal fibers in the mid horizontal plane would help. The resulting configuration would be a complete hybrid of a01 and a05.

a21

Please see figure 4.19. A21 is a single-sided version of the a19. X bends gain some torsion due to the asymmetric configuration. The influence on +Y bending stiffness is completely removed with relative stiffness back to 1. The -Y bending stiffness is the same as in a19. Z torsion stiffness is significantly lower than in a19. This is because the axis of rotation is maintained in the center in a19 while it is moved closer to the fibers in a21. In a19, fibers on both sides of the flexure can contribute evenly while in a21 the fibers contribute less. For this reason, the a21 configuration would result in smaller torsional stiffness than a19 even if the fibers were twice as stiff.

a22

Please see figure 4.20. A22 is a single-sided configuration similar to a21. The fibers increase Y bending stiffness in one direction and also in both X bending directions. Tendency to yaw in +Y direction is observable in X bendings and Z torsions due to the asymmetry.

a23

Please see figure 4.21. A23 is a partially asymmetric configuration that exhibits slight asymmetry in X bending, strong stiffening effects against Y bending, and moderate stiffening against Z torsion.

a24

Please see figure 4.22. A24 is yet another partially asymmetric configuration. X bendings exhibit slight direction dependency while both Y bendings and Z torsion

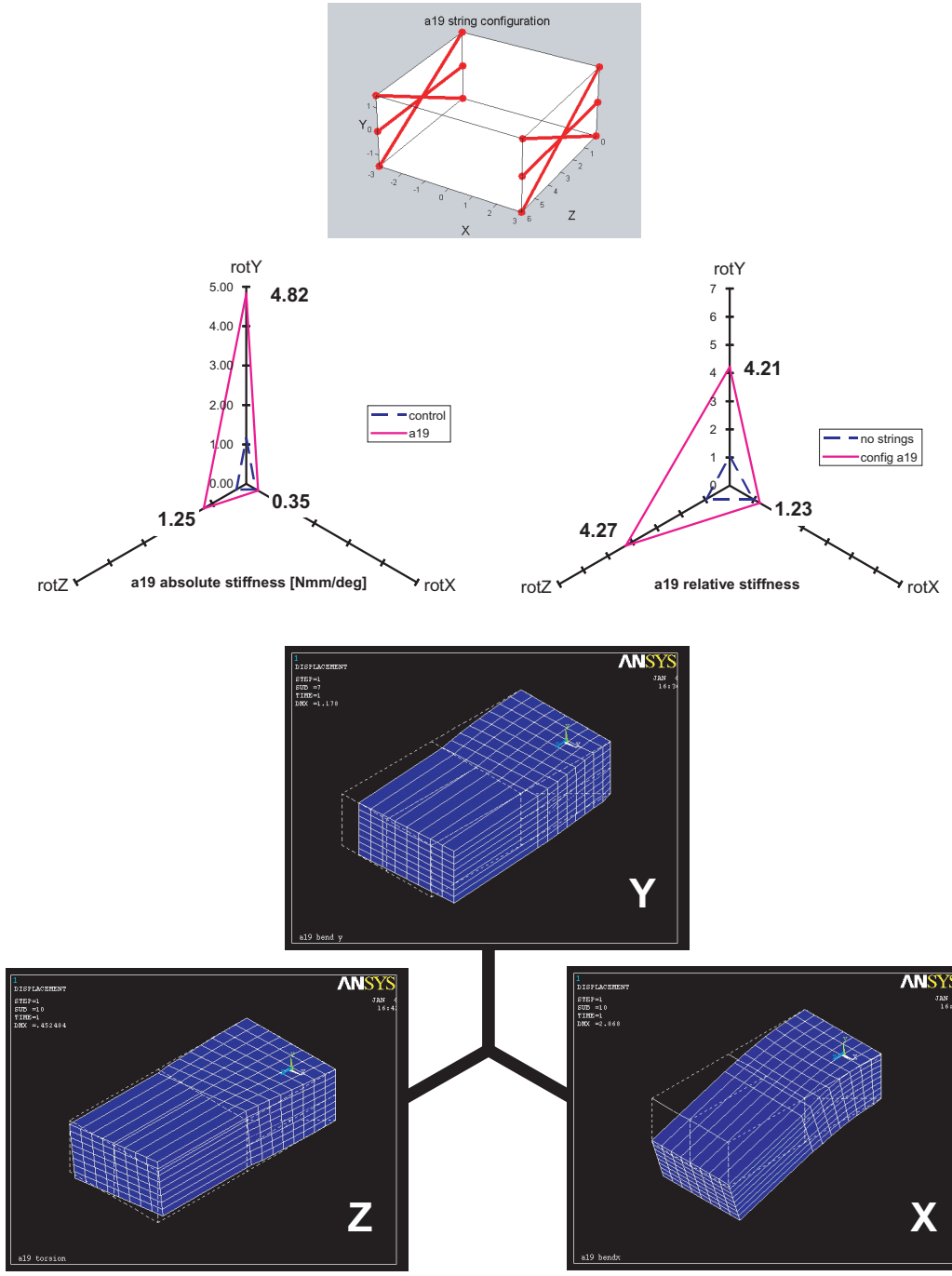


Figure 4.18: Configuration a19 FEA results

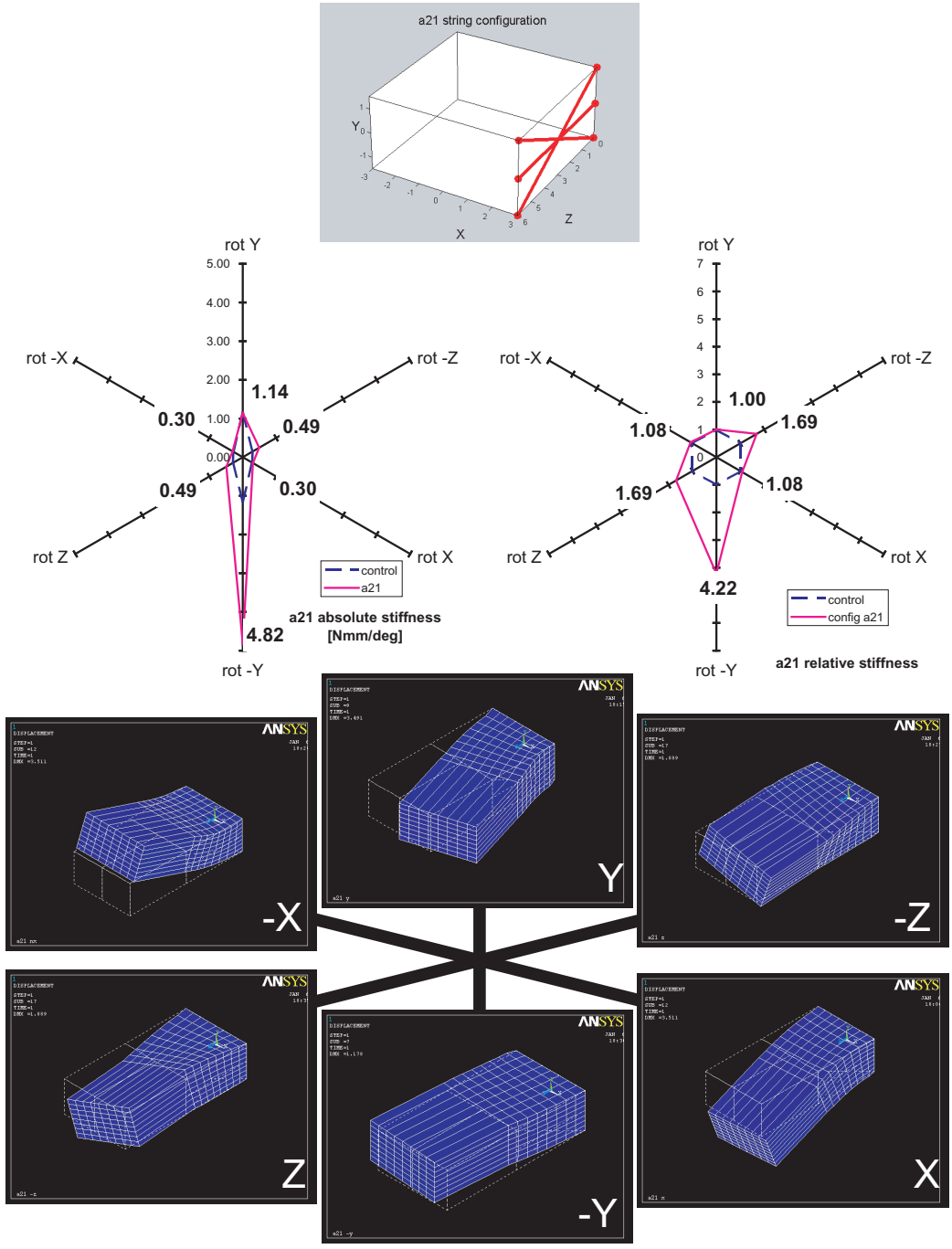


Figure 4.19: Configuration a21 FEA results

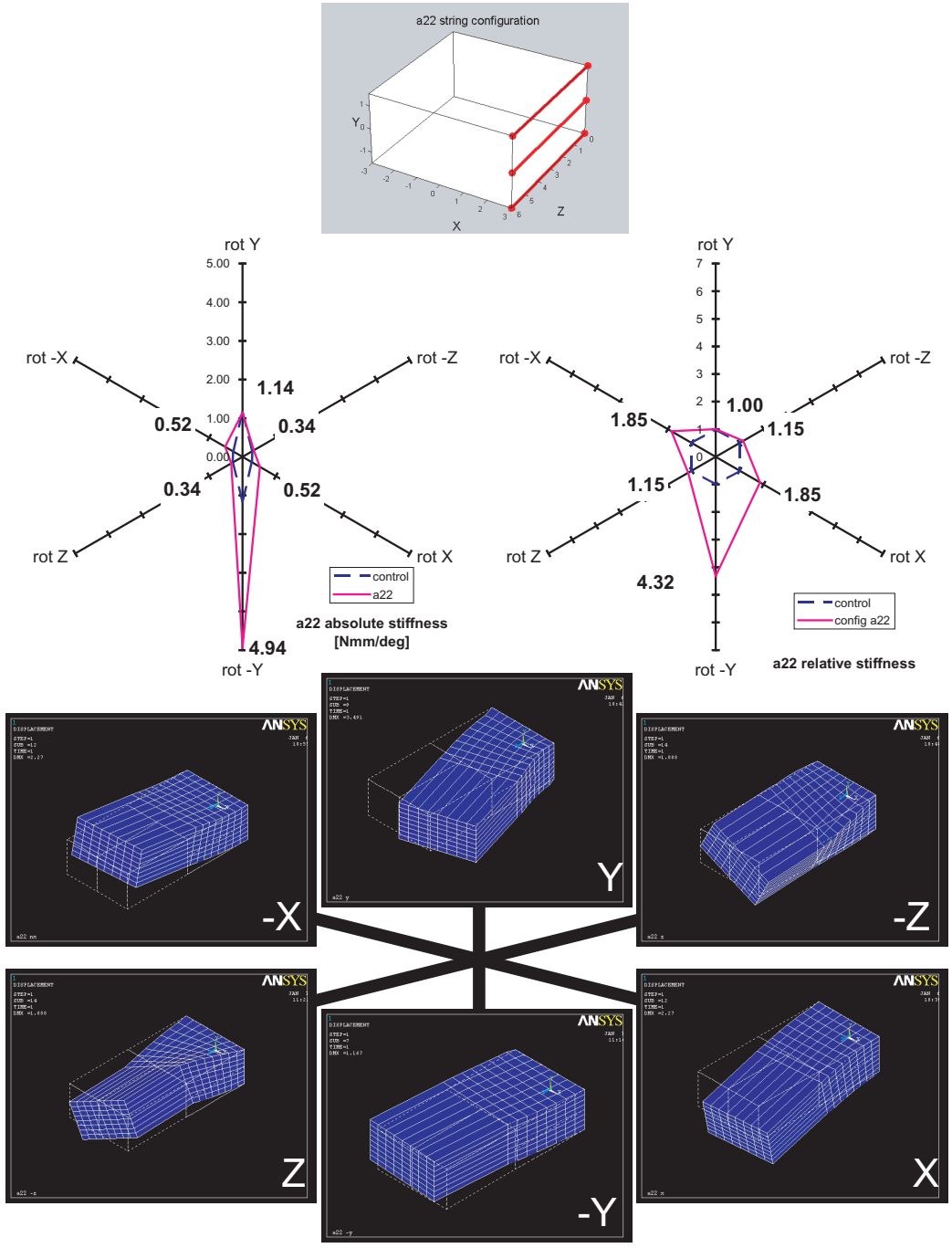


Figure 4.20: Configuration a22 FEA results

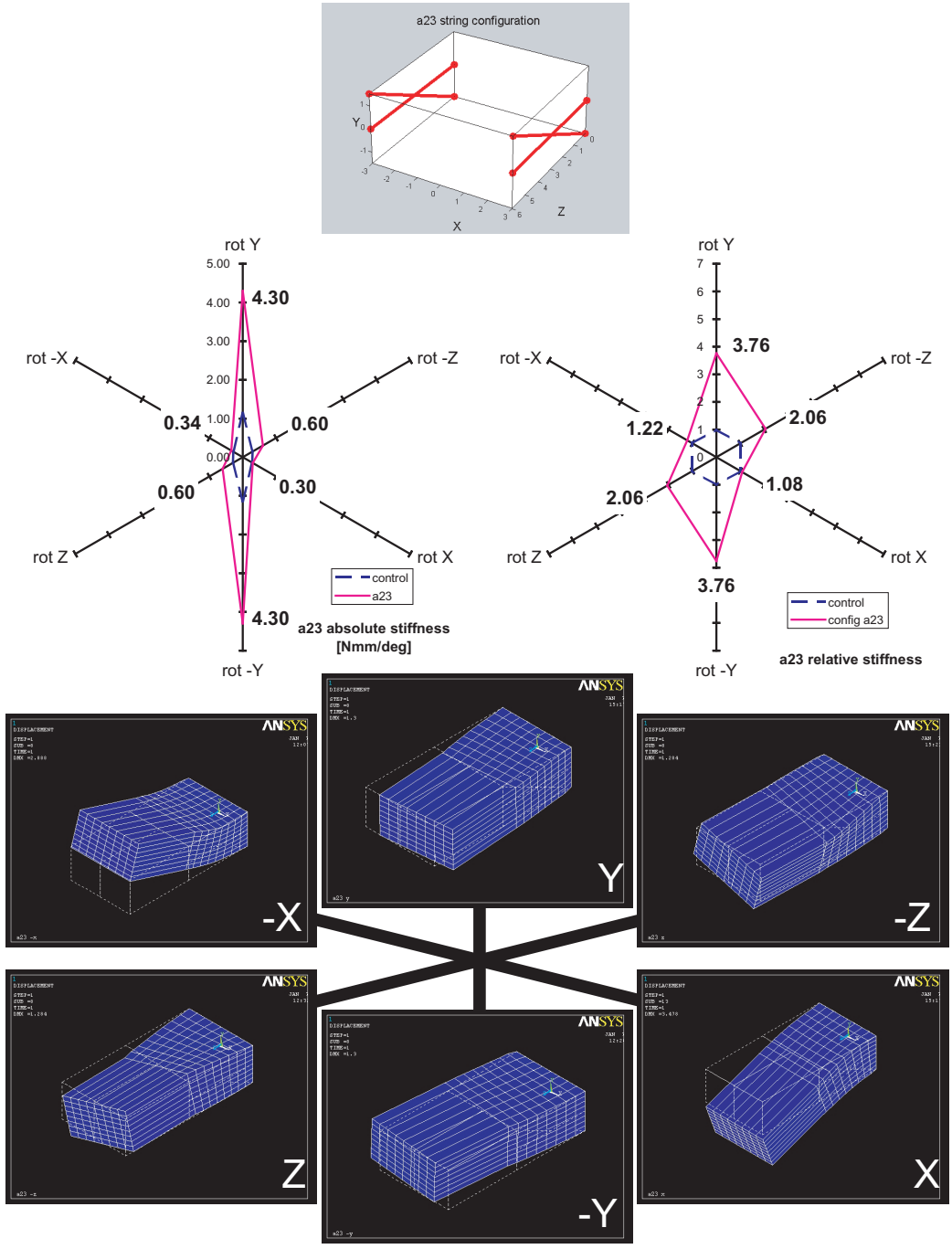


Figure 4.21: Configuration a23 FEA results

contain complex deformations.

a25

Please see figure 4.23. A25 is a 90°rotated version of a24 in which the X- and Y-axes are interchanged. The results are similar in that Y bendings show direction dependency and X bendings and Z torsions involve complex deformations.

b05

Please see figure 4.24. The b05 configuration is identical to that of a05. However, the fiber stiffness is doubled. All other conditions, including the flexure material stiffness, are exactly the same as in a05. The stiffnesses in Y and Z only increased by less than 10%relative to a05. This suggests that the positioning of the fibers is more influential than their stiffness in changing the structural properties. It would be interesting to determine, in general, at what stiffness the reinforcement fibers begin to show significant influence on the mechanical properties of the structure. Performing a sensitivity analysis of the structural properties compared to fiber stiffness is needed. There are theoretical limits as to how much anisotropic structural stiffening can be done. This is because fibers only interfere with stretching and not compression.

4.3.3 Analysis conclusion

The analysis results suggest the validity of the design strategy to stiffen up by placing fibers along the lines of major strain. For stiffening the X bending (pitch), fibers are to be oriented lengthwise in the top and bottom planes. It is least interfering with other two rotational degrees of freedom to have the fiber run in the middle of the faces. For stiffening the Y bending (yaw), fibers are to be oriented lengthwise in the side planes. Again, it is least interfering with other two rotational degrees of freedom to have the fiber run in the middle of the faces. For stiffening the Z torsion (roll), fibers are to be oriented diagonally in the side planes. However, this influences the Y bending stiffness inevitably. Asymmetric configurations evoke direction-dependent properties and complex deformations. For quick reference of stiffening effects by fiber

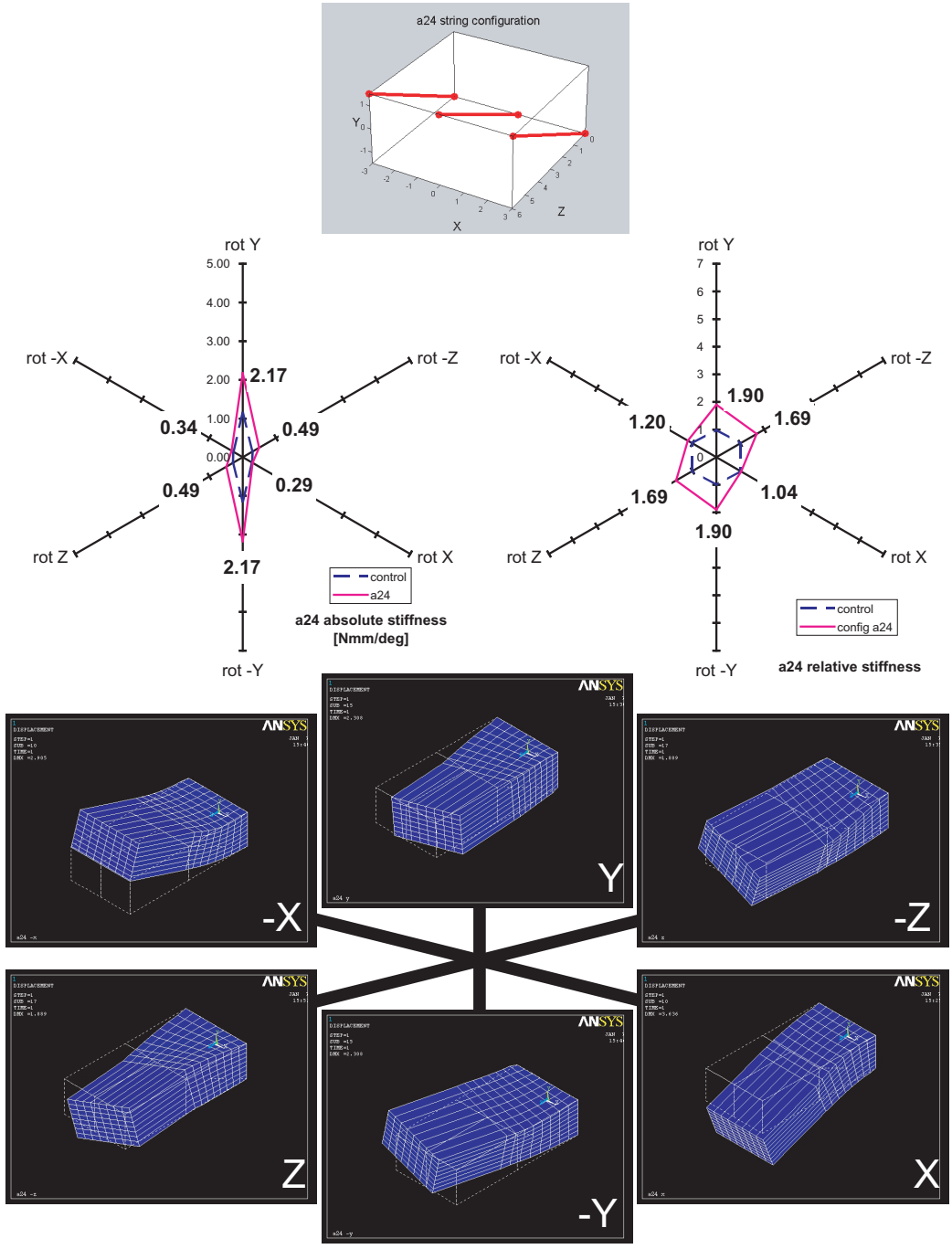


Figure 4.22: Configuration a24 FEA results

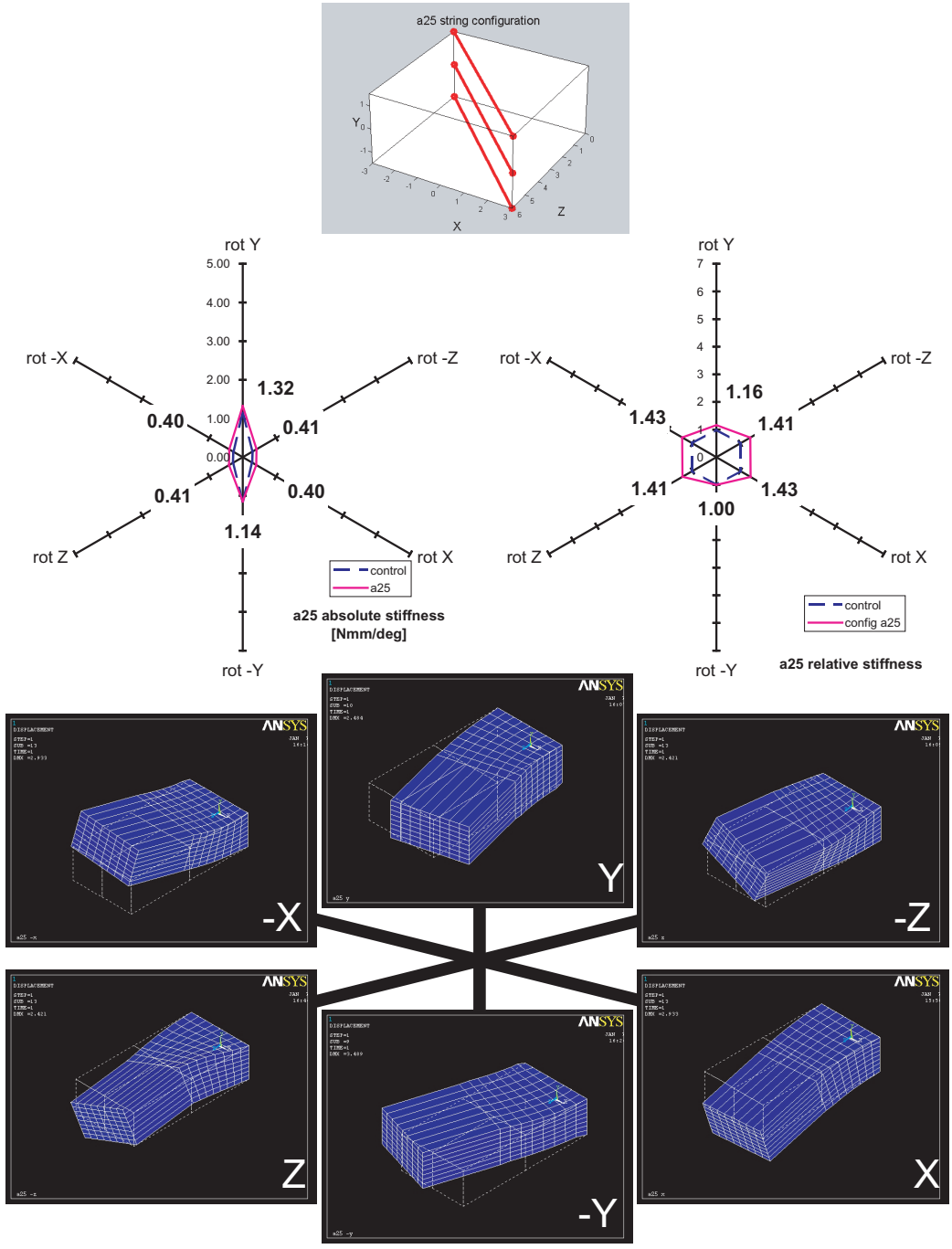


Figure 4.23: Configuration a25 FEA results

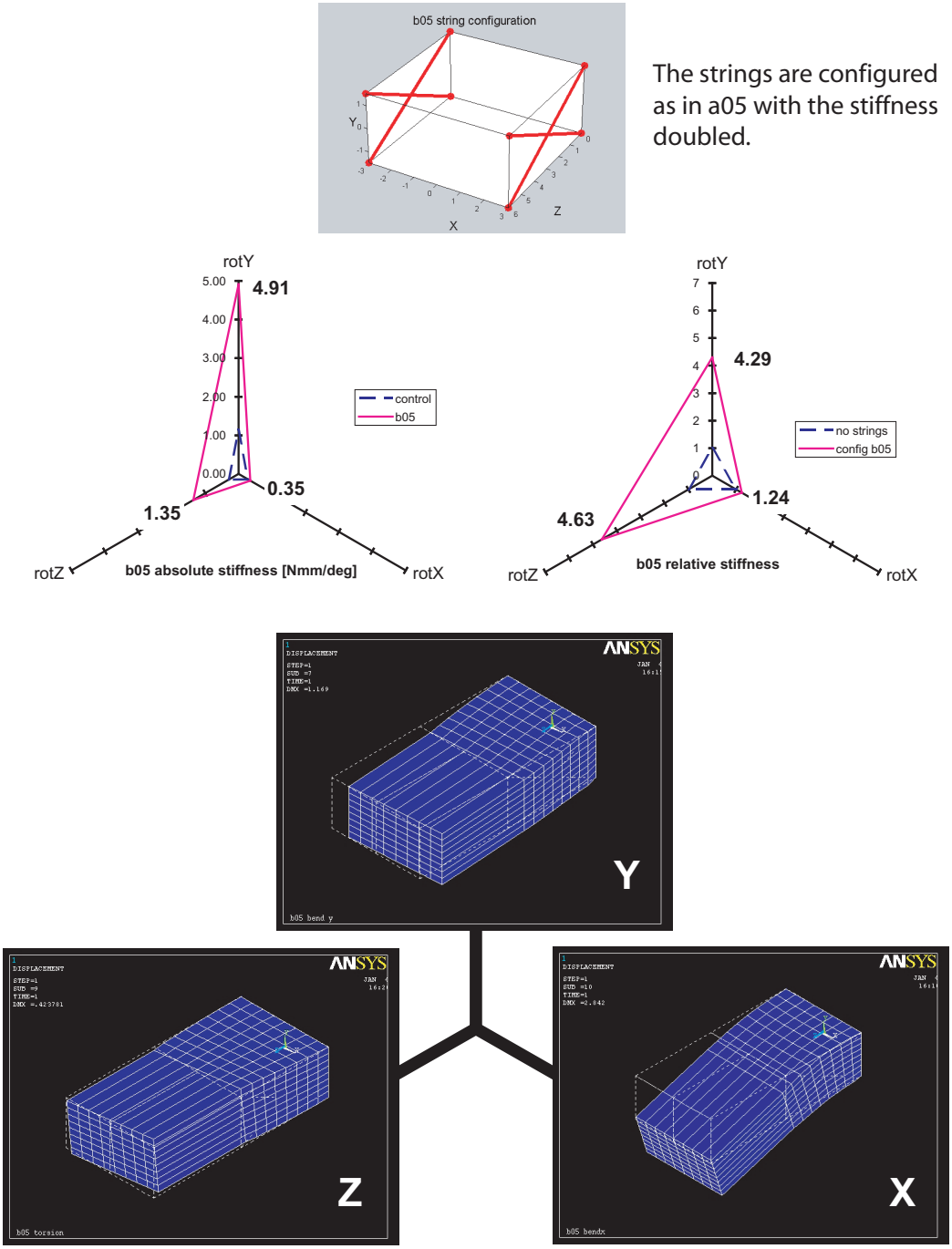


Figure 4.24: Configuration b05 FEA results

reinforcement, a selected number of configurations are plotted for the stiffening of Y bending and Z torsion stiffnesses relative to a control piece in figure 4.25.

4.4 Fabrication method

The fiber-stiffened flexures were fabricated by Shape Deposition Manufacturing (SDM) using custom-built suspending fixtures for the fibers as indicated in the previous chapter. The fixtures had two anchor blocks, with $3 \times 5\phi 0.8[mm]$holes in each with the centers 1.0[mm] and 1.2[mm] apart in the horizontal and vertical directions respectively, held together at the top with a support block. Cotton/polyester blend thread was strung in tension between the two anchor blocks, and the resulting structure was suspended in a mold cavity to be embedded within a flexure between two rigid polyurethane (Innovative polymers IE-72DC) end pieces. The support block had positioning pins which were matched into corresponding holes on the wax mold. Flexible polyurethane (Innovative polymers IE-90A) was cast into the cavity to form the fiber-stiffened flexure. The manufacturing sequence is illustrated in figure 4.26. Figure 4.27 is a photograph of the anchor assembly and a completed flexure.

The external dimensions of the flexure are the same as in the FEA model. However, the locations of the fiber ends are not exactly the same. This is partially because the fiber holes in the anchor blocks have finite dimensions and also because fibers have finite thickness. The most significant outcome of these deviations is that the fiber end locations on the outside are all some fractions of a millimeter inside the edges. The FEA analysis has shown that fibers are more influential as they are further away from the center. That suggests that the fibers in the prototypes may exhibit less dramatic effects on the performance, and they did.

There were also several sources of quality inconsistency in the prototypes. Luckily, these problems were identified in early stages of prototyping such that later models were fabricated with the greatest possible care to minimize the faulty effects. Fiber tension could not be reliably consistent even within one assembly, far less across different samples. One of the reasons for this inconsistency in tension was the insufficient stiffness of the fiber anchor assembly. The cantilevered anchor blocks deflect

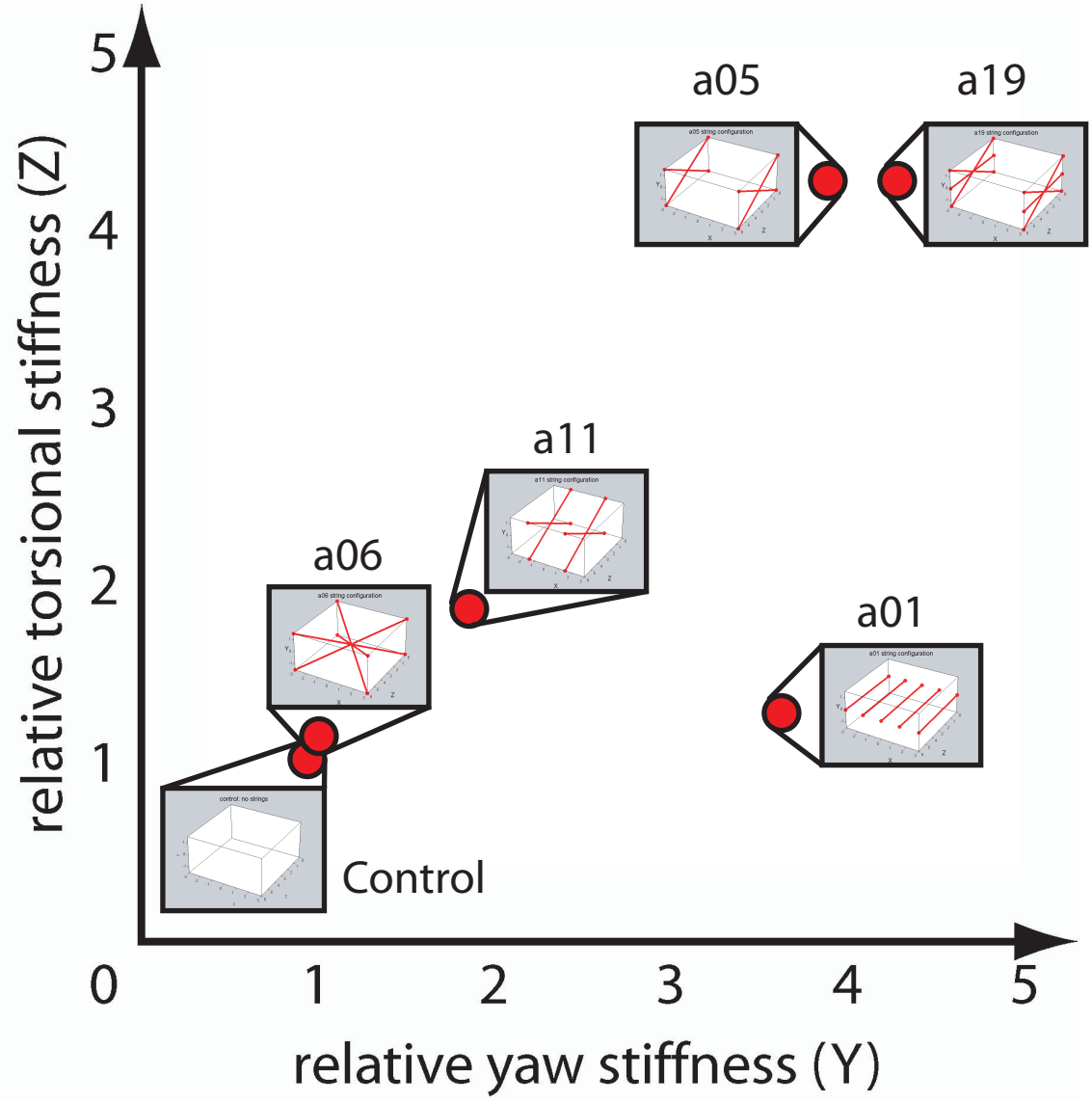


Figure 4.25: Relative stiffenings in Y bending and Z torsion

inwards under fiber tension, and the magnitude of deflection is larger at the tips. The deflection of the fiber anchor blocks is due to their own material flexibility as well as that of the top support block. The anchor assembly was designed such that the anchor blocks would be forced back into their straight position upon insertion into the mold, and this led to extra tension in the bottom fibers, furthest away from the top support block. It would not have been a problem if fibers were free to slide to even out the tension, but there was too much friction for that. Because these problems were identified before the production of the final test pieces, the final production was done with the utmost care to minimize inconsistency. The most noteworthy of the countermeasures is the use of a separation block, i.e. a spacer, to prevent the anchor blocks from being pulled toward each other. The resulting prototypes exhibited reasonable consistency among each individual samples such that the collected data gave meaningful insights as discussed in the following section. However, a significant improvement of the process would be necessary for producing reliable hardware for real applications. A solution to the tension consistency problem might be to use stiffer fibers that are virtually inextensible such that they can be strung without applying much tension.

4.5 Stiffness testing

4.5.1 Test method

X and Y bending angles were measured with a protractor with 5° resolution. Samples were warmed up immediately before experiments by manually flexing them several times about the axis of interest. They were then loaded by hanging 100[g] and 200[g] weights on the unsupported end of the sample, 15[mm] away from the middle of the flexure, producing 14.7[Nmm] and 29.4[Nmm] of torque, respectively. The supported end was tilted such that the loaded end would be horizontal. The angle between the two end blocks was measured after 30[s] to allow the deformation to have reasonably stabilized. Loading for samples with asymmetrical fiber configurations that exhibit complex deformations were adjusted such that the offset twisting and/or bending were

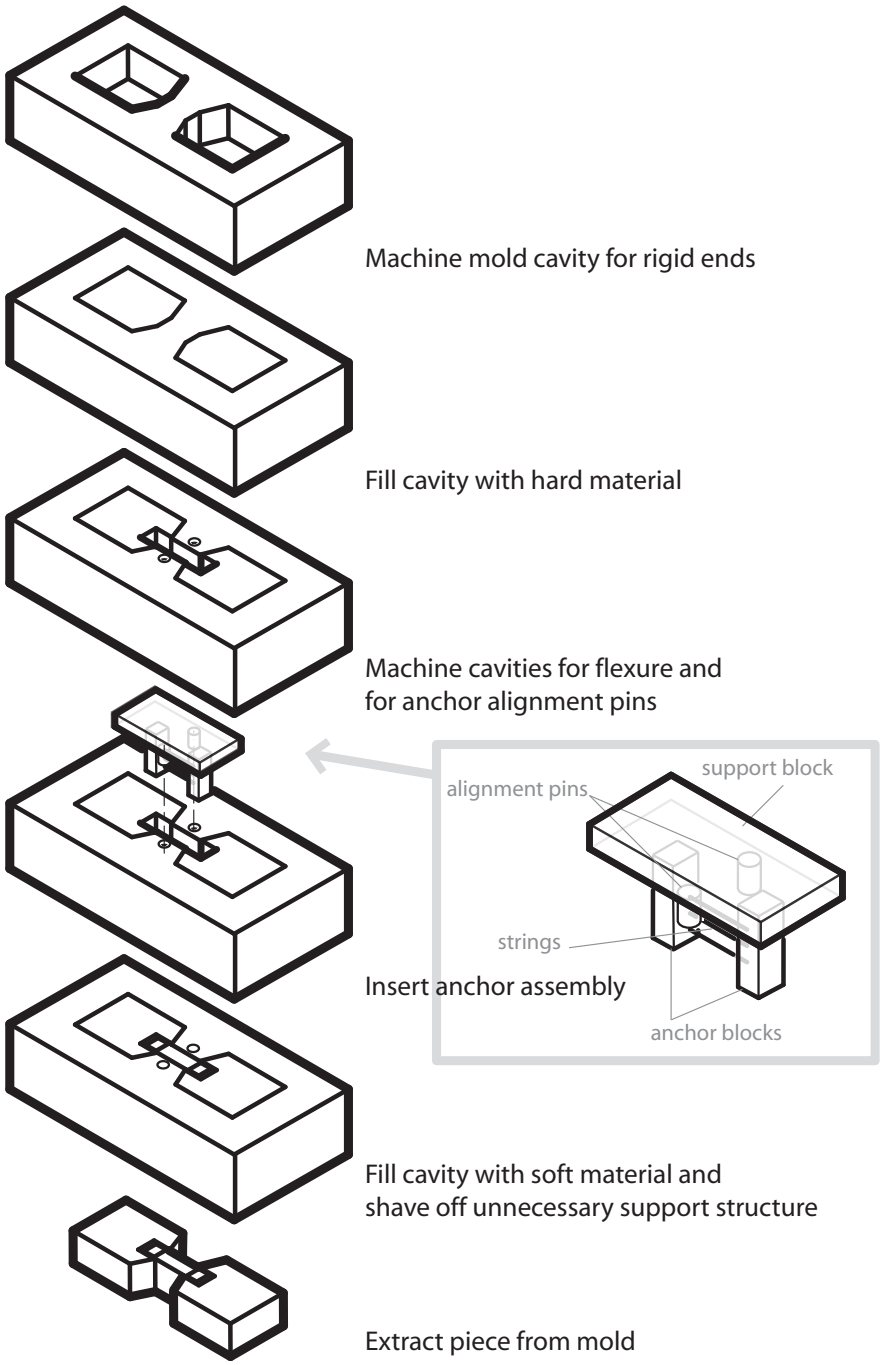


Figure 4.26: Fabrication sequence of a fiber-reinforced flexural joint using the suspending fixture method

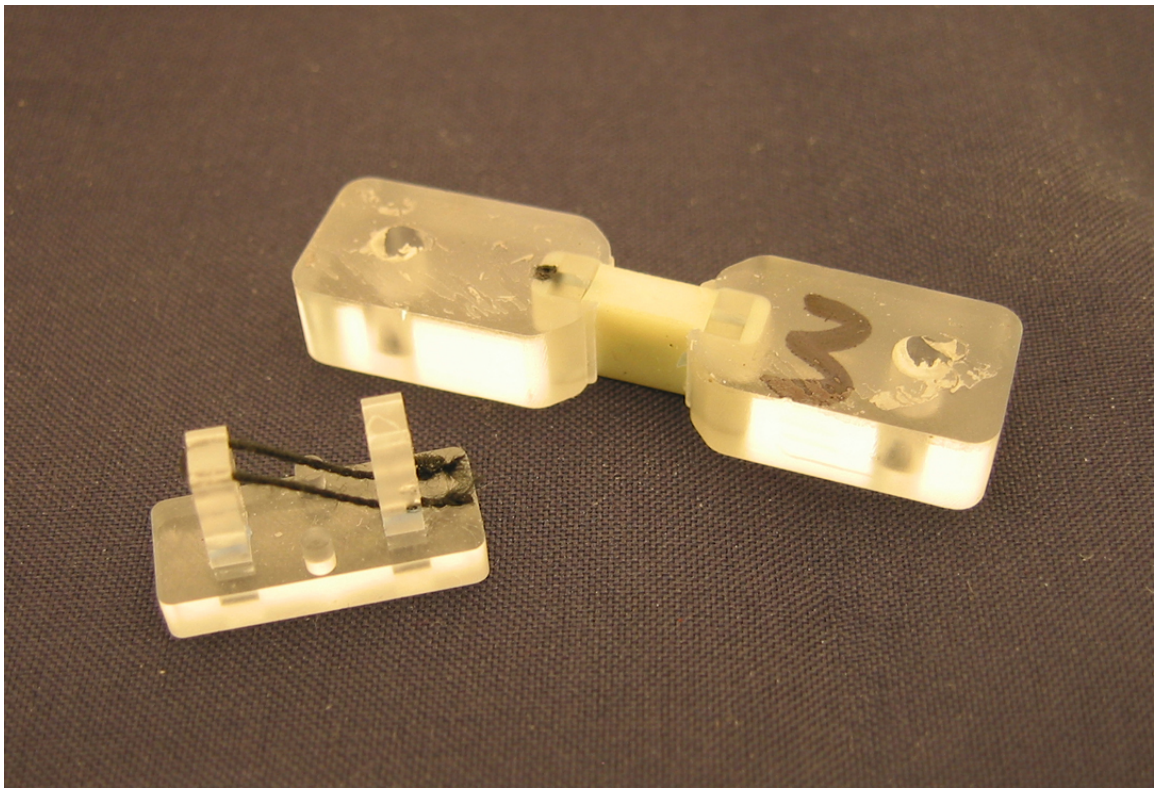


Figure 4.27: Anchor assembly placed upside down and a completed flexure

largely prevented to simplify measurement. This made the results appear slightly stiffer than they really are.

Z torsion was also measured using a protractor but with approximately 2° resolution. The samples were also warmed up by manual twisting immediately before the experiments. A torque application apparatus and a vise were used for the experiment along with 700[g] weight that was hung with a fiber around a $\phi 6.35[mm]$ diameter axle producing $21.8[Nmm]$ of torque. Again, the flexure was left to deform for 30[s] before measurement. The experimental apparatus prevented offset deformations. This may also have made the results appear slightly stiffer than they really are.

Deflection measurements were made on two to four samples per configuration and averaged. The results were used to calculate single stiffness values per loading. This linearization is not necessarily correct for representing the properties of a non-linear material. However, it was considered adequate for the purpose of observing the qualitative performance of the structures.

The warm up and the time lag between loading and measurement are essential in obtaining consistent data for measuring a highly damped elastomer like the soft polyurethane used here. Most importantly, the initial deformation cycles will minimize errors due to Mullins effect, the rapid material property change that occurs during the initial cycles of deformation(Mullins, 1969). As an alternative to waiting for deformation stabilization, one can also measure deformation change over a certain time period. Even then, warm up or good temperature monitoring would be desirable as suggested by (Lloyd-Lucas, 1999).

The flexures go under larger deformation than in the FEA analysis. The deformations had to be kept small in FEA for the analysis software to be able to solve. On the other hand, larger deformations were preferred for the experiments for obtaining sufficient measurement resolution. For future improvement, FEA should be able to handle larger deformations if hyper-elastic material models are employed in the analysis instead of linear elastic material models. The X and Y bending measurement would benefit from a higher resolution measurement equipment of, for example, up to 1°. However, it would not be of great use to increase the resolution much further unless test sample production quality control is improved.

4.5.2 Test results

Test results are shown with a fiber configuration schematic at the top and absolute and relative stiffness plots of both the FEA results (middle) and test results (bottom). The FEA rotational stiffness plots are labeled rotX, rotY, rotZ, rot-X, rot-Y, rot-Z. The experimental rotational stiffness plots are labeled KrX, KrY, KrZ, KrnX, KrnY, KrnZ for the same properties. The n's here represent negative directions. The data are to be interpreted mainly by comparing the FEA and test results by looking at the plots. Below are some guides to data interpretation. Some information is repeated from the FEA section as reminder.

The individual FEA predicted values and test data for absolute stiffnesses sometimes match. The suspected reasons for their matching or mismatching are discussed along with the data for the control piece. The main reason for the disagreement is the use of linear elastic model in FEA based on a linearized simple stretching test which is an oversimplification of the hyperelastic nonlinear material. This also means matching results may well be mere coincidences. However, as you will soon see, qualitative performance predictions reasonably match experimental results.

Symmetry of triangles or hexagons in the absolute value plots indicate the similarity of stiffness ratios of X versus Y versus Z stiffnesses in the FEA model and the test specimen. In a triangular plot, if a corner is sharper, that degree of freedom is stiffer relative to the others. Conversely, a blunt corner indicates relative flexibility. The shape and size of these triangles or hexagons are important in real application. However, the relative stiffness plots are more meaningful for understanding the stiffening effects of fiber embedding.

The relative stiffening effects can be assessed and compared as follows. The individual values indicate how much the structure has stiffened for each of the degrees of freedom relative to the control piece plotted inside with dashed lines as an equilateral triangle or hexagon. For example, when we want to stiffen up the Y and Z compliances while maintaining X flexible, we want large Y and Z values and small X value. In other words, we want sharp corners for Y and Z and a blunt corner for X for the triangle plot. The symmetry of the triangle or hexagon plots indicates similarity in the relative stiffening effects between the analysis and reality.

Control piece

Please see figure 4.28. The measured Z torsion stiffness for the control piece match that of the FEA. However, the X and Y bending stiffness are approximately half of the predicted values. The main reason for the disagreement is the use of linear elastic model in FEA based on a linearized simple stretching test which is an over-simplification of the hyperelastic nonlinear material. The Z stiffness may have been well predicted since torsional loading mainly imposes extensive stress while bending imposes both extensive and compressive stresses. Hence, using a multilinear material model in the FEA with compressive deformation test data may improve the simulation accuracy.

a01

Please see figure 4.29. The near-symmetry of the triangles in relative stiffness plots indicate similar tendencies in stiffening effects, i.e. small X stiffening, modest Z stiffening, and significant Y stiffening. Please note that the X stiffness has been enhanced much more than predicted on FEA. This probably owes to the fact that fibers have finite bending stiffness and also finite thickness which may add further to the bending stiffness. In addition, the mechanical properties of an elastomer-infiltrated fiber have not been properly characterized. Such information may help improve the analysis.

a02

Please see figure 4.30. There are two possible ways of interpreting the data. By looking at the relative stiffness plots, one might identify the similar inclination angles between Y and -Z axes and -Y and Z axes in both the FEA and experiment plots. Although both Y and Z have stiffened much more than predicted, this could suggest that the +X stiffening was the irregular one which did not stiffen as much assuming that it should have stiffened further along with the Y and Z values. In other words, there was something largely mismatching between the FEA and prototyping regarding the +X stiffness. The -X can be ignored since its values are very close to unity in

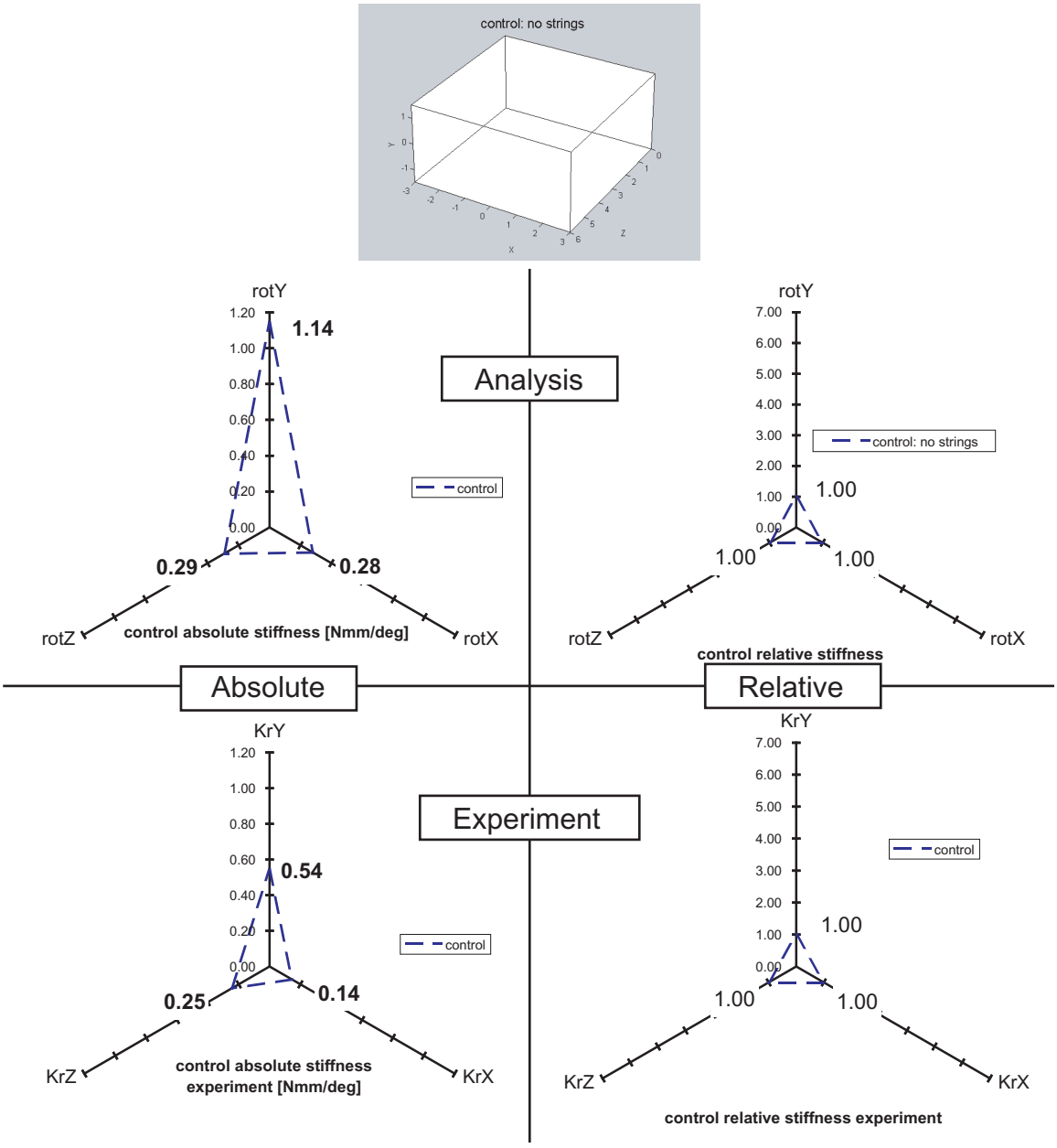


Figure 4.28: Comparison of FEA and test results for the control piece

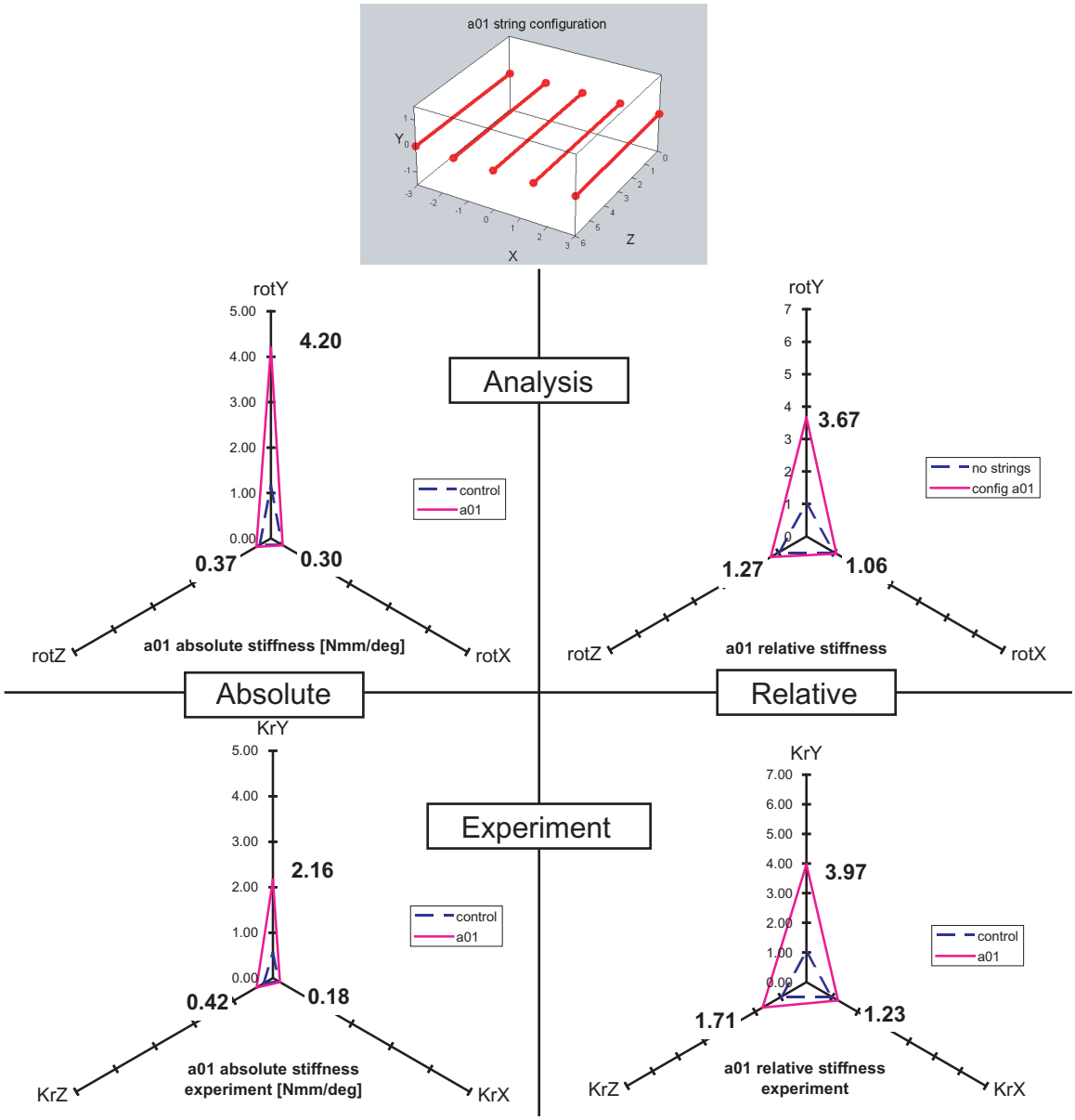


Figure 4.29: Comparison of FEA and test results for a01

both plots. The alternative interpretation is the exact opposite of this, that is to say X is the regular one and Y and Z are the irregular. Something caused the Y and Z to stiffen up much further than the analysis prediction due to discrepancies between FEA modeling and prototyping.

Thorough observation and consideration of data and analysis and prototyping conditions for all of the tested configurations suggest that the first reasoning better describes the reality. Y and Z relative stiffening primarily owing to fibers running lengthwise in the side planes show somewhat larger values than predicted. This may be partly explained by the undervalued stiffness of the fibers in FEA both in stretching and bending but the truth is unclear. However, this is considered a relatively minor error in the larger scope of the problem. The same goes for the slightly larger stiffening effect of X stiffness by the side diagonal fibers. X stiffening by top surface lengthwise-running fibers and Z stiffening by side plane diagonal fibers both indicate smaller values than the FEA prediction. This may be because of the inward offset positioning of the fiber ends at the anchor blocks as discussed in the fabrication section. The amount of offset of the anchor points from the side and top and bottom faces are about the same. However, the relative offset compared to the thickness is much larger than that compared to the width. Hence, the height wise offsetting diminished the X and Z stiffening while the widthwise offsetting did not diminish Y stiffening. Another observation made among the plots was that the Y stiffening owing to the diagonal fibers in the side planes, for example in a05, is more influential than predicted. This could well be explained by the reduction of angles of the fibers. The fibers are close to the lengthwise orientation, which is more ideal for preventing Y deformation and less ideal for preventing Z deformation.

These observations will be pointed out configuration by configuration in the subsequent comments.

a05

Please see figure 4.31. The diagonal fibers in the side planes contribute to more-than-predicted enhancement of the Y stiffness and less-than-predicted stiffening for Z. This has previously been explained as the influence of height wise offsetting of fiber end

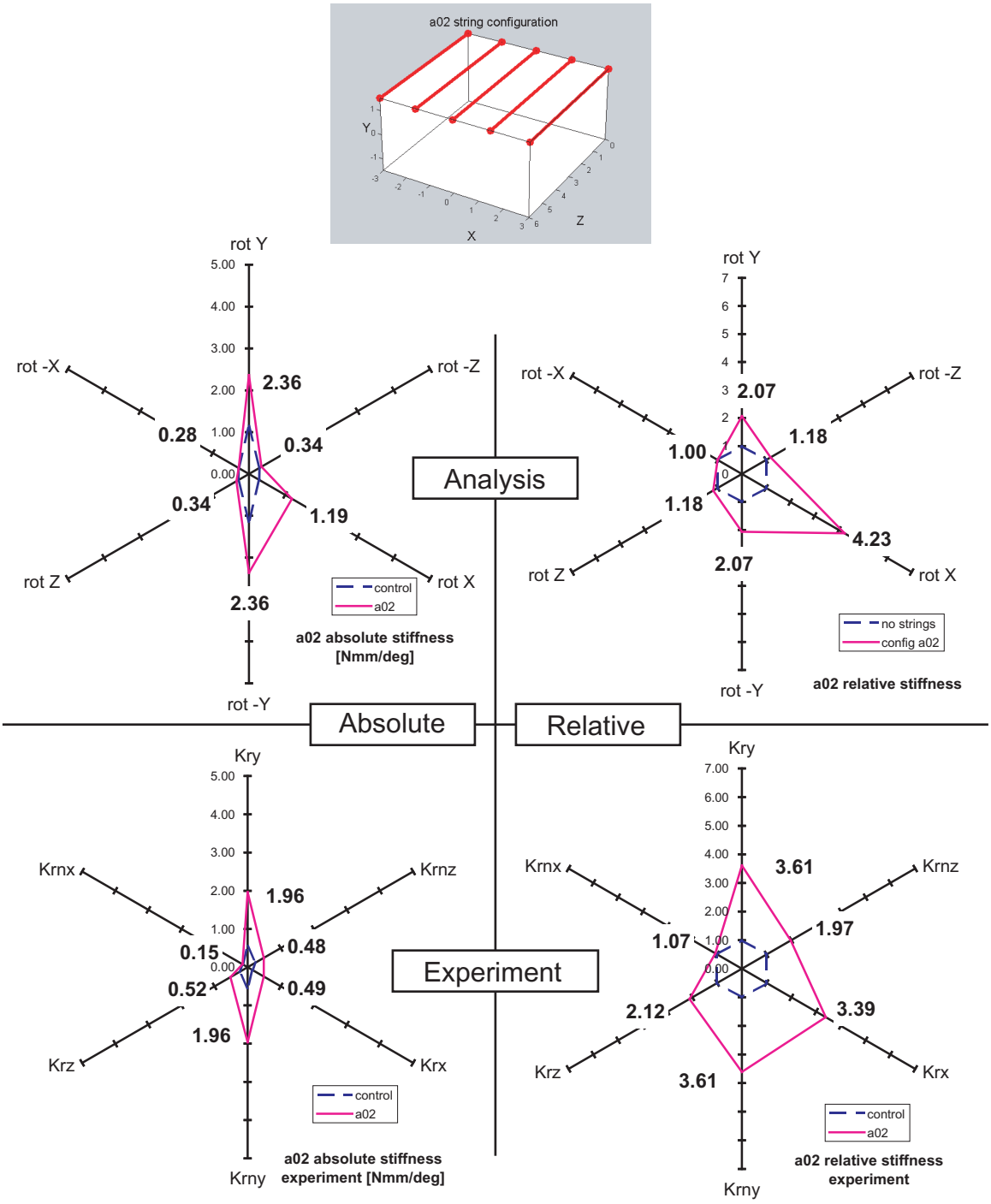


Figure 4.30: Comparison of FEA and test results for a02

locations.

a12

Please see figure 4.32. Again, the Y stiffness is enhanced further and Z stiffness is increased less than predicted by side-plane diagonal fibers.

a19

Please see figure 4.33. The same tendencies follow from a05 and a12. The middle fibers in the side planes also successfully add to the Y stiffening.

a21

Please see figure 4.34. Results are similar to a19.

4.5.3 Error quantification

Some follow up experiments and analyses were done to quantify the sources of error in stiffness prediction using FEA.

Experiments for X bending under various loads revealed nonlinearity, showing lower stiffnesses at larger deflections. The X-bending results for the non-reinforced control piece indicate +100% difference between the experimental data 0.14[Nmm/deg] measured at around 100° deflection and the analysis data 0.28[Nmm/deg] at 21°. The large difference is due to the nonlinearity which cannot be properly represented with FEA using a simple linear elastic material model. However, the analysis result is very close to the interpolated experimental stiffness at 21°, 0.25[Nmm/deg]. Here, the error is only +12%. This suggests that bending stiffness analysis error on FEA can be reasonably small, i.e. 10% or so, at limited deflections of up to about 20° when compared to experimental results at equal deflection. On the other hand, simplified analyses for larger deflections result in errors as large as +100% since the stiffness remains basically constant in the FEA which does not reflect reality. Application of proper nonlinear material model and consideration for nonlinear geometric effects should improve the results. Although loads were applied in multiple steps to account

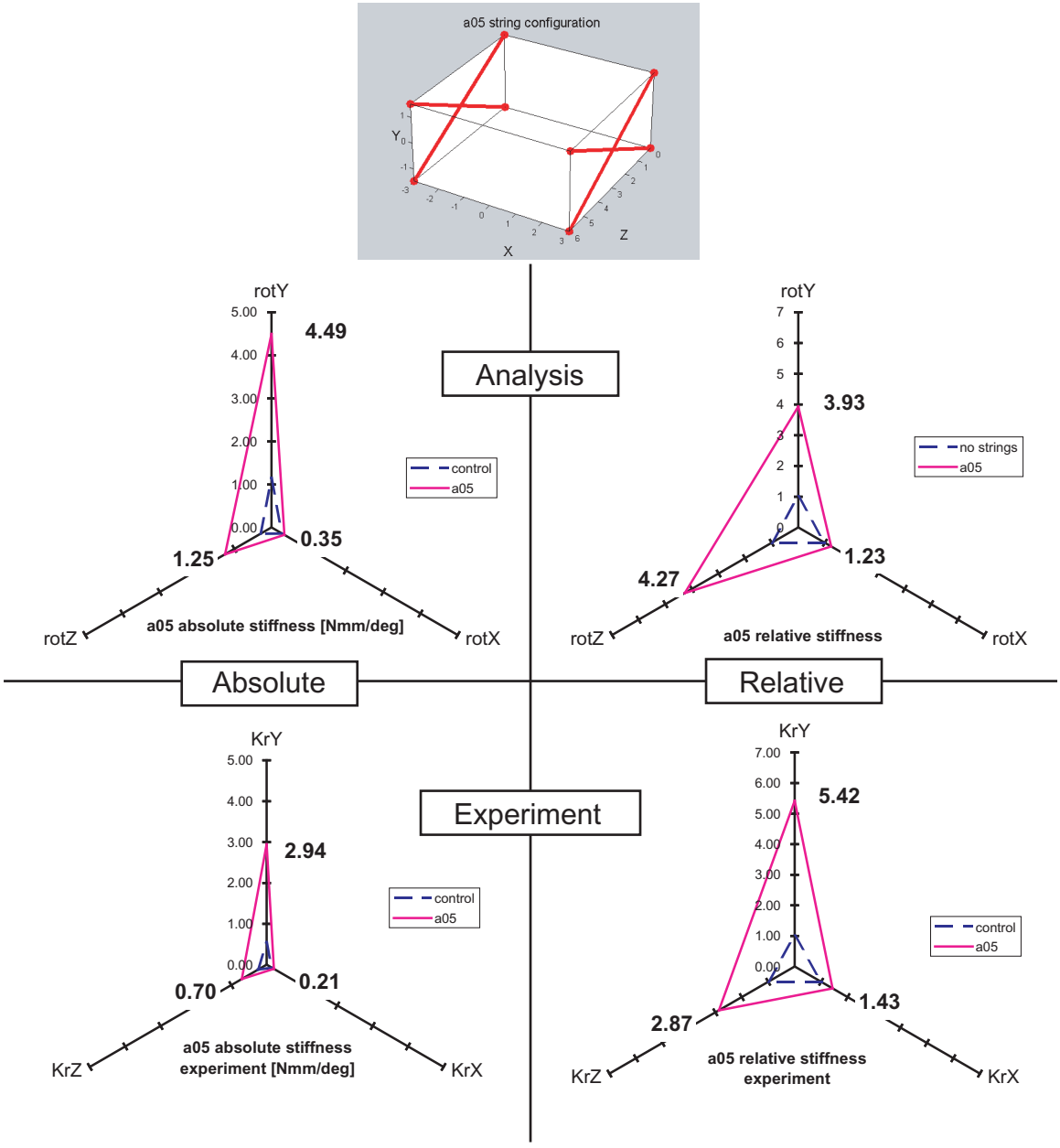


Figure 4.31: Comparison of FEA and test results for a05

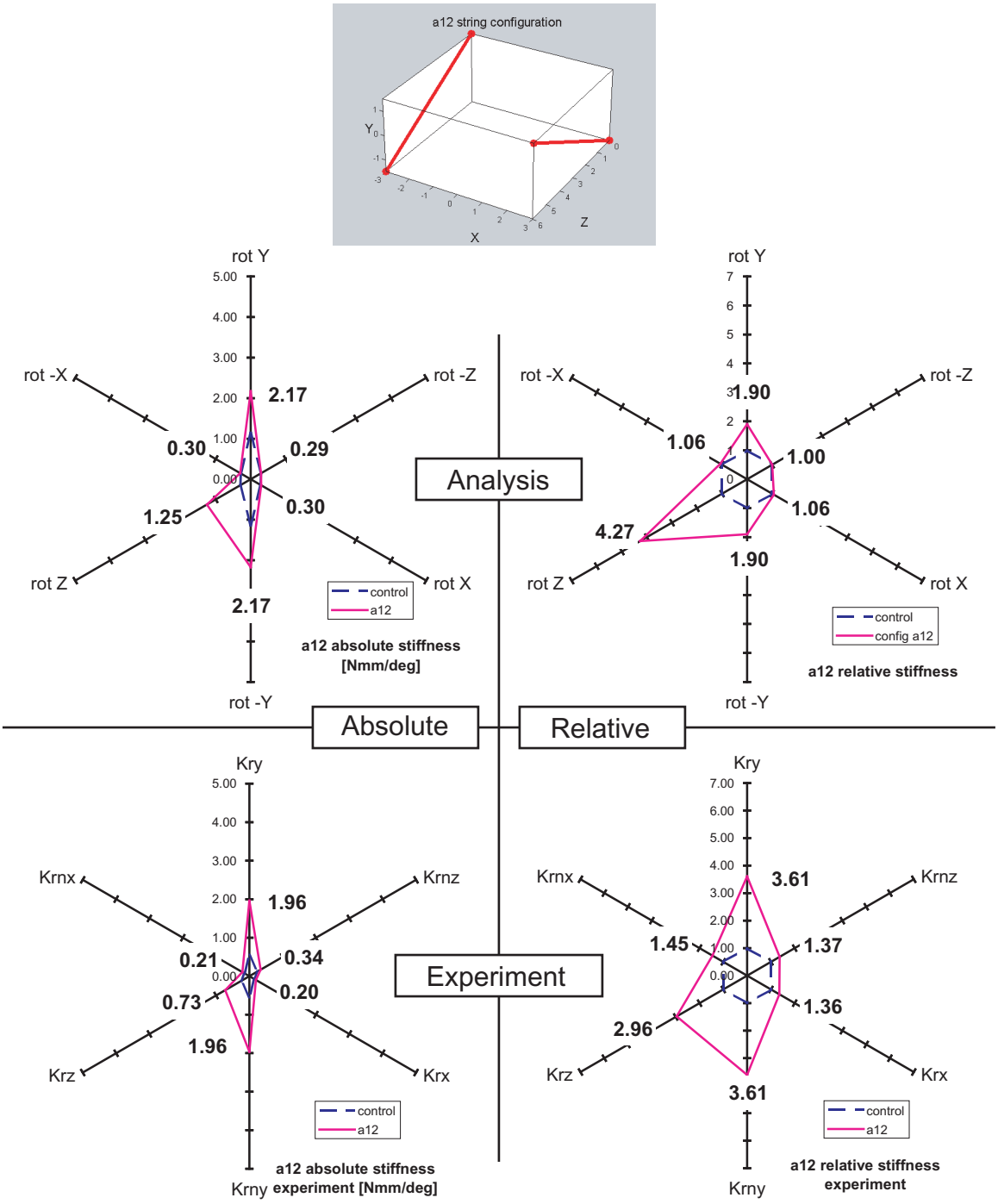


Figure 4.32: Comparison of FEA and test results for a12

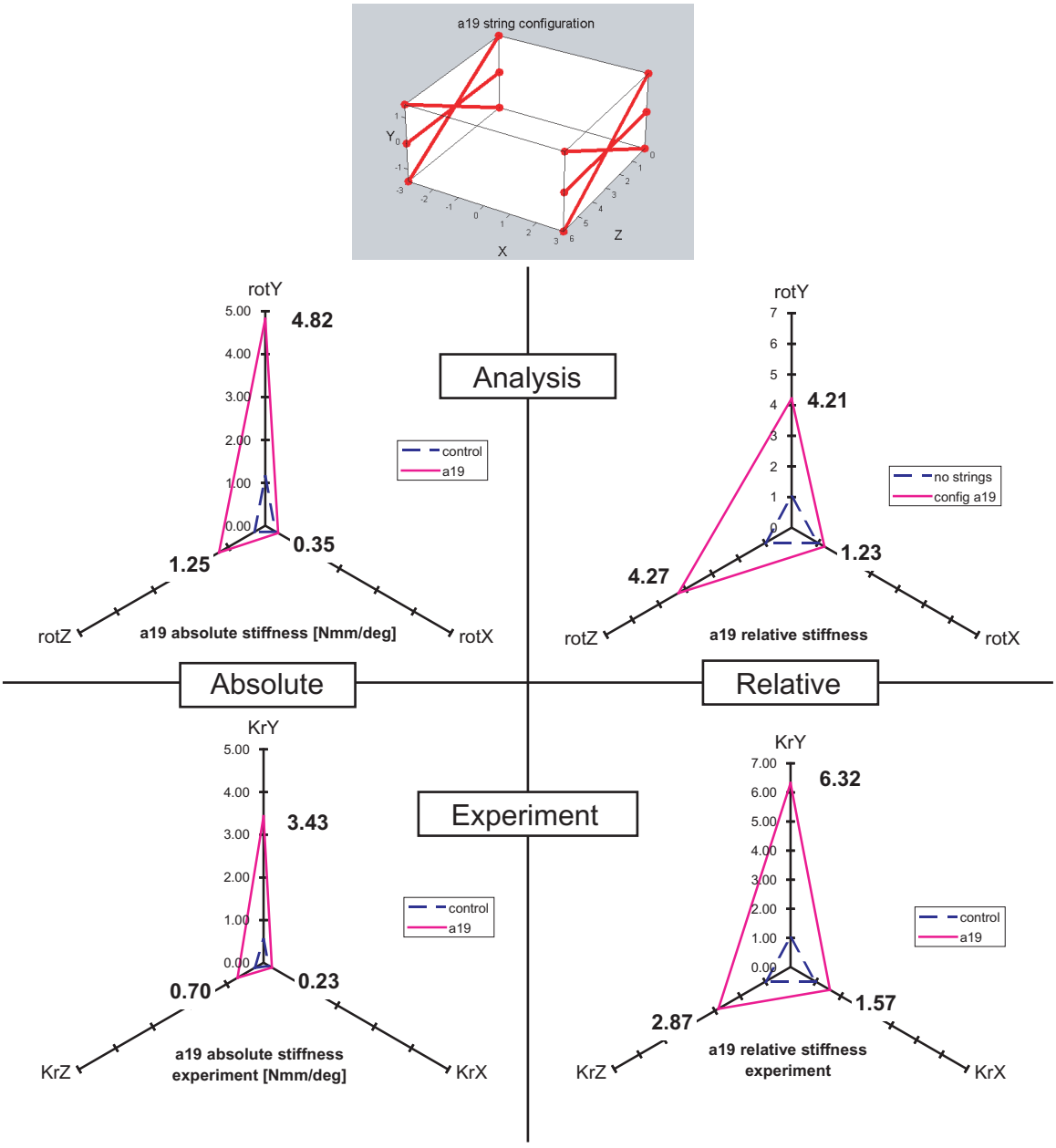


Figure 4.33: Comparison of FEA and test results for a19

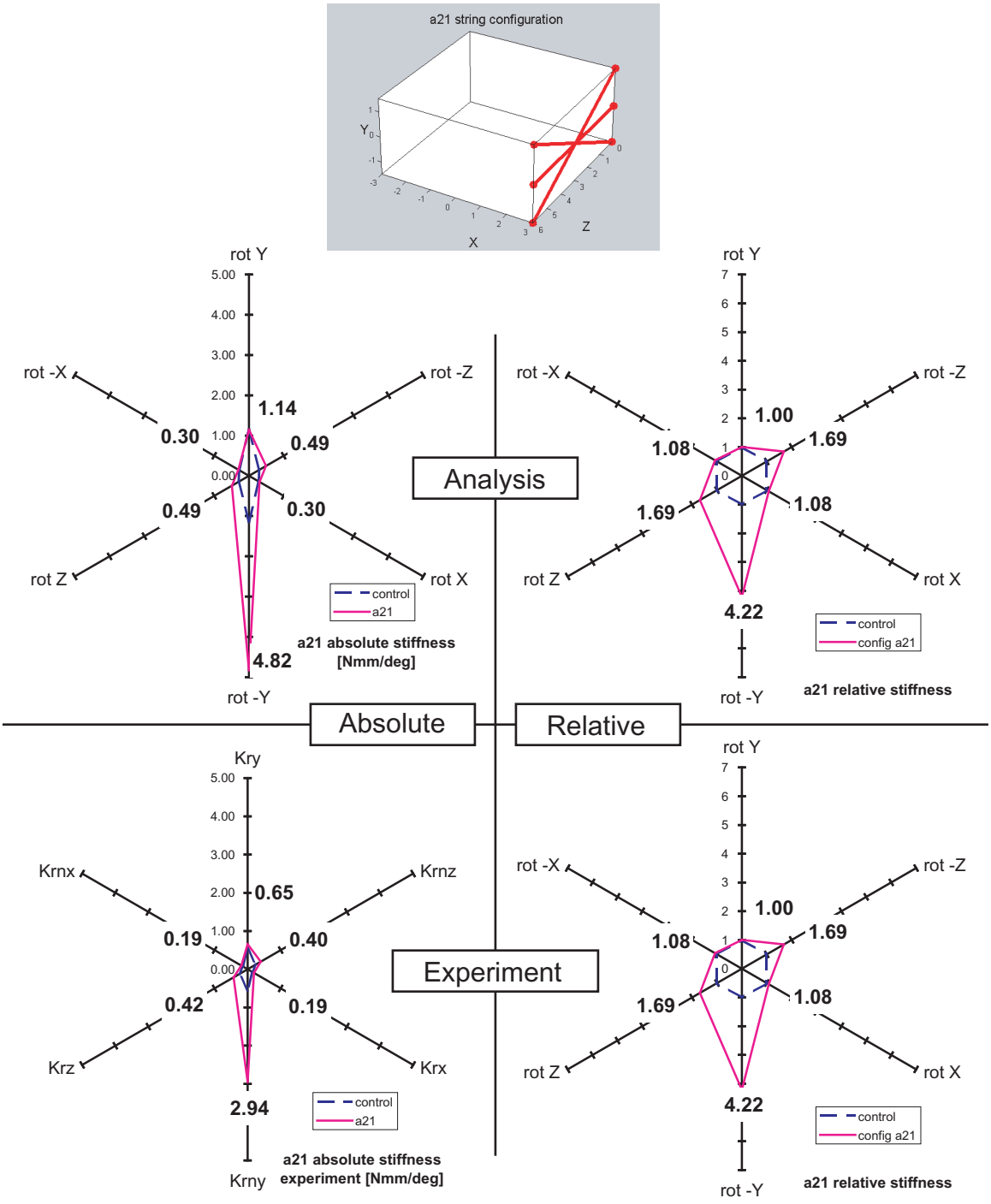


Figure 4.34: Comparison of FEA and test results for a21

for the geometric nonlinearity, that may not have been enough. Adaptive remeshing might be an effective method for improvement. The situation for Y bending is likely to be very similar to that for X bending since they undergo the same kind of deformation.

On the other hand, the experimental results for the torsional stiffness about the Z axis remained largely constant up to around 90°. The FEA results also indicated constant stiffness over a wide range. This enabled the FEA to provide a reasonable estimation of the torsional stiffness even though the experiment and analysis were done at different angles, 90° and 30° respectively. The error was only +16% and this may even simply be due to the inaccuracy of the Young's modulus.

Since the elastomer model is most reliable for Z torsion, errors due to fiber positioning and fiber properties were quantified based on torsional deformation. Configuration a05 was selected for the purpose. The experimental and analytical stiffnesses were 0.70[Nmm/deg] at 31° and 1.25[Nmm/deg] at 7.2° respectively. The apparent error here is +79%. However, this computed value is in fact 303% more than the experimental result of 0.31[Nmm/deg] measured at 10° which is closer to the deflection in the analysis. The error is significant. The experimental results also indicate the nonlinearity in stiffness at different deflections. In a modified FEA model in which the fiber positioning was adjusted to reflect the reality better, stiffness at 10° deflection was 0.45[Nmm/deg] which is +45% off the experimental value but still much better than before. This strongly suggests that proper representation of fiber location is very important. The +45% error is partially due to the elastomer modeling which indicated +16% error in the previous paragraph. The remaining, 29% by simple subtraction, would be due to the inappropriate fiber modeling which should have included initial tension or slack condition, nonlinearity in tensile stiffness, and bending stiffness. In addition, fiber-elastomer bonding condition may not have been so well represented and lengthwise compressive stiffness may also have influenced. Experimental testing of an elastomer-infiltrated fiber would probably help construct a better model.

Several iterations were also made on the analysis for improved representation of the elastomer. However, none of them were successful. Finer meshes with two to

eight times more elements did not improve the nonlinearity representation. Yeoh model for natural rubber was incorporated in an otherwise identical setup to observe the general effect of material nonlinearity. However, the resulting torque-deflection relationship turned out to be just as linear as prior results done with linear elastic elements. Here, a published Yeoh model for natural rubber (55pph CB) was used since no hyperelastic material models were available for the particular polyurethane that was used in the prototypes (Bergstrom, 2005). It was also not possible to obtain better results by altering the Poisson's ratio in the linear elastic model.

4.5.4 Test conclusion

Test results were quantitatively different from the FEA predictions. However, qualitative tendencies proved to be similar and discrepancies could also be explained. The main sources of error are thought to be the simplified FEA model using linear elastic elements and offsetting of fiber end positions in manufacturing. Fine tuning of the FEA model was not done because the material properties in required form (Mooney-Rivlin or Ogden model) were not available and meaningful quantitative predictions cannot be expected without them. The tests showed the validity of FEA as a qualitative prediction tool even with simplified material models.

4.6 Strength test

Selected samples (non-reinforced control piece and reinforced pieces with configurations a01, a02, a05, and a06) were tested for failure strength by hanging weights. Ultimate failure load and failure deformation were compared with those of a non-reinforced flexure. Failure modes were also observed for design improvement. The results are shown in table 4.1. Photographs of the broken flexures are shown in figures Figure:failphotoa08, Figure:failphotoa01, Figure:failphotoa02, Figure:failphotoa05, and Figure:failphotoa06.

The fiber-reinforced flexures could bear roughly two to three times larger load than an un-reinforced flexure. The ultimate deformation size varies. For all of the observed

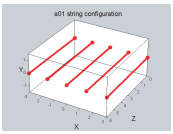
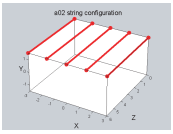
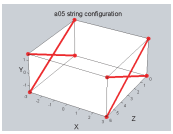
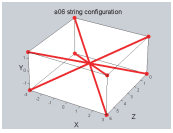
	X-bend	Y-bend	Z-torsion
Control	Max strain 110° reached at 2[N] or 30[Nmm.] Ultimate failure around 70[N] due to material interface debonding at anchor face.	Failure at 100° with 5[N] load or 75[Nmm] torque. Material interface debonding at anchor face.	Failure at 210° with 53[Nmm] torque. Material interface debonding at anchor face.
a01 		Failure at 100° with 10[N] load or 150[Nmm] torque. Material interface debonding with fiber stretch, followed by fiber breakage.	
a02 	Max strain 110° reached at 7[N] or 105[Nmm]. Minor debonding with 50[N] load, still OK at 100[N]. Held up to about 150[N] in failure process.		
a05 			93° torsion at 53[Nmm] load. Ultimate failure at around 155[Nmm]. Failure mode and deflection N/A. (Less than 180°.)
a06 			Material interface debonding observed around 155[Nmm]. Ultimate failure at around 187[Nmm] with >330° torsion. Elastomer breakage along string led to final failure.

Table 4.1: Strength test results

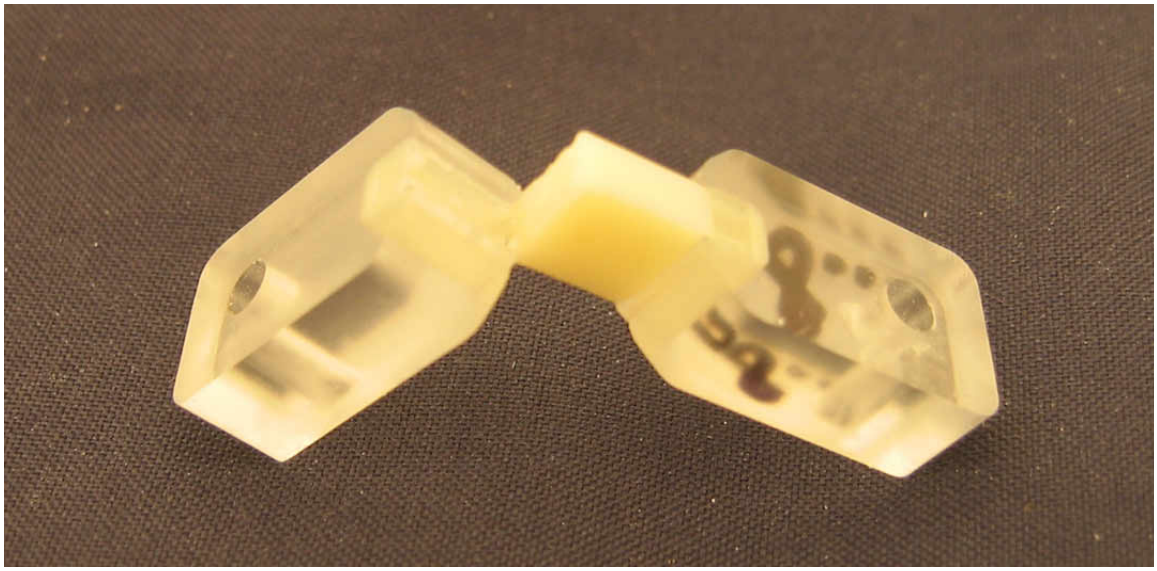


Figure 4.35: Photograph of failed a08

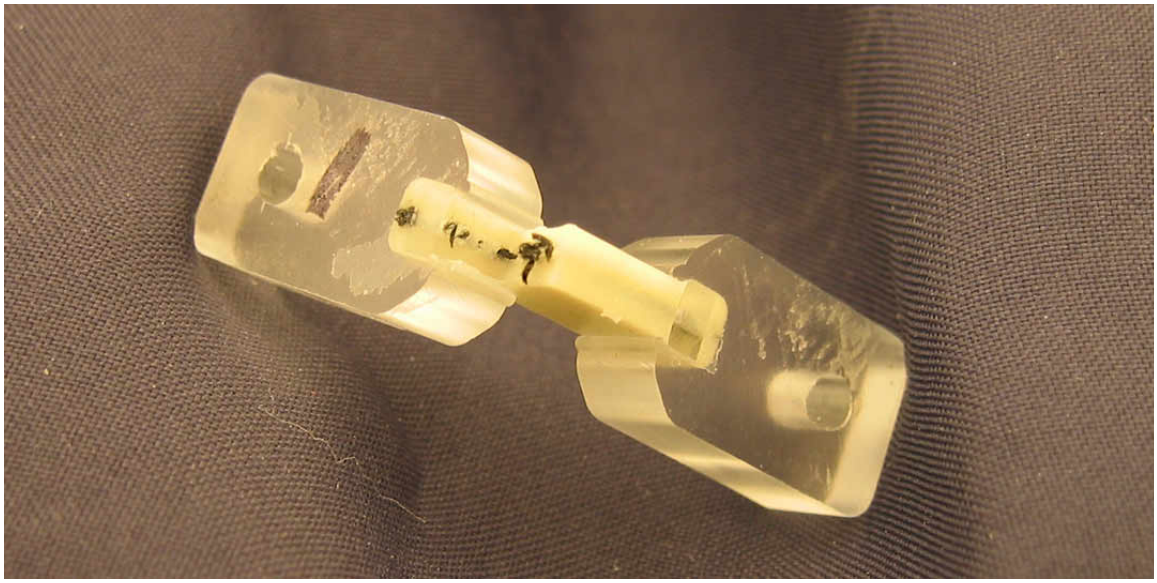


Figure 4.36: Photograph of failed a01

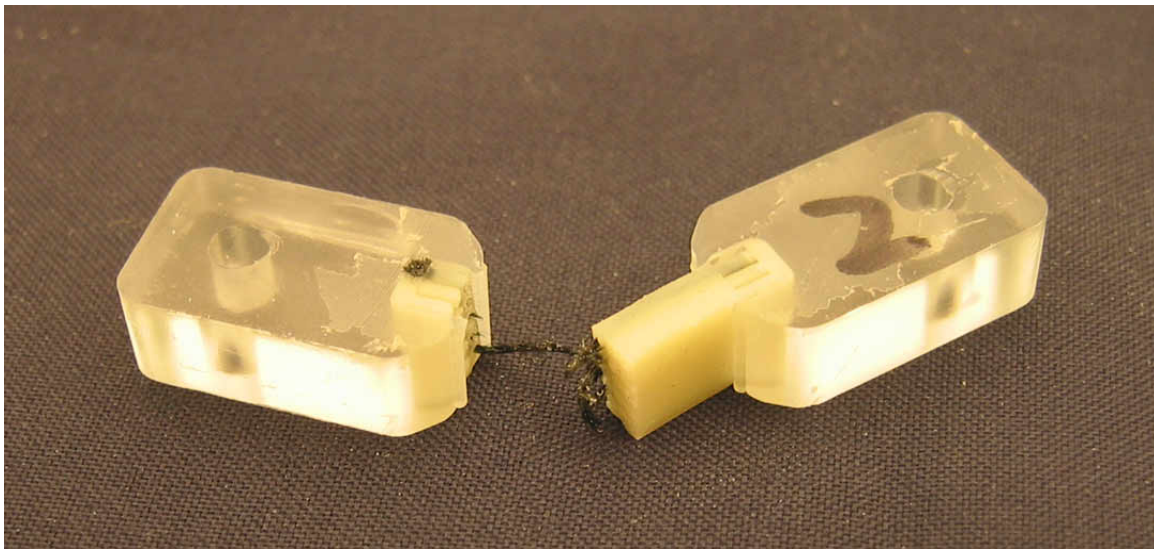


Figure 4.37: Photograph of failed a02

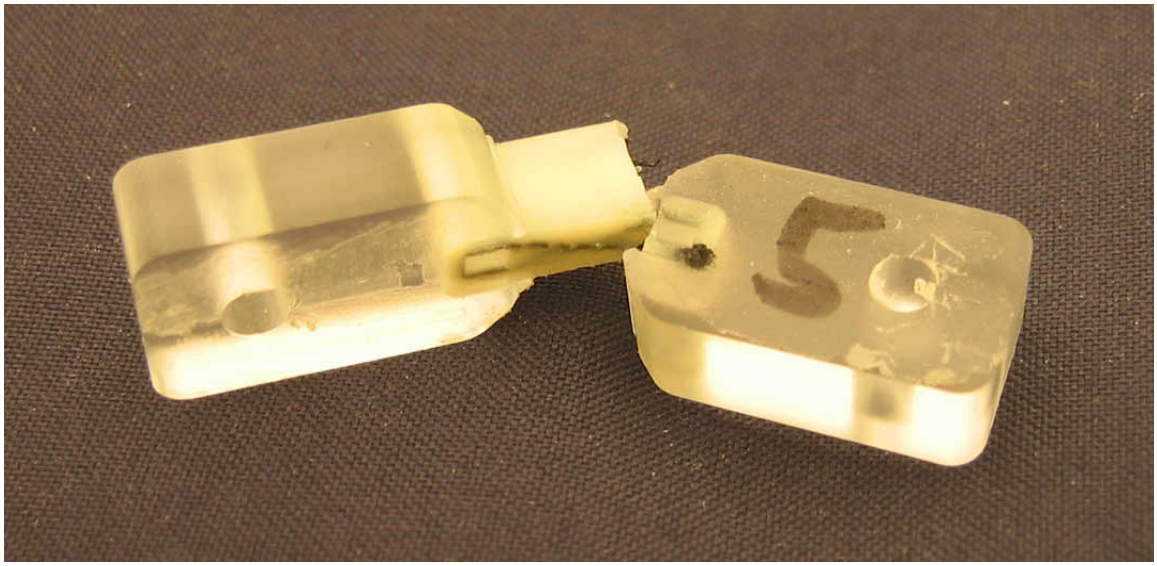


Figure 4.38: Photograph of failed a05

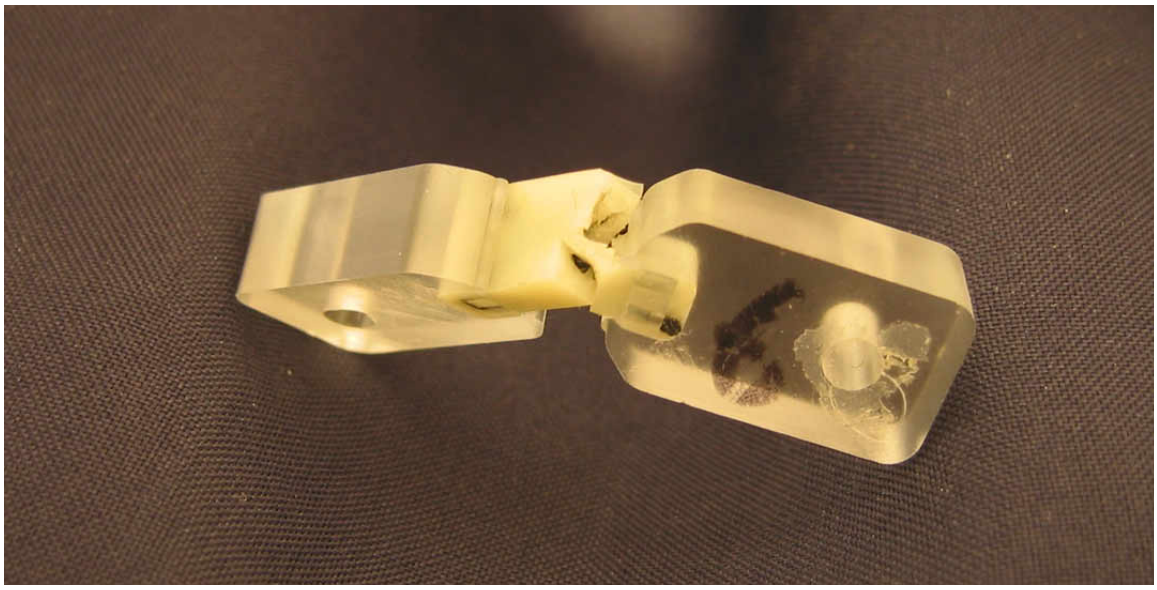


Figure 4.39: Photograph of failed a06

samples, failure initiated at the material interface between the flexure elastomer and the rigid anchor piece. The failure mode could not be observed on a05 since it took place very quickly. In a01 and a02, it was followed by fiber extension and breakage resulting in complete interfacial debonding and total failure. A similar failure mode is suspected to have happened for a05 as well. However, a06 exhibited a different pattern of failure. The flexure elastomer broke along the reinforcement fibers.

A06 was a configuration that indicated no significant stiffening effects in the finite element analysis. This suggests that the fibers do not bear much load against strain. Not to our surprise, it showed no significant torsional stiffening effect experimentally either. However, experimental results showed high ultimate load and deformation. The fibers seem to have reduced stress at the materials interface preventing debonding and failure. The detailed mechanism of this change in stress condition is yet to be discovered.

Fiber breakage occurred in or behind the anchor pieces except for a06(fibers broke near the center). Debonding between the flexure elastomer and the fiber was also observed in the form of fiber pull-out. Close observation of the fibers indicate no firm

evidence of elastomer infiltration.

In general, stiffening fibers can strengthen a flexure in terms of ultimate load. The amount of deflection at failure varies. It is expected that the reinforced flexures can bear the similar amount of deflection as a non-reinforced flexure after fiber breakage though the load would also be of similar magnitude. As shown by a06, non-stiffening fibers can also help increase ultimate strength both in load and deflection.

Several measures can be taken for improving the strength. Inter material debonding can be strengthened by more even stress distribution and load bearing by the reinforcement fibers. Changing the anchor surface properties, geometry, and location would also be effective. Fiber failure can be inhibited by using more fibers or stronger fibers, be it a different material or simply a thicker fiber. Failure of the elastomer can be inhibited by adding extra reinforcement fibers.

4.7 Chapter conclusion

Design, analysis, and fabrication methods were developed and verified for anisotropic stiffness modification of elastomeric flexure joints using embedded fibers. Identification of major principal strain vectors helps determine where fibers should be embedded. The strains pertaining to unwanted deformations should be suppressed and those related to desired deformations should be kept uninterfered. Finite element analysis based on simplified models provides sufficient qualitative information about the fiber stiffening. Here, flexure material was modeled as linear elastic material despite its hyperelastic nonlinearity, and fibers were modeled as linear elastic elements that only resist tension and not compression or bending. Despite some limitations in fabrication, the prototypes indicated qualitative consistency with the FEA predictions and proved the concept. The major limitations were in keeping consistent fiber tension and in positioning the fiber ends close to the flexure faces as possible. Stiffening fibers also help improve the flexure strength in terms of loading. Even non-stiffening fibers can improve strength.

4.8 Future directions

There are three categories for future directions, namely improving the state of the art, discovering the unknown, and exploring further possibilities. The analysis and fabrication methods already tried can be improved. There are unknown properties about the flexures yet to be discovered. There are also new technological developments that can be explored based on the current knowledge.

4.8.1 Improvements

As have been repetitively mentioned, the FEM model is not accurate enough to provide quantitative predictions. The starting point is the elastomer material characterization to obtain Mooney-Rivlin or Ogden models that would enable better modeling. Proper nonlinear modeling of the fiber would also be desirable. Its bending and compressive stiffnesses may or may not be useful, and that is also to be determined. Once the fiber end positions are better known, modifying them in the model to better represent reality would also help tune the simulation.

Fabrication can also be improved. To make the effective fiber stiffness (i.e. stiffness including the pretension) more consistent, stiffer support structure is desirable for the anchor assembly and a stiffer fiber would reduce stiffness variability. Using additional devices such as weights for tensioning and ball bearing for reducing fiber friction seem unrealistic for the current hardware size. However, they may be applicable for larger scale production.

Strength can be improved by various design changes. This includes alterations in fiber configuration, component geometry and materials. Better strength is essential for providing reliable components for real applications.

4.8.2 Discovering the unknown

Long term effects of fiber stiffening are yet to be discovered. Stress concentration at the fiber-elastomer interface may cause fatigue failure under repetitive loading and result in fiber pull-out or possible slicing effect by fibers pressing against the

elastomer, similar to those observed in strength testing. These properties must be properly understood for assuring reliable long term performance of the structure.

Another unknown is the influence to dynamic performance. Fibers added stiffness anisotropically. Though the effects might be less significant, they may also influence damping properties. If not, one can also think about other ways of performing anisotropic damping modification. For example, loosely bonded embedded fibers may add some damping effect in the form of friction loss or energy dissipation when breaking bonds.

4.8.3 Further applications

The strain distribution analysis results are especially useful for other related applications. One of the uses of the information is for avoiding large strains from occurring in fragile or sensitive embedded components. For example, electric signal or power lines embedded inside a flexure should usually be routed in the less straining area. Similarly, stiff components should be embedded in the non-straining locations if the flexibility is to be maintained. (An exception is when the lines are to be loaded acting as structural reinforcement.)

Another area of application is sensor design and fabrication. Custom strain gages constructed by embedding thin wires along the high-strain lines may provide a new robust sensing solution for various applications including robots and medical devices, both of which are often exposed to harsh environments. The embedded sensor elements are protected from the environment and the vice versa is also true which, for example in the case of medical devices, eliminates the risk of sensor elements hurting the patient. Similarly, actuators and variable stiffness flexures may be produced by embedding shape memory alloy wires.

Moreover, replacement of discrete joints such as pin joints and ball joints is yet another area of application. As mentioned in the motivations section, some applications which dislike contamination from lubrication and/or debris would particularly benefit from a flexural joint. The typical areas include space and surgical applications. However, fatigue of the flexure may remain as a challenge when replacing discrete

joints that undergo large number of cycles.

Chapter 5

Conclusion

5.1 Summary

Several new fabrication and design methods for shape deposition manufacturing were developed, tested, and evaluated. Developments in fabrication included new fixturing solutions for embedding flexible components and methods of cross-boundary embedding and its emulation. The new design method is for anisotropic strength modification of elastomeric flexures by fiber reinforcement. The new developments enable the design and production of multimaterial flexural mechanisms that are functionally integrated and structurally improved which may bridge the gap between conventional flexural and discrete joints.

5.1.1 Developments in fabrication

Criteria for flexible component fixturing are stiffness for reliable handling during manufacturing and flexibility to deform afterwards. (If the component no longer has to deform after being embedded, then the fixturing would only have to provide stiffness.) Pre-encapsulation added adequate stiffness permanently for handling while keeping it flexible enough for the post-manufacturing application. Suspending fixtures provided stiffness temporarily and were removed after the component embedding for

it to regain flexibility. The suspending fixture method is also applicable in rigid-component embedding for potential labor, time, and material savings.

Cross-boundary embedding methods were organized around selective removal or selective deposition of part or sacrificial material. One selective (=controlled) process has to be involved in a cross-boundary embedding process. Photolithography is a variation of the selective removal process. Some of the cross-boundary benefits can be emulated by alternative processes in which the embedded components do not cross boundaries. These are named the pseudo-boundary formation method and the pre-encapsulation method. The methods have yet to be refined and also developed, for example to enable vertical cross-boundary embedding.

5.1.2 Developments in design

Design method was developed for anisotropic stiffness modification of elastomeric flexures with fiber reinforcement. Fibers are used to selectively constrain extensive strain for undesired modes of deformation while maintaining that freedom for desirable modes of deformation. Finite element analysis using simplified models could provide reasonable qualitative performance predictions. Fabrication was done using the suspending fixture method. Strengthening effects were also identified in both stiffening and non-stiffening fiber configurations. Fabrication and analysis techniques are to be improved. The flexure properties are to be better understood and improved accordingly. Some of the findings can already be applied for determining component embedding locations and sensor fabrication.

5.1.3 Application

Integrated flexure-based multimaterial functional mechanisms can be created applying the technology discussed in this dissertation. For example, the robot leg linkage mentioned in Chapter 3 figure 3.16 can be improved both structurally and functionally. To be more precise, the flexures can have fiber reinforcement and have added torsional stiffness hence reduced flimsiness upon actuation. Links can have contact and force sensors, and the information can be transferred to a CPU in the main body

via embedded wiring that runs across joints. Such applications will greatly enhance the potential for demanding mechanical and mechatronic systems.

5.2 Beyond SDM

The research work was based on SDM and the newly developed methods remained primarily within its realm. However, integration with other technologies will open up possibilities. For example, selective deposition of materials using methods such as FDM is applicable for cross-boundary embedding. Fiber-reinforced flexures may encourage wider applications of such elastomeric hinges in industry.

Bibliography

ABAQUS (2005). http://www.abaqus.com/.

Adkins, J. and Rivlin, R. (1952). Large elastic deformations of isotropic materials. ix. the deformation of thin shells. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 244(888):505–531.

Adkins, J. and Rivlin, R. (1955). Large elastic deformations of isotropic materials x. reinforcement by inextensible cords. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 248(944):201–223.

Akasaka, T. (1959). Various reports/bulletins, 1959-64. Technical report, Faculty of Science and Engineering, Chuo University.

Akasaka, T. and Yoshida, N. (1972). In *Proc. Intl. Conf. Mech. Behavior of Mater.*, volume 5, pages 187–197. Kyoto, Japan.

Alley, V. and Fairslon, R. (1972). Experimental investigation of strains in a fabric under biaxial and shear forces. *J. Aircraft*, 9(55).

ANSYS (2005a). Structural analysis guide.

ANSYS (2005b). www.ansys.com.

Arruda, E. M. and Boyce, M. C. (1993). A three-dimensional constitutive model for the large stretch behavior of rubber elastic materials. *Journal Mech. Physics Solids*, 41:389–412.

Ashby, M. (1999). *Materials Selection in Mechanical Design*. Butterworth-Heinemann, Oxford, UK, second edition edition.

AxelProducts (2000). Testing elastomers for hyperelastic material models in finite element analysis, http://www.axelproducts.com/downloads/testingforhyperelastic.pdf.

Bailey, S. A., Cham, J. G., Cutkosky, M. R., and Full, R. J. (2000). Biomimetic robotic mechanisms via shape deposition manufacturing. In Hollerbach, J. and Koditschek, D., editors, *Robotics Research: the 9th intl. Symposium*. Springer-Verlag, London.

Bergstrom, J. (2005). www.polymerfem.com.

Biderman, V., Gusliter, R., Sakharov, S., Nenakhov, B., Seleznev, I., and Tsukerberg, S. (1963). Automobile tires, construction, design, testing and usage. *NASA*, TT F-12(382). Original publication in Russian, State Scientific and Technical Press for Chemical Literature, Moscow.

Binnard, M. (1999). *Design by Composition for Rapid Prototyping*. Ph.d. thesis, Stanford University.

Binnard, M. and Cutkosky, M. R. (1998). Building block design for layered shape manufacturing. In *Proceedings of ASME DETC98, September 13-16, 1998, Atlanta, GA, 1998*.

Bloomenthal, M., Riesenfeld, R., Cohen, E., Fish, R., and Drake, S. (2001). Rapid manufacturing with custom fixturing. *IEEE Robotics and Automation Magazine*, pages 25–32.

Cadge, D. and Prior, A. (1999). Finite element modelling of three-dimensional elastomeric components. In Boast, D. and Coveney, V., editors, *Finite Element Analysis of Elastomers*, pages 187–206. Professional Engineering Publishing, London.

Cham, J., Pruitt, B., Cutkosky, M., Binnard, M., Weiss, L., and Neplotnik, G. (1999). Layered manufacturing with embedded components: Process planning issues,

paper detc99/dfm-8910. In *Proceedings of the 1999 ASME DETC/DFM Conference*. Las Vegas, NV.

Cham, J. G., Bailey, S. A., Clark, J. E., Full, R. J., and Cutkosky, M. R. (2002). Fast and robust: Hexapedal robots via shape deposition manufacturing. *The International Journal of Robotics Research*, 21(10).

Chou, T.-W. (1992). *Microstructural Design of Fiber Composites*. Cambridge University Press, Cambridge, UK.

Chou, T.-W. and Takahashi, K. (1987). Nonlinear elastic behavior of flexible fiber composites. *Composites*, 18(25).

Clark, J. E., Cham, J. G., Bailey, S. A., Froehlich, E. M., Nahata, P. K., Full, R. J., and Cutkosky, M. R. (2001a). Biomimetic design and fabrication of a hexapedal running robot. In *Intl. Conf. Robotics and Automation (ICRA2001), Seoul, Korea, May 21-26 2001*.

Clark, J. E., Thelen, D., and Cutkosky, M. R., editors (2004). *Dynamic Simulation and Analysis of a Passively Self-Stabilizing Hexapedal Running Robot*. Proceedings ASME IMECE 2004, Anaheim, CA, November 13-20, 2004.

Clark, J. E., Xia, L., and Cutkosky, M. R. (2001b). An interactive aid for designing and planning heterogeneous layered prototypes. In *Proceedings of the 2001 ASME DETC/DFM Conference*. Pittsburgh, Pennsylvania, USA.

Clark, S. (1963a). Internal characteristics of orthotropic laminates. *Textile Res. J.*, 33:935–953.

Clark, S. (1963b). The plane elastic characteristics of cord-rubber laminates. *Textile Res. J.*, 33:295–313.

Clark, S. (1964). A review of cord-rubber elastic characteristics. *Rubber Chem. Tech.*, 37:1365–90.

Cooper, A. (1999). *Fabrication of Ceramic Components Using Mold Shape Deposition Manufacturing*. Ph.d. thesis, Stanford University.

Daley, J. and Mays, S. (1999). The complexity of material modelling in the design optimization of elastomeric seals. In Boast, D. and Coveney, V., editors, *Finite Element Analysis of Elastomers*, pages 119–128. Professional Engineering Publishing Limited, London.

Deckard, C. (1988). *Selective laser sintering*. Ph.d. thesis, University of Texas at Austin.

DeLaurentis, K., Mavroidis, C., and Kong, F. F. (2002). Rapid fabrication of non-assembly robotic systems with embedded components. *IEEE Robotics and Automation Magazine*.

Digiantonio, R. (1992). Two-shot molding of thermoplastic elastomers, http://pages.prodigy.net/plastics101/twoshot.pdf.

Digiantonio, R. (2005). Other molding (co-injection, two-shot, insert), http://pages.prodigy.net/plastics101/other.pdf.

Dohta, S., Ban, Y., and Matsushita, H. , . (2000). Application of a flexible strains sensor to a pneumatic rubber hand. In *Proceedings of sixth triennial international symposium on fluid control, measurement, and visualization (FLUCOME 2000), August 13-17, 2000. Sherbrooke, QC, Canada*.

Feygin, M. and Hsieh, B. (1991). Laminated object manufacturing (lom): A simpler process. In *Proceedings of the Solid Freeform Fabrication Symposium, University of Texas at Austin, Austin, TX, August 12-14, 1991*, pages 123–130.

Gaylord, R. (1958). Fluid actuated motor system and stroking device, u.s. pat. no. 2844126.

Gough, J., Gregory, I., and Muhr, A. (1999). Determination of constitutive equations for vulcanized rubber. In Boast, D. and Coveney, V., editors, *Finite Element*

Analysis of Elastomers, pages 5–26. Professional Engineering Publishing Limited, London.

Gough, V. (1968). Stiffness of cord and rubber constructions. *Rubber Chem. Tech.*, 41:988–1021.

Gupta, B. (1998). Medical textile structures: An overview. *Medical Plastics and Biomaterials Magazine*.

Gupta, B. (2001). Frictional properties of textile materials. In Pastore, C. and Kiekens, P., editors, *Surface Characteristics of Fibers and Textiles*. Marcel Dekker, New York.

Helnwein, P., Liu, C., Meschke, G., and Mang, H. (1993). A new 3d finite element model for cord-reinforced rubber composites application to analysis of automobile tires. *Finite element in analysis and design*, 14:1–16.

Jacobs, P. (1992). *Rapid prototyping & manufacturing: Fundamentals of stereolithography*. Society of Manufacturing Engineers, Dearborn, MI.

Johannknecht, R., Jerrams, S., and Clauss, G. (1999). The uncertainty of implemented curve-fitting procedures in finite element software. In Boast, D. and Coveney, V., editors, *Finite Element Analysis of Elastomers*, pages 141–152. Professional Engineering Publishing Limited, London.

Kataria, A. and Rosen, D. (2000). Building around inserts: Methods for fabricating complex devices in stereolithography. In *Proceedings of the 2000 ASME DETC/DFM Conference, Baltimore, Maryland, September 10-13, 2000*.

Kietzman, J. (1998). *Rapid Protptyping Polymer Parts via Shape Deposition Manufacturing*. PhD thesis, Stanford University.

Kim, S., Clark, J. E., and Cutkosky, M. R. (2004). isprawl: autonomy, and the effects of power transmission. In *CLAWAR 7th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines, September 22-24, 2004*. MADRID, SPAIN.

Li, X., Stampfl, J., and Prinz, F. (1999). Design and fabrication of materials for laser shape deposition manufacturing,. In Cohen, L. e. a., editor, *44th International SAMPE Symposium, Long Beach, May 1999*, volume 44(2), pages 1849–1856.

Li, X. C., Golnas, A., and Prinz, F. (2000). Shape deposition manufacturing of smart metallic structures with embedded sensors. In *SPIE's 7th International Symposium on Smart Structures and Materials 2000, Newport Beach.*

Liou, F. e. a. (2001). Research and development of a hybrid rapid manufacturing process. In *Proceedings of the Solid Freeform Fabrication Symposium*, pages 138–145.

Lloyd-Lucas, F. (1999). Finite element analysis of rubber for product development. In Boast, D. and Coveney, V., editors, *Finite Element Analysis of Elastomers*, pages 152–168. Professional Engineering Publishing Limited, London.

Luo, S.-Y. and Chou, T.-W. (1990). Finite deformation of flexible composites. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 429(1877):569–586.

Luo, S.-Y. and Mitra, A. (1995). An experimental study of biaxial behavior of flexible fabric composite. In Gibson, R., Chou, T.-W., and Raju, P., editors, *Innovative processing and characterization of composite material*. ASME, San Francisco.

Mackerle, J. (1998). Rubber and rubber-like materials, finite-element analyses and simulations: a bibliography (1976-1997). *Modelling and Simulation in Materials Science and Engineering*, 6:171–198.

Mackerle, J. (2004). Rubber and rubber-like materials, finite-element analyses and simulations, an addndum: a bibliography (1997-2003). *Modelling and Simulation in Materials Science and Engineering*, 12:1031–1053.

Madou, M. (2002). *Fundamentals of microfabrication : the science of miniaturization*. CRC Press, Boca Raton.

Mavroidis, C., DeLaurentis, K., Won, J., and Alam, M. (2001). Fabrication of non-assembly mechanisms and robotic systems using rapid prototyping. In *Journal of Mechanical Design, Transactions of the ASME, Dec, 2001*, volume 123, pages 516–524.

McHenry, P. (1988). Adobe construction. In Wilkes, J., editor, *Encyclopedia of Architecture: Design, Engineering and Construction*, volume 1, pages 104–112. John Wiley and Sons, New York.

Merz, R. (1994). *Shape Deposition Manufacturing*. PhD thesis, Technical University of Vienna.

Merz, R., Prinz, F., Ramaswami, K., Terk, M., and Weiss, L. (1994). Shape deposition manufacturing. In *Proceedings of the Solid Freeform Fabrication Symposium, University of Texas at Austin, Austin, TX, August 8-10, 1994*, pages 1–8.

Mitra, A. and Luo, S.-Y. (1994a). The importance of thickness strain on the behavior of flexible fabric composites. In Kwon, Y. and Chung, H., editors, *Recent advances in structural mechanics*. ASME, Chicago.

Mitra, A. and Luo, S.-Y. (1994b). Parameter study of the flexible fabric composite. In Chou, T.-W. and Vinson, J., editors, *Textile structural composites III*. Technomonic publishing co., Lancaster.

Mitra, A. and Luo, S.-Y. (1995). Prediction of biaxial behavior of flexible fabric composite utilizing the uniaxial test results. In Mruthyunjaya, T., editor, *Advances in mechanical engineering, Vol I, Design and Manufacturing*. Narosa Publishing House, New Delhi, India.

MSCsoftware (2005). Marc, http://www.mscsoftware.com.

Mullins, L. (1969). Softening of rubber by deformation. *Rubber Chem. Technol.*, 42:339–362.

Ngo, D. and Scordelis, A. (1967). Finite element analysis of reinforced concrete beam. *J. American Concrete Institute*, 64:152–163.

Nutt, K. (1991). Selective laser sintering as a rapid prototyping and manufacturing technique. In *Proceedings of the solid freeform fabrication symposium, University of Texas at Austin, Austin, TX, August 12-14, 1991*, pages 131–137.

Ogden, R. (1982). Elastic deformation of rubber-like solids. In *Mechanics of Solids*, pages 499–537. Pergammon press.

Park, B. (2002). *Design and fabrication of miniature assemblies with SDM processing*. Ph.d. thesis, Stanford University.

Park, B., Shantz, M., and Prinz, F. (2003). Scalable rotary actuators with embedded shape memory alloys. In *Proceedings of SPIE*.

Peel, L. and Jensen, D. (2000). Nonlinear modeling of fiber-reinforced elastomers and the response of a rubber muscle actuator. In *Proceedings of the 158th Fall Technical Meeting of the Rubber Division, American Chemical Society, Cincinnati, Ohio, October 17-20, 2000*.

Peel, L., Jensen, D., and Suzumori, K. (1998). Batch fabrication of fiber reinforced elastomer prepreg. *SAMPE Journal of Advanced Materials*, 30(3).

Prinz, F. and Weiss, L. (1994). Method for fabrication of three-dimensional articles, u.s. pat. no. 5,301,415.

Rajagopalan, S. and Cutkosky, M. R. (1998). Tolerance representation for mechanism assemblies in layered manufacturing, paper detc98/dfm-5726. In *Proceedings of the 1998 ASME DETC/DFM Conference*. Atlanta, GA.

Rajagopalan, S. and Cutkosky, M. R. (1999). Optimal pose selection for in-situ fabrication of planar mechanisms, paper detc99/dfm-8958. In *Proceedings of the 1999 ASME, DETC/DFM Conference, Las Vegas, NV, Sept 1215, 1999*.

Rajagopalan, S., Goldman, R., Shin, K.-H., Kumar, V., Cutkosky, M. R., and Dutta, D. (2000). Representation of heterogeneous objects during design, processing, and freeform-fabrication. *Materials & Design Journal*, 22(3):185–197.

Ramsay, A. (1999). Recent developments in finite element analysis of elastomeric components. In Boast, D. and Coveney, V., editors, *Finite Element Analysis of Elastomers*, pages 223–234. Professional Engineering Publishing Limited, London.

Reinhardt, H. (1976). On the biaxial testing and strength of coated fabrics. *Exp. Mech.*, 11(71).

Rivlin, R. and Saunders, D. (1951). Large elastic deformations of isotropic materials. vii. experiments on the deformation of rubber. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 243(865):251–288.

Roark, R. J. (1989). *Formulas for Stress and Strain*. McGraw-Hill, New York.

Sachs, E., Cima, M., Bredt, J., and Curodeau, A. (1992). Cad-casting: The direct fabrication of ceramic shells and cores by three dimensional printing. *Man. Rev.*, 5(2):117–126.

Shariff, M. and Stalker, I. (1999). A single constant strain energy function for elastomers and its finite element implementation. In Boast, D. and Coveney, V., editors, *Finite Element Analysis of Elastomers*, pages 41–60. Professional Engineering Publishing Limited, London.

Skelton, J. (1971). The biaxial stress-strain behavior of fabrics for air-supported tents. *J. Mat., J.M.L.S.A*, 6(656).

Stefanini, C., Cutkosky, M. R., and Dario, P. (2003). A high force miniature gripper fabricated via shape deposition manufacturing. In *Proceedings of the 2003 IEEE International Conference on Robotics & Automation, September 14-19, 2003*. IEEE, Taipei, Taiwan.

Stratasys, I. (1991). Fast, precise, safe prototypes with fdm. In *Proceedings of the solid freeform fabrication symposium, The University of Texas at Austin, August 12-14, 1991*, pages 115–122. Austin, TX.

Stubbs, N. and Thomas, S. (1984). A nonlinear elastic constitutive model for coated fabrics. In Nernat-Nasser, S., editor, *Mechanics of Material*, volume 3, pages 157–68. Elsevier science publishers, Amsterdam.

SU-8 (2001). Su-8: a thick photo-resist for mems, http://aveclafaux.freeservers.com/su-8.html.

Suzumori, K. (1996). Elastic materials producing compliant robots. *Robots and Autonomous Systems*, 18:135–140.

Suzumori, K., Koga, A., Kondo, F., and Haneda, R. (1996). Integrated flexible microactuator systems. In *Robotica 1996*, pages 493–498. Cambridge University Press.

Takagi, K. and Suzumori, K. (1996). Development of a new flexible microactuator by finite element. In *Theoretical and Applied Mechanics, Proceedings of the 45th Japan National Congress for Applied Mechanics*, volume 45, pages 9–14.

Tanaka, H., Suzumori, K., and Iikura, S. (1991). Flexible microactuator for miniature robots. In *IEEE MEMS'91, Nara, Japan, February 1991*, pages 204–209.

Tanaka, Y. (1993). Study of artificial rubber muscle. *Mechatronics*, 3(1):59–75.

Tanaka, Y., Gofuku, A., and Fujino, Y. (1996). Development of a tactile sensing flexible actuator. In *Advanced Motion Control '96, Mie University, Tsu-City, Japan, 1996*, pages 723–728.

Turner, D., Boast, D., and Jarosz, R. (1999). Definitions and calculations of stress and strain in rubber. In Boast, D. and Coveney, V., editors, *Finite Element Analysis of Elastomers*, pages 61–74. Professional Engineering Publishing Limited, London.

Wake, W. and Wootton, D. (1982). *Textile Reinforcement of Elastomers*. Applied Science Publishers, Essex, England.

Watanabe, Y. and Kaldjian, M. (1983). Modeling and analysis of bias-ply motorcycle tires. *Computers & Structures*, 17(5-6):653–658.

Weiss, L. E., Merz, R., Prinz, F. B., Neplotnik, G., Padmanabhan, P., Schultz, L., and Ramaswami, K. (1997). Shape deposition manufacturing of heterogeneous structures. *JOURNAL OF MANUFACTURING SYSTEMS*, 16(4):239–248.

Williams, H., Jamil, S., and Coveney, V. (1999). Novel hyperelastic constitutive laws for elastomers. In Boast, D. and Coveney, V., editors, *Finite Element Analysis of Elastomers*, pages 27–40. Professional Engineering Publishing Limited, London.

Xu, X., Cheng, W., Dudek, D., Hatanaka, M., Cutkosky, M. R., and Full, R. J. (2000). Material modeling for shape deposition manufacturing of biomimetic components. In *ASME DFM 2000, September 10-14*.

Yeoh, O. H. (1993). Some forms of the strain energy function for rubber. *Rubber Chem. Technol.*, 66:754–771.