University of Southern Queensland

Faculty of Engineering and Surveying

Evolutionary Structural Optimization for Multi component Structural Systems

A dissertation submitted by

Chuah Yew Pin

In fulfillment of the requirements of

Courses ENG4111 and 4112 Research Project

Towards the degree of

Bachelor of Engineering (Mechanical Engineering with Honors)

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Chuah Yew Pin
Student Number: W0050027400

_____
Signature

_____
Date

Acknowledgement

This thesis was completed within the School of Engineering, Department of Mechanical Engineering at University of Southern Queensland, under the joint supervision of Dr Wenyi Yan and Dr Sai-Cheong Fok. I would like to express my sincere thanks to Dr Wenyi Yan and Dr Sai-Cheong Fok for their kind assistance and advice with guidance throughout this thesis.

Furthermore, I would like to thank to all my friends who were anticipated in the progress of this thesis. Many thanks also extended to my parents for mentally, financial support, and encouragement during my final semester of university.

ABSTRACT

Engineering design problems involve multiple components or structure elements for the consideration of manufacturing, transportation, storage and maintenance. Therefore, it is necessary to develop a design optimization procedure for multi-component structural systems. Several factors like convention, experience and manufacturing play a dominant role in determining the type, positioning and proportioning in the design of a connection pattern. An optimization of interconnection is of great practical significance and capablity to provide reliable solutions to the design of an entire multi-component system. Evolutionary Structural Optimization (ESO) technique has been extensively researched; relatively it proves effective in dealing with a variety of design criteria with single component systems. In this study, the extension of ESO method to the multi-component system with a range of design criteria as minimum utilization of interconnection elements and, maximum overall stiffness will be developed. In other words, ESO is based on the simple idea that the optimal structure (maximum stiffness, minimum weight) can be produced by gradually removing the ineffectively used material from the design domain.

This paper has been extended and proposed to the generic design problems of connection topology. The proposed approach consists of a simple cycle of a finite element analysis followed by a rule-driven interconnection element removal process. The physical concept behind ESO method is intuitive and simple. Evolutionary Structural Optimization (ESO) technique proves effective in dealing with a variety of design criteria with single component systems. The primary goal of this study is to extend the ESO method to multi-component system with a range of design criteria as (1) minimum utilization of materials, (2) maximum overall stiffness, (3) minimum stress and (4) control of natural frequency. The project will integrate the fundamental knowledge of finite element method, numerical sensitivity analysis, design optimization and computer aided design techniques in some practical problems.

Table of Content

Chapter 1 Introduction

Chapter 2 Literature Review   **5**

Chapters 3 Optimization of Interconnection Elements under Single Load Cases

List of Figures

List of Symbols

σ_p	Von Mises stress
σ_{max}	Maximum von Mises stress
RR_{ss}	Rejection Ratio
SS	Addition ratio
ER	evolutionary rate
$[K]$	global stiffness matrix
$\{u\}$	nodal displacement vector
$\{P\}$	nodal load vector.
C	mean compliance
$[K^*]$	stiffness matrix
$[K^i]$	stiffness matrix of the i th element
ε_i	change of the compliance due to the removal of the ith element.

Chapter 1   Introduction

1.1 Introduction

The physical concept behind Evolutionary Structural Optimization (ESO) method is intuitive and simple. The main objective of applying ESO method is to produce an optimum connection of the structure or elements. This objective can be achieved by progressively removing a certain amount of under-utilized material or adding some material to over-utilized regions until the structure evolves towards an optimum. Next few chapters develop a systematic procedure for the positioning of fasteners within the connection design space. At the same time as considering fastener location, the conventional ESO process can be applied to the components being connected, thereby producing an overall approach to the topology optimization of a multi-component structure.

Locations and patterns of connections in a structural system that consists of multiple components strongly affect the performance of the whole structure of design. Hence, it is important in designing the position and patterns of the connections in the system. There are mainly two approaches for topology optimization of continuum structures, namely, homogenization and density methods. The premise of the homogenization method is to compute an optimal distribution of microstructures in a given design domain. Then, the premise of density method is to compute an optimal distribution of an isotropic material.

In real life, engineering design problems involve multiple component or structure elements. Therefore, it is necessary to develop the design optimization procedure for multi-component structural systems. Here, ESO is the proposed method to develop or to improve the design optimization. Finite Element Analysis software is to be used in this project as numerical solutions to even very complicated stress problems can be obtained routinely using FEA. Furthermore, finite element codes are less complicated than many of the word processing and spreadsheet packages found on modern microcomputers.

University of Southern Queensland

Faculty of Engineering and Surveying

ENG4111 & ENG4112 *Research Project*

Limitations of Use

The Council of the University of Southern Queensland, its Faculty of Engineering and Surveying, and the staff of the University of Southern Queensland, do not accept any responsibility for the truth, accuracy or completeness of material contained within or associated with this dissertation.

Persons using all or any part of this material do so at their own risk, and not at the risk of the Council of the University of Southern Queensland, its Faculty of Engineering and Surveying or the staff of the University of Southern Queensland.

This dissertation reports an educational exercise and has no purpose or validity beyond this exercise. The sole purpose of the course pair entitled "Research Project" is to contribute to the overall education within the student's chosen degree program. This document, the associated hardware, software, drawings, and other material set out in the associated appendices should not be used for any other purpose: if they are so used, it is entirely at the risk of the user.

Prof G Baker
Dean
Faculty of Engineering and Surveying

1.2 Objective

Evolutionary Structural Optimization (ESO) technique proves effective in dealing with a variety of design criteria with single component systems. The primary goal of this study is to extend the ESO method to multi-component system with a range of design criteria.

As specified in the Project Specification under Appendix A, the sub-objectives are as follows

1. Research the background information relating to ESO in the generic design problems of connection topology.

2. Construct the methodology of ESO and evaluate the solutions.

3. Analyse a typical optimum interconnection and the simultaneous optimization of the project.

4. Give some examples of the application of ESO in the industry areas like Middle Pillar to Rocker Joint Design and Hat section Design.

5. Analyse the optimization of interconnection elements under single load cases and multiple load cases

1.3 Project Methodology

The execution of the research project is planned in several stages. After the project is allocated and approved by the examiner and staff of ENG4111, the next step is to specify the details of the project such as the objectives, the requirements and the plan for the project workload. At the same time, research and literature survey are carried out to find the background of the evolutionary structural optimization and other information related to the project.

The literature survey undertaken is mainly from the books, journal papers and information from the Internet. After that, a review is written to explain, summarize and critically report on all other relevant information found in the materials mentioned. The

review summarize the ESO method to multi-component system with a range of design criteria as (1) minimum utilization of materials, (2) maximum overall stiffness, (3) minimum stress and (4) control of natural frequency. Besides that, information on the industrial applications of ESO is equally important to make use of their advantages to the design project.

Thirdly, Modeling of the inter-connection of the analysis is set as a reference for the application of Evolutionary Structural Optimization method. Other than that, it is necessary to have a methodology that can address the design of multi-component systems and generate designs for the optimal layouts of individual structures and locations for interconnections. This is because structural optimization methods for continuum structures consider the design of mainly single structural components. However, in most real life engineering design problems involve multiple components or structures; it is a subject of great relevance. In general, the designs of the individual components are usually coupled. The changes made in the design of one component may influence the design of a multi-component system into design of single components.

For the calculation and analysis part, software ANSYS is used to assist in the calculation of the connected structure analysis. An Evolutionary Structural Optimization (ESO) has been developed and implemented to provide the engineering design community with an alternative optimization technique whereby traditional mathematical programming based optimal processes is replaced by a simple heuristic approach. By progressively eliminating certain amount of under-utilized connection elements to the over-utilized regions, the structures evolve towards an optimum. The ESO method provides significant simplicity in its computer implementation such as ANSYS programming. A great number of numerical examples in a wide range of engineering and physical disciplines have demonstrated the ESO method to be very effective and robust.

In this project the analysis of this method will be carried out to apply on the interconnection of various shapes that stated. To prove the effective in dealing with a variety of design criteria, this technique will be applied on the design of *middle pillar to rocker joint* to demonstrate the industrial applications.

Middle pillar to rocker joint design is part of the automobile body that the joint consists of four panels with complex shapes and it is corresponding to different load cases.

Stiffness is one of the key factors that need to be taken into account in the design of structures. It is often required that a structure be stiff enough so that the maximum deflection is within a prescribed limit. Hence, this method involves a single cycle of a finite element analysis and continued with a rule driven element removal process without sacrificing the structural performance of the joint to lead the optimal interconnection elements as close to a uniform performance as possible. This reduction of spot-welds has a significant effect on the design considering each spot-weld can cost several thousands of dollars in an assembly line each year.

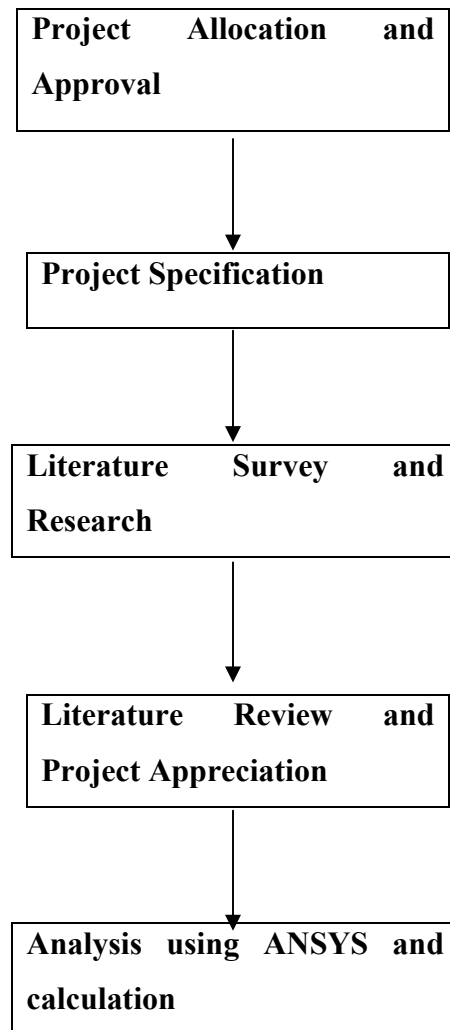The order methodology of this project as explained above is illustrated in the schematic diagram, Figure 1

```
┌─────────────────────────────────┐
│ Project   Allocation   and      │
│ Approval                        │
└─────────────────────────────────┘
                │
                ▼
┌─────────────────────────────────┐
│ Project Specification           │
└─────────────────────────────────┘
                │
                ▼
┌─────────────────────────────────┐
│ Literature   Survey   and       │
│ Research                        │
└─────────────────────────────────┘
                │
                ▼
┌─────────────────────────────────┐
│ Literature   Review   and       │
│ Project Appreciation            │
└─────────────────────────────────┘
                │
                ▼
┌─────────────────────────────────┐
│ Analysis using ANSYS and        │
│ calculation                     │
└─────────────────────────────────┘
```

Figure 1 – Project Methodology

Chapter 2   LITERATURE REVIEW

2.1 Background Information

2.1.1 Physical Concept of ESO

Evolutionary structural optimization (ESO) is the method to produce optimal structure by progressively removing a certain amount of under-utilized material from regions of low stress or adding some material to over-utilized regions by a mesh of finite elements. This chapter develops a systematic procedure for the positioning of fasteners within the connection design space which is constructed by the finite element method (FE). At the same time as considering fastener location, the conventional ESO process can be applied to the components being connected, thereby producing an overall approach to the topology optimization of a multi-component structure.

Locations and patterns of connections in a structural system that consists of multiple components can strongly affect its performance. There are mainly two approaches for topology optimization of continuum structures, namely, homogenization and density method (Jiang and Chirehdast, 1997). The premise of the homogenization method is to compute an optimal distribution of microstructures in a given design domain. In other words, the main idea of the homogenization method is to replace the difficult "layout" problem of material distribution by a much easier "sizing" problem for the density and effective properties of a perforated composite material obtained by cutting small holes in the original homogeneous material. The premise of density method is to compute an optimal distribution of an isotropic material where the material densities are treated as design variables. The density method is used to formulate the topology optimization problem for connections. Almost the entire work in the area of topology optimization, however, has been for a single component.

Normally, an engineering structure failure occurs either in the component at the point of attachment of the connection or at the connection itself. There are several possible causes of structural failure that are influenced by the actual design of the structure, such as poor adaptability of the structure to functional requirements and inadequate stiffness. For example, machine tools should be able to hold tolerances and prevent chattering, or certain components have undesirable natural frequencies; and also the failure of structural

connections. In order to extend the usage life and performance of a structure, it is significant to make sure that the loads borne by the connections are distributed as uniformly as possible.

Presently, structural optimization methods for continuum structures consider the design of mainly single structural components. However, most real life engineering design problems involve multiple components or structures. For present investigation, finite element based optimization of structural systems is proposed and performed in a single structural components or multiple components of trusses, beams and frames. A single changes made in the design of one component may influence the design of a multi-component system or the whole structure of design. Therefore, it is necessary to have a methodology that can address the design of multi-component systems and generate designs for the optimal layouts of individual structures and locations for interconnections.

Choosing a topology is the first step in structural design; it is therefore the layout optimization that is important in the optimal design of structures. It should be connected to one or more redesigned polygon-shaped components to maximize the stiffness of the entire ensemble. One of the methods used is called the homogenization-based design method. It has the ability to change the topology smoothly with a fixed reference domain. A number of objective criteria including stiffness, strength, natural frequency, flexibility, dynamic response, and stability have been used in the application of this method to structural optimization. Besides, an optimality criteria method combined with the steepest descent method also was used to minimize the mean compliance to obtain the stiffest structure for a given volume of material for the connecting structure.

2.1.2 Modeling

The optimization approach is stress-based selecting low and high stressed regions as the areas to be modified. In other words, the connection failure may be caused by an excessive of stress or strain, and an inappropriate allocation of interconnections. In a multi-component system, it is frequently found that failure occurs either at the connection itself or around the attachment regions in the connected components. It may reflect an inefficient use of the connection material, when the low stress or strain is applied.

The geometry of the component is described using NURBS (Non-uniform Rational B-Splines). The reason for use of NURBS is it offers one common mathematical form for

both, standard analytical shapes and free form shapes. Furthermore, it provides the flexibility to design a large variety of shapes which can be evaluated reasonably fast by numerically stable and accurate algorithms. NURBS are defined by control points which become the design variables of the problem.

The main steps of the basic algorithm are summaries as follows:

Step 1 : The shape or geometry of the structure is defined with load and constraints application.

Step 2 : A boundary element analysis (BEA) is carried out.

Step 3 : Material removal process is performed by selecting the least stressed nodes within the boundary mesh and effectively moving the control points nearest to those nodes. At the same time, material addition is carried out if a node is found with a stress higher than the yield stress or a certain maximum stress criterion. This satisfies the objective of this project where to remove a certain amount of under-utilized material from regions of low stress or adding some material to over-utilized regions by a mesh of finite elements.

Step 4 : Finally, such a procedure is repeated, from Step 2, until the evolution of the objective function shows no improvements.

2.1.3 The main steps of the basic algorithm

2.1.3.1 Geometry Definition

Points may be defined in a local co-ordinate system. According to the applied constraints, loads or any other design requirements, the boundary domain can be divided into three types of curves; i.e. design domain, non-design domain and symmetry lines. Lines can be straight, arcs, ellipses, splines, circles or NURBS. These lines that can change freely along the process are identified as design domain, whereas those lines that cannot change due to constraints are identified as non-design domain. Symmetry lines can be regarded as an

intermediate step between design and non-design domain. These three types of lines maybe defined as the intersection between analytical shapes (planes, spheres, cylinders or cones) or grouped together to form combined lines. Furthermore, these lines can be split (or joined) using the cursor and defined as a fillet between 2 existing lines.

2.1.3.2 Boundary element model

The boundary element method is derived through the discretisation of an integral equation that is mathematically equivalent to the original partial differential equation. The boundary surface is divided into elements, thus the essential re-formulation of the partial differential equations that underlies the BEM consists of an integral equation that is defined on the boundary of the domain and an integral that relates the boundary solution to the solution at points in the domain. The advantage of this method relates to the mesh since only the surface of the structure needs to be discretised.

2.1.3.3 Removal and addition of material

If the efficiency of a connection element is lower than a threshold level or a so-called removal ratio RR then this connection element is considered to be relatively structurally less efficient. Therefore, it should be removed from the specific connection region. The material can be removed from the structure if any node p satisfies

$$\sigma_p \leq RR\sigma_{max} \tag{1}$$

and added to the structure if any node p satisfies

$$\sigma_p \geq \sigma_y \qquad OR \qquad \sigma_p \geq AR\sigma_{max} \tag{2}$$

where σ_p *is* the node von Mises stress or any other selected criterion, σ_{max} is the maximum von Mises stress or any other selected criterion, which varies as the optimization progresses. Is the yield stress or any other maximum tress criterion and AR is the addition ration ($0 \leq$ RR, AR ≤ 1).

When the removal cycle is repeated by using the same value of RR$_{ss}$, an ESO steady state (*SS*) will be reached at the end of the process. This means that there are no more interconnections

that can be removed. An ESO steady state means the lowest efficiency within a specific connection region has become higher than a certain percentage of RR_{ss}. To advance such as optimization process, an evolutionary rate (ER) is introduced and added to RR as

$$RR_{ss+1} = RR_{ss} + ER \qquad (3)$$

with the increased threshold efficiency or rejection ratio, the iterations take place again until a new steady state is attained.

Chapter 3 Optimization of Interconnection Elements under Single Load Cases

3.1 Summary

Nowadays many engineering design problems involve multiple components or structures, but in this chapter there are only involves to the single load cases. The component interconnections such as rivets, bolts, springs, spot-welds and others may be used in this design system. It is known that the allocation and design of component interconnections play a crucial role in the entire design system. In this chapter, the evolutionary structural optimization method has been extended to develop connect design problems. This method involves a single cycle of a finite element analysis and continued with a rule driven element removal process. The maximum strain energy has been adopted as the design criterion to lead the optimal interconnection elements as close to a uniform performance as possible. In this chapter, the ANSYS program has been implemented to model and solve the design problems. To demonstrate the capabilities of the proposed procedure, a number of design examples are presented herein.

3.2 Introduction

In past few decades, the design refinement and structural optimization for systems made of single components have been focused. Because there is no determinist process for the design refinement, the traditional method of design is to:

· Start with some initial geometry and material,

· Check it against the functional criteria obtained using deterministic processes,

· Update the design until it fulfils those criteria.

This method of control of the design system is driven by a non-deterministic process and will produce a design satisfying the functional criteria. However it may not be so good when measured in commercial terms. It is not unusual for a design to reach the detailed phase before any stress analysis is performed. The resulting iterative cycle of detail drawing and analysis is then extremely laborious and time consuming.

Traditionally, in order to simplify the modeling and design process, multi-component systems are usually analyzed at the level of individual components. In the analysis, the interconnections are treated as the form of sub-boundaries with appropriate load transfer. The

position of the support points and the magnitude of the load cases need to be carefully determined in advance. Obviously, this procedure is useable only when the connection patterns between the components can be identified. As a result, a single component design is really an optimum if the fastener locations and sizes have been decided at the outset of the analysis.

Even though highly efficient mathematical programming and analysis capabilities are available to the designer, the widespread use of structural optimization methods to practical engineering problems is still not a reality. Moreover, most engineering structures consist of more than one component part. In various engineering applications, there are a large number of multi-component design examples such as aircraft structures, machine tools, frames of car bodies, computer cases, and pin joint trusses.

Several aspects such as convention, experience and manufacturing factors play an important role in determining the fastener type, positioning, and proportioning, when tried to design a connection pattern. To achieve a best possible structural performance within the manufacturing constraints, an optimization of interconnection is of great practical significance and is also capable of providing a more reliable solution to the entire multi-component system.

An Evolutionary Structural Optimization (ESO) has been developed and implemented to provide the engineering design community with an alternative optimization technique. By progressively eliminating certain amount of under-utilized connection elements to the over-utilized regions, the structures evolve towards an optimum. The ESO method provides significant simplicity in its computer implementation such as ANSYS programming. A great number of numerical examples in a wide range of engineering and physical disciplines have demonstrated the ESO method to be very effective.

In this chapter, a strain energy based approach is developed and proposed to design an optimization procedure for single component structure system that achieves a uniform strain energy level in each interconnection element. Basically, the fundamental idea is to model the connection between components using non-adjacent discrete brick elements for every possible candidate fastener location. The strain energy levels of these interconnection elements are treated as an indicator to determine the requirement of its presence.

The importance of strain energy can be described in terms of the structural load paths in the vibration mode. When a particular vibration mode stores a large amount of strain energy in a particular structural load path, the frequency and displacement shape of that mode are highly sensitive to changes in the impedance of that load path. Thus, strain energy is a logical choice of criteria in model update mode selection. In the case of structures with dominant global behavior, such as a cantilevered beam, the lowest frequency modes may also contain the best overall distributions of structural strain energy.

The results will show that it is better to choose those modes that store the highest level of total structural strain energy over the entire structure, and specifically those modes that store the highest level of strain energy. This is because by using the highest strain energy as the design criterion, the under utilized material (lower strain energy) can be removed from time to time.

This chapter also develops a systematic procedure for the positioning of fasteners within the connection design space. To consider the fastener locations, the conventional ESO process can be applied to the components being connected, hence the evolutionary design optimization for a single component structure can be produced. Several design examples are presented to demonstrate the efficacy and capabilities of the proposed methodology.

3.3 Stiffness Design Criterion

Stiffness is one of the key factors that need to be taken into account in the design of structures. It is often required that a structure be stiff enough so that the maximum deflection is within a prescribed limit. In this section, it describes the evolutionary structural optimization procedures for the multi-component connections with the stiffness criterion.

In finite element analysis (FEA), the static behavior of a structure is represented by the following equilibrium equation:

$$[K] \, \{u\} = \{P\} \tag{3.1}$$

Where [K] is the global stiffness matrix, $\{u\}$ is the nodal displacement vector and $\{P\}$ is the nodal load vector.

The strain energy of the structure, which is defined as

$$C = \frac{1}{2} \{P\}^T \{u\} \tag{3.2}$$

This equation is commonly used as the inverse measure of the overall stiffness of the structure. C is also known as the mean compliance. It is obvious that maximizing the overall stiffness is the same as minimizing the strain energy.

Consider the removal of the i th element from a structure comprising n finite elements. The stiffness matrix will change by

$$\Delta [K] = [K^*] - [K] = - [K^i] \tag{3.3}$$

Where $[K^*]$ is the stiffness matrix of the resulting structure after the element removal and $[K^i]$ is the stiffness matrix of the i th element. It is assumed that the removal of the element has no effect on the load vector $\{P\}$. By ignoring a higher order term, we obtain the change of the displacement vector from Equation (3.1) as

$$\{\Delta u\} = - [K]^{-1} \Delta [K] \{u\} \tag{3.4}$$

From Equations (3.3) and (3.4) then,

$$\Delta C = \frac{1}{2} \{P\}^T \{u\}$$
$$= - \frac{1}{2} \{P\}^T [K]^{-1} \Delta [K] \{u\}$$
$$= \frac{1}{2} \{u^i\}^T [K^i] \{u^i\}$$

Where $\{u^i\}$ is the displacement vector of the i th element. Thus define

$$\varepsilon_i = \frac{1}{2} \{u^i\}^T [K^i] \{u^i\} \tag{3.5}$$

as the sensitivity number for problems with an overall stiffness optimization. The value ε_i indicates the change of the compliance due to the removal of the ith element. It should be

noted, in fact, that ε_i is the element strain energy and therefore is always positive. This sensitivity number indicates the change in the strain energy as a result of removing the ith element. In general, each element's contribution to the stiffness of a structure varies from location to location. To achieve a more uniform design of stiffness, the material which contributes the least to the overall stiffness should be removed from the structure.

3.4 Evolutionary Structural Optimization Procedure

In a traditional ESO, the optimization starts from a more conservative design, where the fasteners are initially allocated over all possible positions. To achieve the optimal connection pattern, those lowly energy stored (under-utilized) connection elements are gradually removed. Therefore, the relative strain energy of the remaining interconnections becomes more uniform. The relative efficiency of connection elements is given as:

$$\alpha_i = \varepsilon_i / \varepsilon_{max} \tag{3.6}$$

where ε_{max} is the highest strain energy over the connection domain. To eliminate those under-utilized connection elements, the ESO algorithm introduces a simple rejection formula which already stated in chapter 2. If the strain energy of a connection element is lower than a threshold level or a so-called rejection ratio (**RR**) which is:

$$\alpha_i \leq RR_{ss} \tag{3.7}$$

This connection element is considered to be relatively less efficient (or underutilized. Therefore, should be eliminated from the specific connection region. To comply with the equation above, a removal cycle is repeated using the same value of RR_{ss}, until there are no more interconnection that can be removed. This means that an ESO steady state **(SS)** has been reached, and the lowest efficiency within a specific connection region has become higher than a certain percentage of RR_{ss}. For further step of the optimization process, an evolutionary rate **(ER)** is introduced and added into RR as

$$RR_{ss+1} = RR_{ss} + ER \tag{3.8}$$

with the increased rejection rate, the iterations take place again until a new steady state is achieved.

In the followings, a detailed optimization procedure can be re-organized for the design optimization of connections:

Step 1: Discrete the component system using an appropriate dense finite element mesh, assign the property type of connection and component elements to a number greater than 0.01, define ESO parameter ER, RR_0 and set $SS = 0$.

Step 2: Perform a FEA to determine the relative efficiency factor $\alpha_i = \varepsilon_i / \varepsilon_{max}$ of all candidate connection elements as Equations (3.1) to (3.6).

Step 3: For all candidate elements, if their relative efficiency satisfies Equation (3.7) then assign their property type to zero, and it will be removed from the system.

Step 4: If the steady state is reached, RR_{ss} has to increase by ER, as in Equation (3.8), and set $SS = SS + 1$, repeat Step 3; or else, repeat Steps 2 to 3 until the optimal connection pattern is achieved.

Besides, the optimal connection patterns also can be determined by plotting a graph of strain energy levels against number of connection elements. The difference of strain energy levels are represented by the highest and the lowest strain energy, in which it can be readily find out by using Equation (3.6). ANSYS program has been used to contribute to the three dimensional finite element analysis for the entire evolution process.

3.5 Design Example

Several typical connection designs are investigated herein. In this chapter, only single load case is applied to the design examples. For all design cases, two or three plates can be connected in an overlapping manner by using rivets, pins, threaded fasteners or spot welds. These connection elements can be represented by brick elements, in which it is meshed with

a 15 x 15 grid as shown in Figure 3.1, where the *b* and *l* are the dimensions of 150mm and 350mm respectively. 7 x 7 candidate interconnections are modeled by eight-node brick with 30 percent of the thickness and 210GPa of the Young's modulus of the plates. In all the evolutionary optimization processes of the design cases, an initial rejection ratio of $RR0 = 0$ and an evolution rate of $ER = 1\%$ have been adopted.

3.5.1 Straight Connection Case

In this design example, two components A and B is connected together as in a straight direction. Figure 3.1 shows the initial model of straight overlapped connection, in which the load case is applied in the lower corner of the free end. Figures 3.2 (a) to (p) show the different connection patterns in each iteration of ESO steady state in the evolution process. As the rejection ratio (*RR*) increases iteration by iteration, the interconnection elements are removed from the candidate location. At the fifth iteration (also the steady state) of the evolution process, there are eighteen interconnection elements removed as shown in Figure 3.2 (f). There are sixteen interconnection elements left when the evolution process reached at tenth iteration as shown in Figure 3.2 (k). It can be found that, by the end of the evolutionary process or at the fifteenth iteration, the optimal interconnection elements are allocated at the four outmost corners of the overlapping square as shown in Figure 3.2 (p). This result could be adopted as a form of validation of ESO process used in connection optimization design problems.

On the other hand, an optimal design can also be identified by referring to the graph of evolution history of strain energy levels as shown in Figure 3.3. The difference of strain energy distribution can be monitored by plotting the highest strain energy and the lowest strain energy against with the number of connection elements. Obviously, it shows that the deviation between the highest and lowest strain energy in the surviving connection elements becomes smaller and smaller with the evolution process, which reflects a path approaching a fully strained energy design. It is also identified the optimal point of interaction between both strain energy levels, which corresponds to the four connection elements located at the outmost corners of the overlapping square as in Figure 3.2 (p).
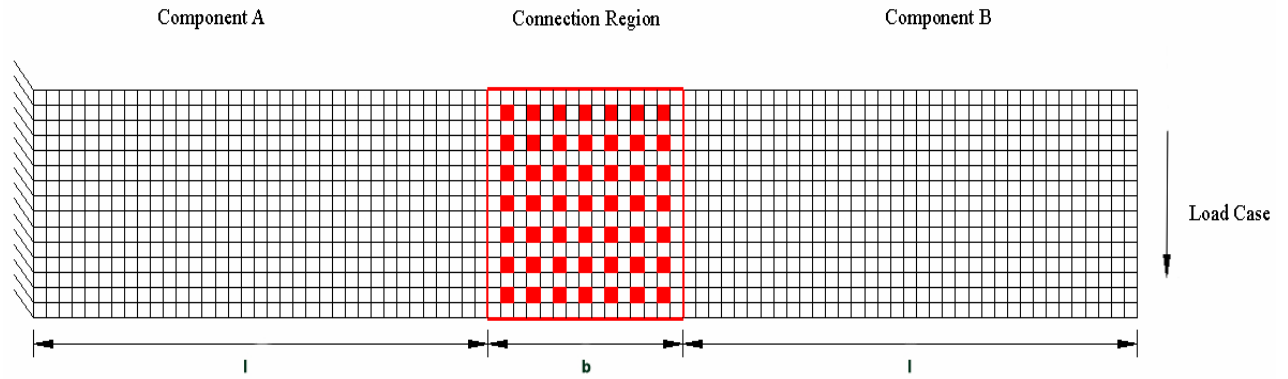
Figure 3.1 The initial model of straight overlapped connection

(a) SS = 0, M = 49

(b) SS = 1, M = 44

(c) SS = 2, M = 36

(d) SS = 3, M = 34

(e) SS = 4, M = 32

(f) SS = 5, M = 31

(g) SS = 6, M = 25

(h) SS = 7, M = 23

(i) SS = 8, M = 21

(j) SS = 9, M = 17

(k) SS = 10, M = 16

(l) SS = 11, M = 14

17

(m) SS = 12, M = 12 (n) SS = 13, M = 8 (o) SS = 14, M = 6

(p) SS = 15, M= 4
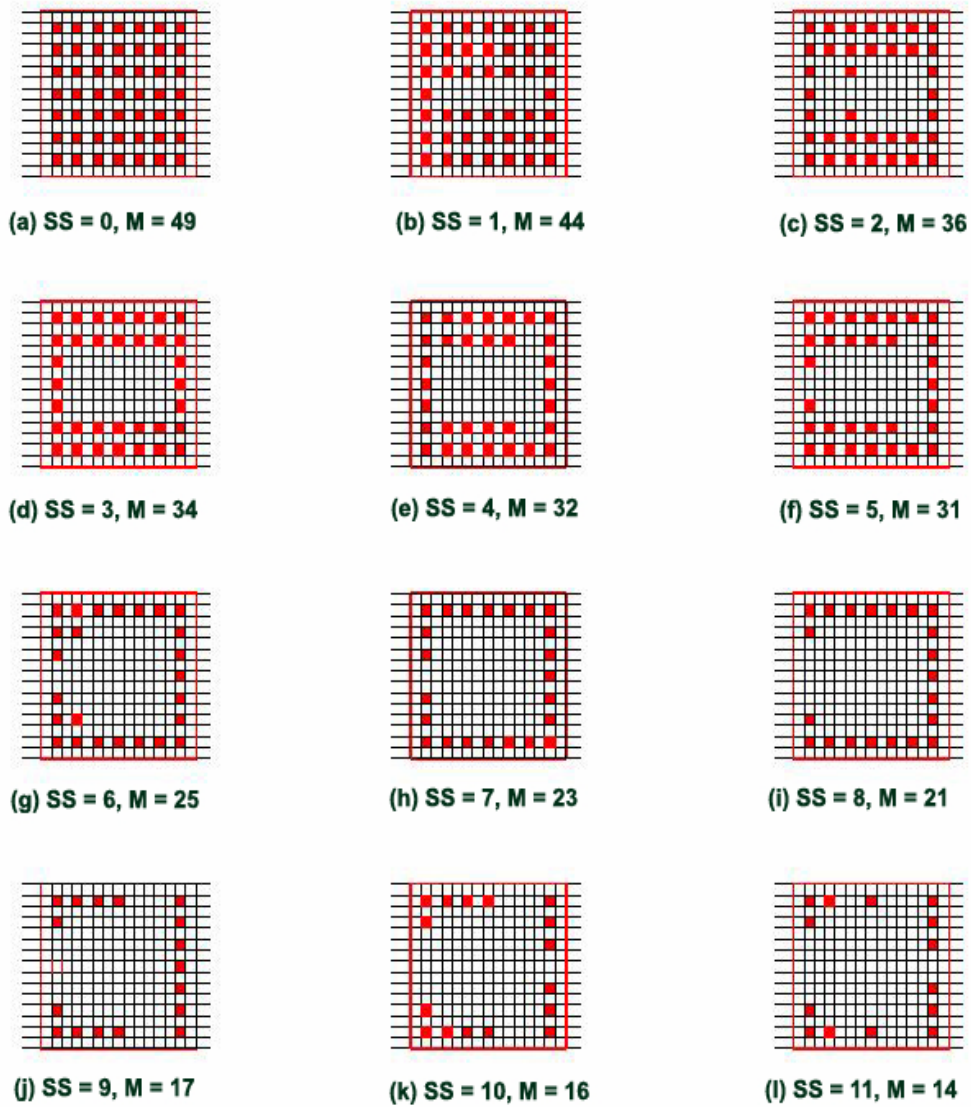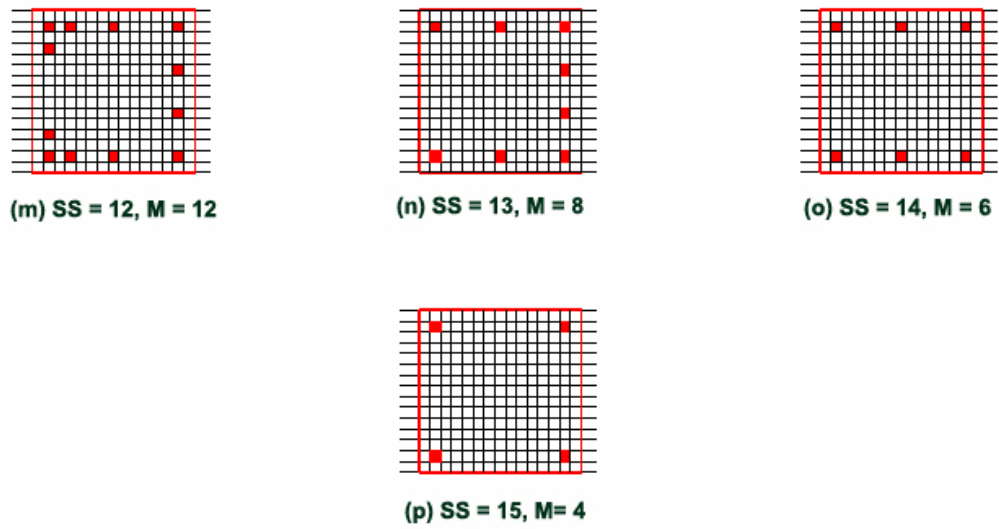
Figure 3.2 ESO connection patterns in the straight joint

**A Graph of Evolution History of Strain Energy Levels
Against Number of Connection Elements**
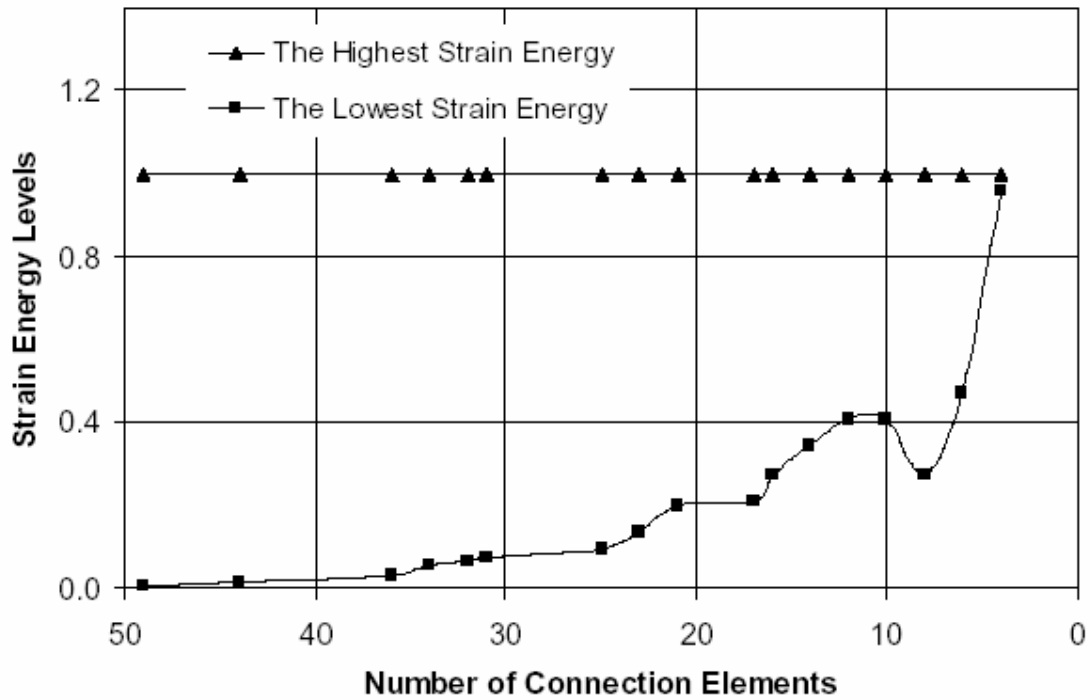
Figure 3.3 The evolution history of strain energy levels of the straight joint optimization

3.5.2 Crossover Connection Case

A crossover connection case is one of the most common design examples that can be seen in the structural engineering. It is jointed by attaching one plate to another at a right angle. The whole design structure is supported on the both ends of the horizontal plate. One of the load cases is applied on the top toward left the vertical plate and another is applied on the bottom toward right at the vertical plate as shown in Figure 3.4. There are only five iterations or steady states in the entire evolution process. The optimal interconnection elements are exactly same as the straight connection case, where the last four surviving interconnection elements also located at the corner positions as in Figure 3.5 (e). To identify an optimal design, the graph of evolution history of strain energy levels against the number of connection elements can be plotted. It is found that the pattern of the four outmost interconnection elements has the smallest strain energy deviation as shown in Figure 3.6. This indicates the surviving interconnection elements have higher usage efficiency in terms of strain energy for this design case. This also provides good evidence to validate the ESO solution.
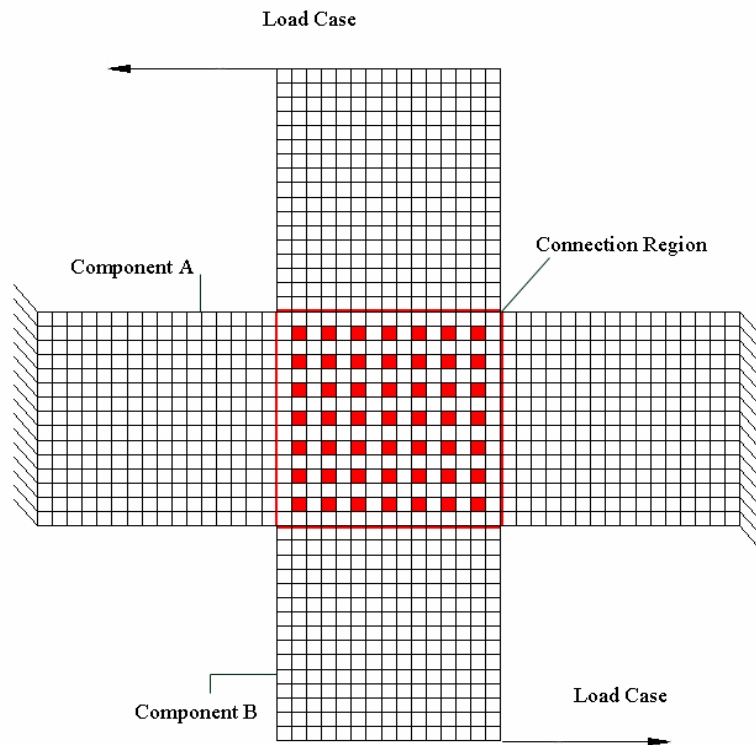
Figure 3.4 The initial model for the cross overlapped connection
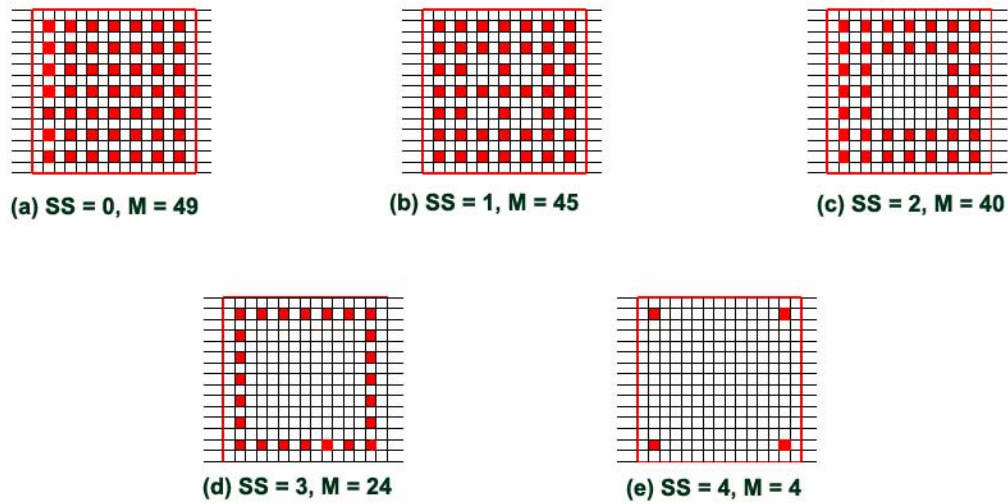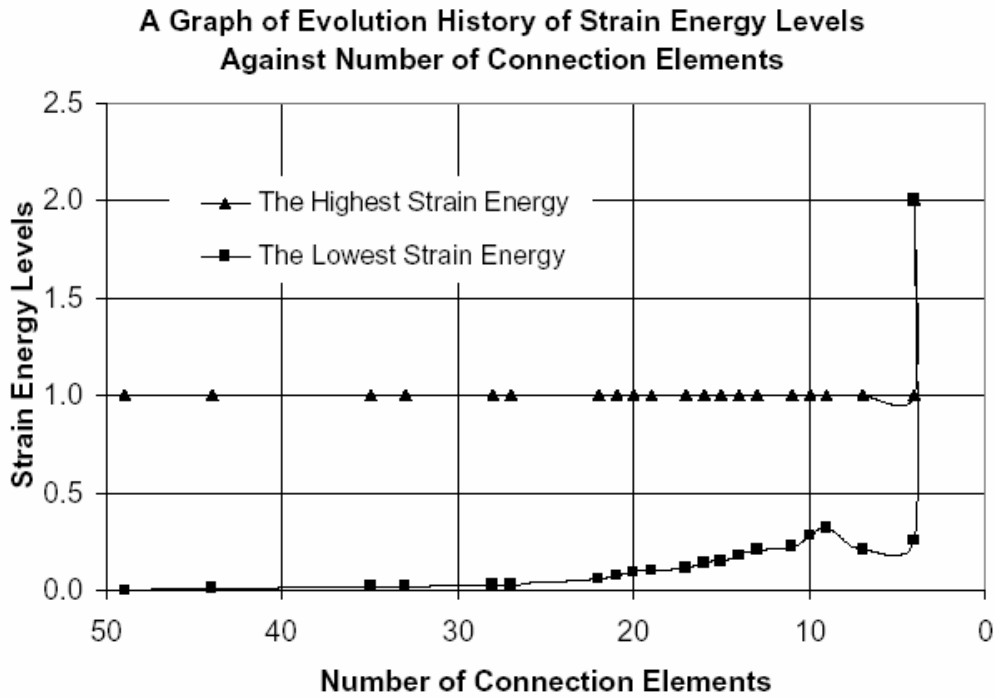
Figure 3.5 ESO connection patterns in the crossover joint
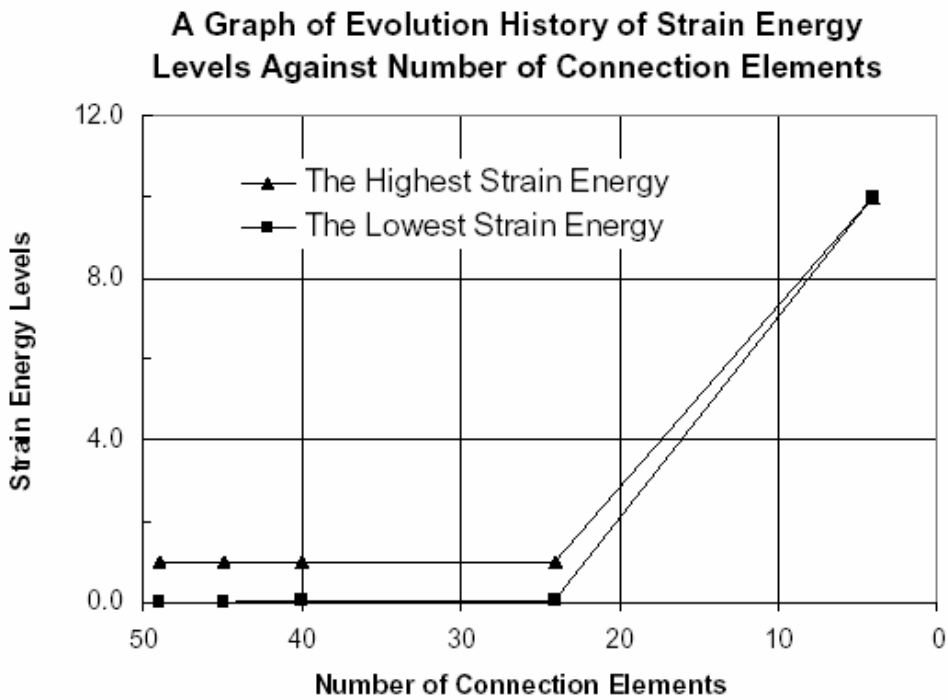
Figure 3.6 The evolution history of strain energy levels of the crossover joint optimization

3.5.3 L- Shaped Connection Case

       The third design example is an L-shaped connection case as shown in Figure 3.7. The L-shaped joint also consists of two components, component A in vertical and component B in horizontal, in which a load case is applied in the lower corner of the free end on the horizontal plate. The entire structure is supported on the top end of the vertical plate. Figures 3.8 (a) to (k) show the evolution results of connection patterns in several different iteration steps 49 fasteners have been used at the initial state, 27 fasteners are removed at sixth steady state, there are only 15 fasteners left when the steady state increased to twelfth, and the optimal connection pattern is at nineteenth steady state in which there are only four fasteners left. It is found that the optimal distribution of the fasteners is different from the previous design examples. The even allocation at the four outmost corners of the overlapping square does not provide an optimum under the fully strain energy criterion. This can be seen in Figure 3.8 (k). From the evolution histories of strain energy deviation, it can identify the range between the highest and the lowest strain energy become smaller and smaller, in which occurs at M equals to four as in Figure 3.9. This can provides further evidence to validate the ESO solution.
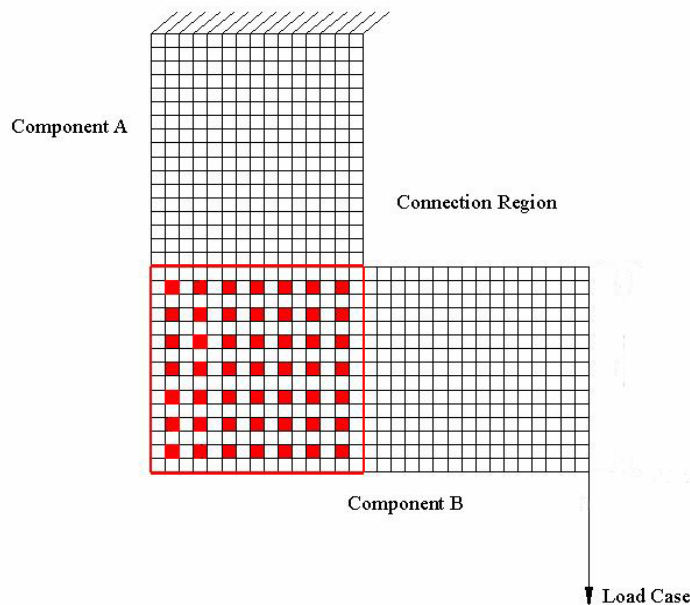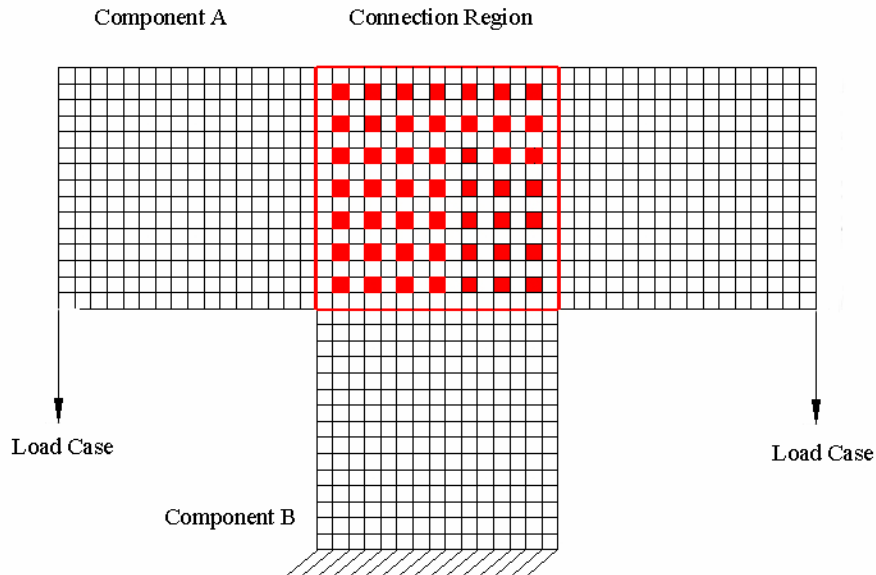

Figure 3.7 The initial model for the L-shape overlapped connection

(a) SS= 0, M = 49

(b) SS = 1, M = 35

(c) SS = 2, M = 28

(d) SS = 3, M = 22

(e) SS = 4, M = 20

(f) SS = 5, M = 17

(g) SS = 6, M = 15

(h) SS = 7, M = 13

(i) SS = 8, M = 10

(j) SS = 9, M = 7

(k) SS = 10, M = 4
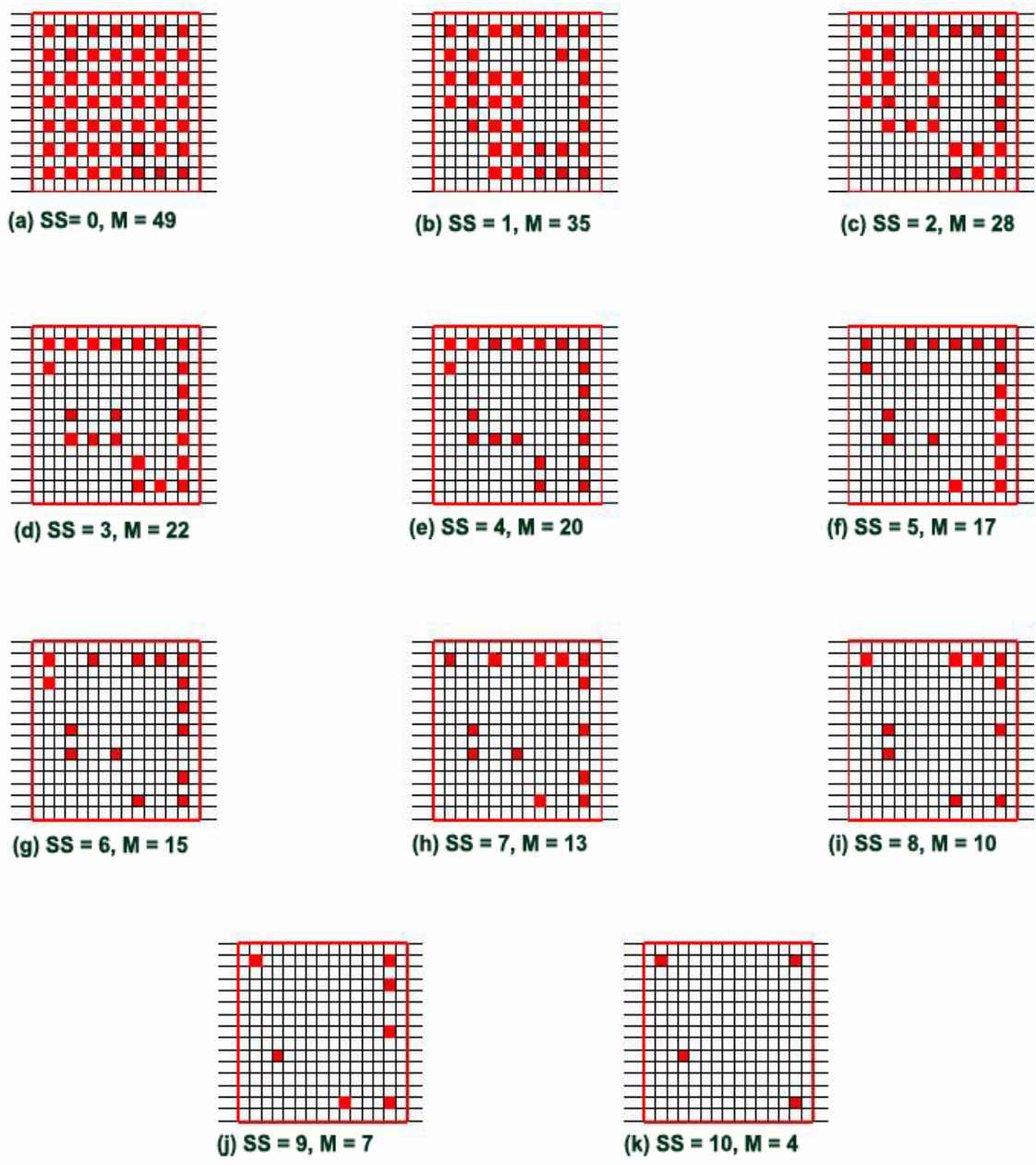
Figure 3.8 ESO connection patterns in the L-shaped joint

**A Graph of Evolution History of Strain Energy Levels
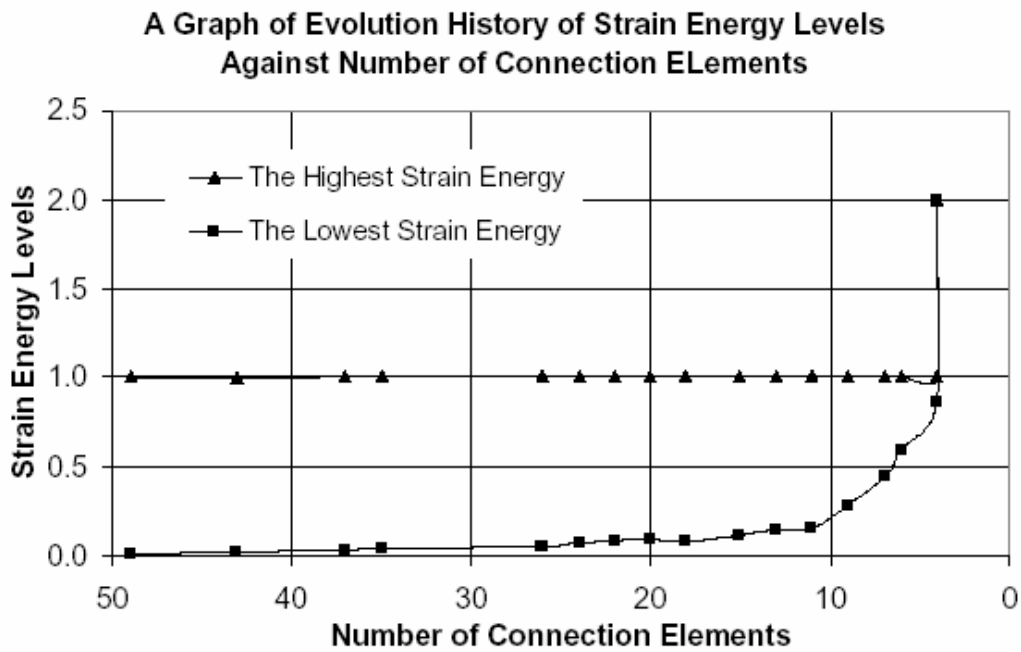Against Number of Connection Elements**

Figure 3.9 The evolution history of strain energy levels of the L-Shaped joint optimization

3.5.4 T-Shaped Connection Case

The fourth design example is a T-shaped connection case. This design structure is different compare to crossover connection case, in which has only one symmetric axis in a vertical direction. This is also one of the most common design examples that have been implemented in the engineering structure. There are two load cases applied at the both ends of the long horizontal plate. And the structure is supported at the lower end of the short vertical plate as shown in Figure 3.10. Figures 3.11 (a) to (i) show the evolutionary patterns at different iterations. For example, twenty three connection elements have been removed at the fourth state of iteration, and there are only thirteen connection elements left when the ESO steady state reached at the tenth iteration. It is found that the optimal connection pattern for this design example is different compared to the previous design examples, although the numbers of the connection elements are the same (M = 4). The last four remaining connections are located near left and right lower corners as shown in Figure 3.11 (i). From the evolution history of strain energy levels, one can identify the optimal connection patterns. The graph

23

shows in Figure 3.12 demonstrates that the optimal interconnection occurred at the number of connection element equal to four, in which the highest strain energy levels approach to the lowest strain energy levels.
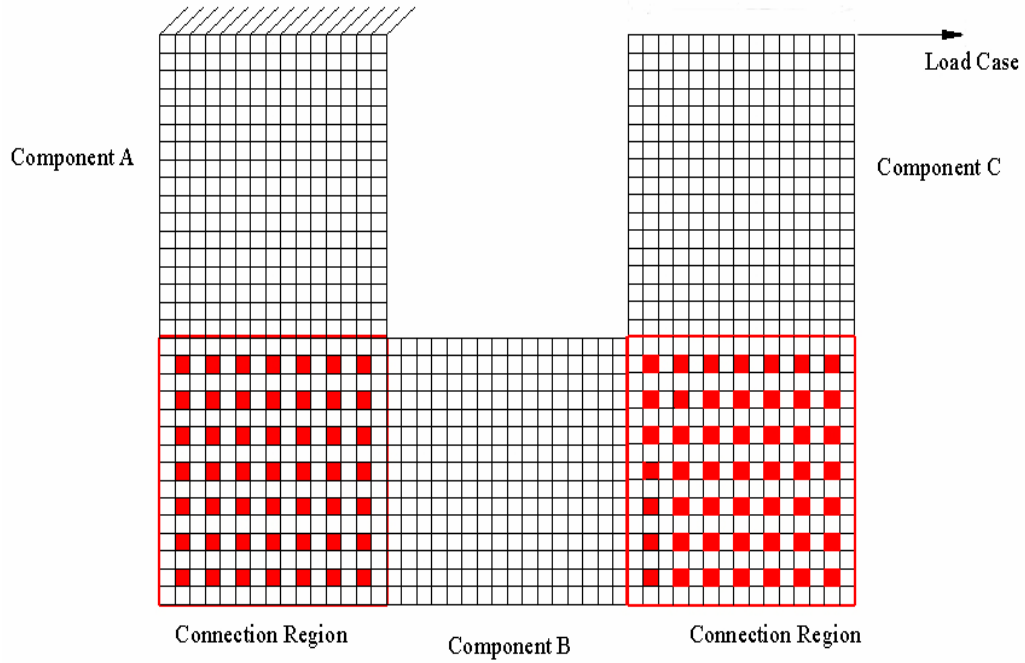

Figure 3.10 The initial model for the T-shape overlapped connection
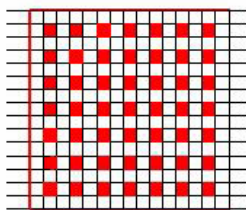
(a) SS = 0, M = 49
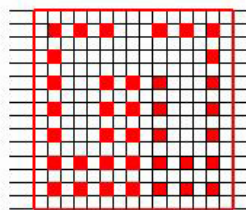
(b) SS = 2, M = 37
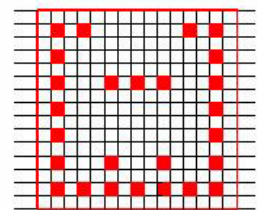
(c) SS = 4, M = 26
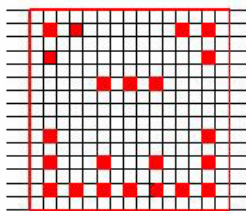
(d) SS = 6, M = 22

(e) SS = 8, M = 18

(f) SS = 10, M = 13

(g) SS = 12, M = 9   (h) SS = 14, M = 6   (i) SS = 15, M = 4
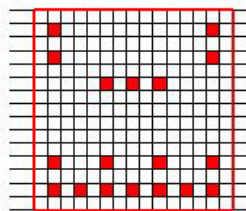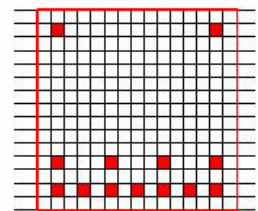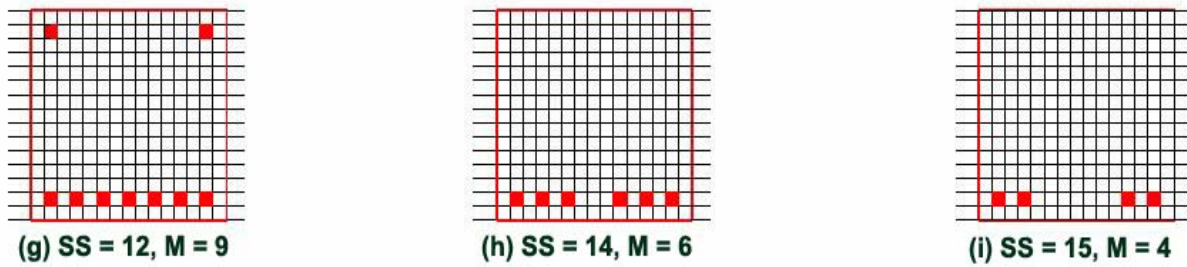
Figure 3.11 ESO solutions for T-connection patterns

Figure 3.12 The evolution history of strain energy levels of the T-Shaped joint optimization

25

3.5.5. U-Shaped Connection

This design example consists of three components A, B, and C, and two groups of fasteners, in which two connection regions are optimized simultaneously. Forty nine connection elements have been used to connect each of the connections AB and BC.

A single load case is applied to the upper right end of the component C, and the entire structure is supported by component A as shown in Figure 3.13. There are several connection patterns achieved at different ESO steady state as in Figures 3.14 (a) to (g). For example, at the third iteration, the connection elements reduced to twenty three at the first connection region and twenty six at the second connection region as in Figure 3.14 (b). At the fifteenth iteration, thirty five connection elements at the first connection region and thirty six connection elements at the second connection region have been removed as shown in Figure 3.14 (d). It is found that the optimal connection pattern of this joint element consists of three interconnection elements in each connection region as in Figure 3.14 (g). The positions of the interconnection elements of both the connection regions are different, this may cause by a vary load case applied at different direction.

The evolution history curves provide the quantitative indication of the design optimization. From Figure 3.15, one can easily find out that the highest and the lowest strain energy levels crossed with each other at the connection elements of three for both connection regions. Obviously, this explores that the connection pattern of M = 3 as in Figure 2.14 (g) is of the best stiffness performance.

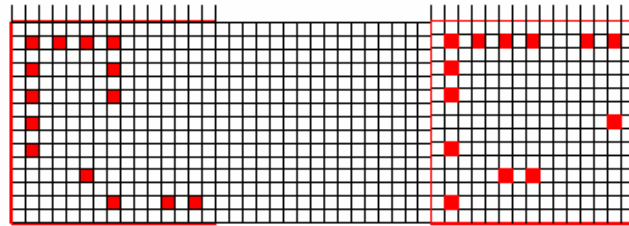Figure (3.13) The initial model for the U-shape overlapped connection of three components
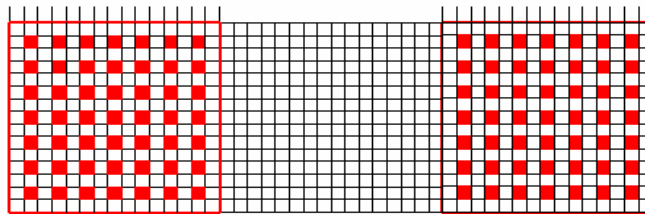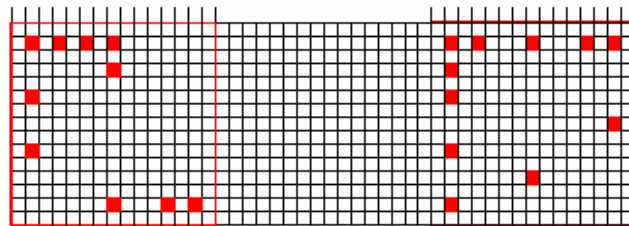

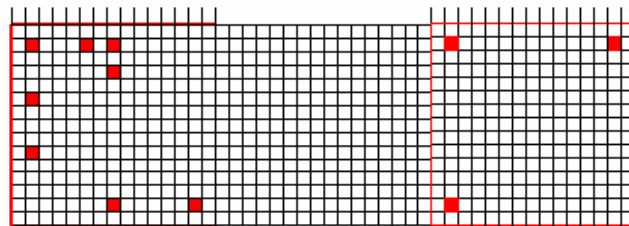(a) SS = 0, M1 = 49, M2 = 49
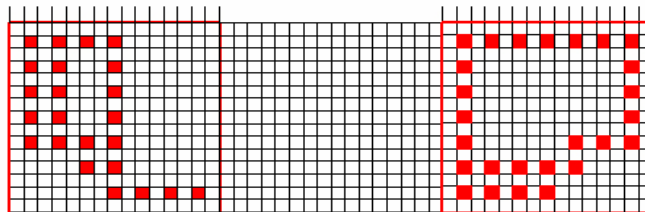
(b) SS = 3, M1 = 23, M2 = 26
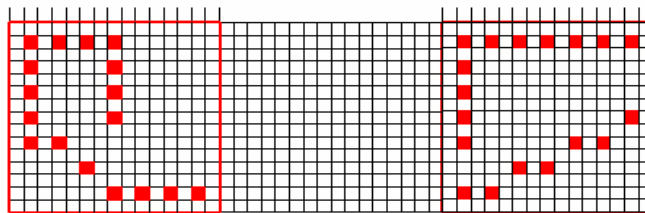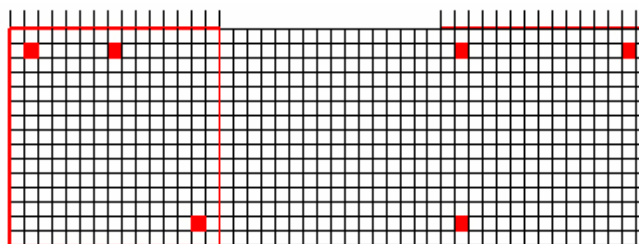

(c) SS = 9, M1 = 17, M2 = 18

(d) SS = 15, M1 = 14, M2 = 13

(e) SS = 21, M1 = 10, M2 = 11

(f) SS = 27, M1 = 8, M2 = 3

(g) SS = 31, M1 = 3, M2 = 3

Figure 3.14 ESO solutions for U-joint patterns
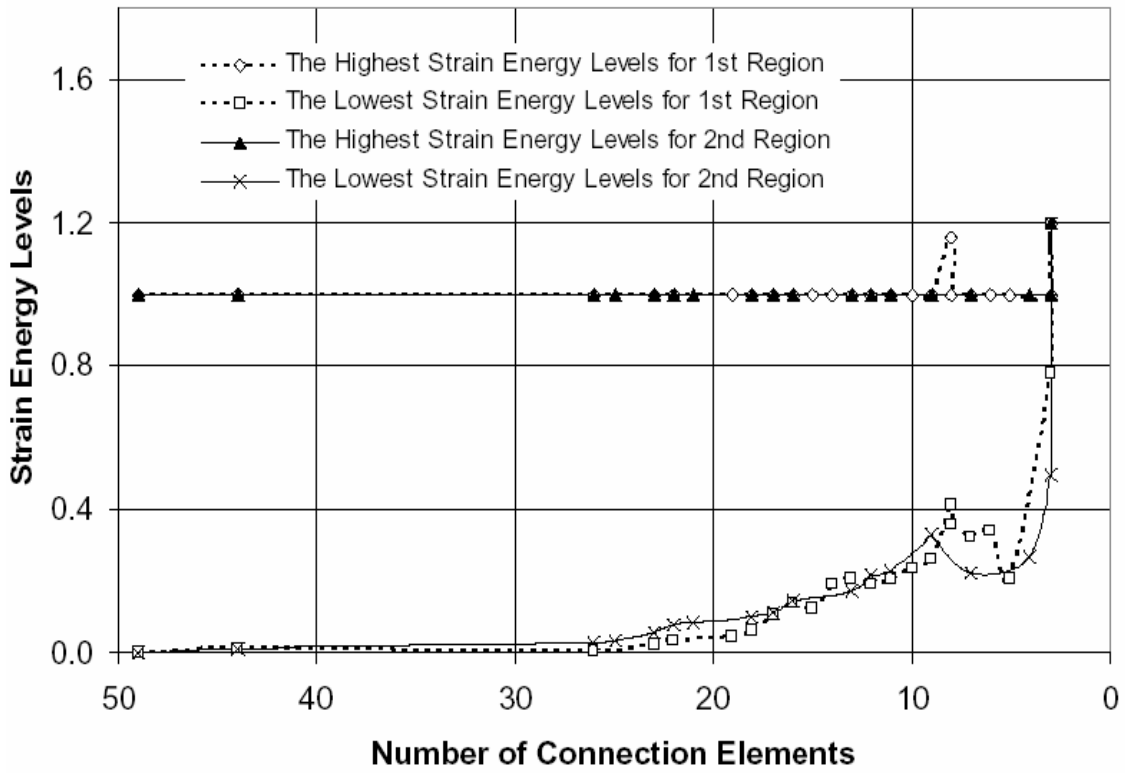
Figure 3.15 The evolution history of strain energy levels of the U-Shaped joint optimization

Chapter 4 Optimization of Interconnection Elements under Multi Load Cases

4.1 Summary

Engineering design problems involve multiple components or structures. Moreover, there are more than single load applied on the designed components of the structure. In this chapter, two load cases have been applied to the design examples, and the evolutionary structural optimization method also has been extended to develop for such multiple load cases design problems. Hence, most of the procedures are similar to the previous chapter. Maximum strain energy also has been adopted as a design criterion to have the interconnection elements as close to a uniform load as possible. To achieve the optimal connection patterns, the ANSYS program has been implemented. Some examples are demonstrated in the following.

4.2 Introduction

In recent years, structural optimization has become the focus of the structural design community and has been researched and applied widely both in academia and industry. However, most engineering structures consist of more than one component or structural part. Traditionally, multi-component systems with multiple load cases are usually analyzed at the level of individual components in order to simplify the modeling and design process. In that analysis, the interconnections are treated as some form of sub-boundaries with appropriate load transfer. In this chapter, however, multiple load cases have been taken into account seek for the optimization of interconnection elements. The position of the support points and the magnitude of the load cases also need to be carefully determined in advance for multi-component analyses.

As mentioned in the previous chapter, to design connection pattern, convention, experience and manufacturing factors play a dominant role in determining the fastener type, positioning and number. To achieve a best possible structural performance within the manufacturing constraints, an optimization of interconnection is of great practical significance and is also capable of providing a more reliable solution to the entire multi component system.

An Evolutionary Structural Optimization (ESO) also has been developed and implemented to provide the engineering design community with an alternative optimization technique whereby traditional mathematical programming based optimal processes is replaced by a simple heuristic approach. By progressively removing a certain amount of under-utilized material or adding some material to over-utilized regions, the structure evolves towards an optimum. Similarly to previous structural optimization methods, this chapter considers multiple load cases instead of single load cases to the entire design examples. A strain energy based approach is proposed to design a fastener layout that achieves an almost uniform strain energy level in each interconnection element. With the ESO method, the connection element itself, rather than its associated physical parameters, such as the stiffness, is treated as the design variable. Three design examples are presented to demonstrate the capabilities and efficacy of the proposed methodology.

4.3 Stiffness Design Criterion

Stiffness design criterion for multi-load cases is similar to the previous single load case. It is often required that a structure is stiff enough so that the maximum deflection is within a prescribed limit. This chapter also describes the evolutionary structural optimization procedures for the multi-component connection with the stiffness criterion, in which multi-load cases are involved.

At a more complex but realistic level, where the multi-component system may be operated under circumstances involving multiple load cases, as governed by the finite element equation:

$$[K]\{u_k\} = \{P_k\} \quad (k = 1,2,....LCN) \tag{4.1}$$

the relative efficiency under all the load cases can be estimated by a weighted average scheme as:

$$\alpha_i = \left(\sum_{k=1}^{LCN} w(p_k) \frac{\varepsilon_i^C(p_k)}{\varepsilon_{\max_i}^C(p_k)} \right) \Bigg/ \sum_{k=1}^{LCN} w(p_k) \tag{4.2}$$

or by an extreme value scheme as:

$$\alpha_i = \frac{\displaystyle\max_{k=1}^{LCN} \varepsilon_i^C(p_k)}{\displaystyle\max_{i=1}^{M_t}\left\{\max_{k=1}^{LCN} \varepsilon_i^C(p_k)\right\}}$$

(4.3)

where, *LCN* denoted the total number of load cases, $\{P_k\}$ (k = 1,2,….LCN) the vector of the *k*th load case, $\varepsilon_i^C (P_k)$ the von Mises strain energy of the *i*th connection element under the *k*th load case, $w(P_k)$ gives the weighting factor for the *k*th load case, $\max_{k=1}^{LCN}\varepsilon_i^C(p_k)$ calculates the highest strain energy level of the *i*th connection under all load cases and $\max_{i=1}^{M_t}\left\{\max_{k=1}^{LCN}\varepsilon_i^C(p_k)\right\}$ calculates the highest strain energy level at all load cases *LCN* over all interconnections M_t in the *t*th connection region. For convenience, the former is termed as the overall efficiency and the latter is named as the extreme efficiency. The efficiency factor provides a criterion to justify which connection elements should remain and which ones should be eliminated.

The formulations in Equations (4.1)-(4.3) could treat various connection regions differently. This means that the goal of equal efficiency can be sought in individual connection regions. This provides a way of dealing with different connection types and sizes. On other hand, if the desired connection type and size among all connection regions are the same, the global maximum strain of all regions

$$\varepsilon_{\max}^C = \max_{t=1}^{T}\left\{\varepsilon_{\max_t}^C\right\}$$

(4.4)

can be adopted as the reference criterion, $(\varepsilon_{\max t}^C)$, where *T* denotes the total number of candidate connection regions. In this sense, stiffness design can be achieved over all connection regions.

4.4 Evolutionary Structural Optimization Procedures

Similarly to the previous chapter of single load cases, to achieve the optimal connection pattern, those inefficiency connection elements are gradually removed. It is therefore, the relative efficiencies of the remaining interconnections become more uniform. Hence, the ESO algorithm introduces a simple rejection formula to eliminate those under-utilized connection elements. If the relative strain energy of a connection element is lower than a threshold level or a so-called rejection ratio (*RR*), which is:

$$\alpha_i \leq RR_{ss} \ (i = 1,2….., M) \ (t = 1,2,….T) \tag{4.5}$$

then this connection element is considered to be relatively less efficient, and therefore, should be eliminated from the specific connection region *t,* To comply with the equation above, a removal cycle is repeated using the same value of RR_{ss} until there are no more interconnection that can be removed. This means that an ESO steady state (*SS)* has been reached, and the lowest efficiency within a specific connection region has become higher than a certain percentage of $RR_{ss.}$ For further step of the optimization process, an evolutionary rate (*ER*) is introduced and added into *RR* as

$$RR_{ss+1} = RR_{ss} + ER \tag{4.6}$$

with the increased of rejection rate, the iterations take place again until a new steady state is achieved.

The following optimization procedures can be determined for the design of\ connections for multi load cases as well:

Step 1: Discrete the component system using an appropriate dense finite element mesh define ESO parameter *ER, RR0* and set *SS* = 0.

Step 2: Perform a FEA to determine the relative efficiency factor of all candidate connection elements as Equations (4.2) to (4.4).

Step 3: For all candidate elements, if their relative efficiency satisfies Equation (4.5), then assign their property type to zero, and it will be removed from the system.

Step 4: If the steady state is reached, RR_{ss} has to increase by *ER*, as in Equation

(4.6), and set $SS = SS + 1$, repeat Step 3; or else, repeat Steps 2 to 3 until the optimal connection pattern is achieved.

Basically, the difference in this chapter compare with the previous chapter is that the average of the highest strain energy on both design structures with the different load cases direction have been taken to solve for the entire process, and the rest of the procedures is similar.

4.5 Design Examples

In this chapter, several typical connection designs are investigated. Such as an L-shaped connection case, T-shaped connection case, and U-shaped connection case are demonstrate at the following paragraphs. Although these several design examples are similar compared to the previous chapter, multi-load cases have been used instead of a single load case. Two or three components can be connected in a connection region by using either threaded fasteners, rivets, pins or spot welds. These connection elements can be represented by brick elements, in which it is meshed with a 15 x 15 grid as shown in Figure 4.1, where the *b* and *l* are the dimensions of 150mm and 450mm respectively. There are 7 x 7 candidate interconnections are modeled by eight-node brick with 30 percent of the thickness and 210GPa of the Young modulus of the plate. In all evolutionary optimization processes of the design cases, an initial rejection ratio of $RR_0 = 0$ and an evolution rate of $ER = 1$ percent have been adopted.

4.5.1 L-Shaped Connection Case

An L-shaped connection case consists of two components A and B, which are jointed together by brick elements as illustrated in Figure 4.1. To due with multi-load cases, two point load cases are applied in the upper and lower corners of the free end, as shown in Figure 4.1 (a) and (b). Figure 4.2 shows the connection patterns at different ESO steady states for the entire evolution process. The evolution process started with forty nine connection elements, and reduced to thirty three connection elements at the second iteration as shown in Figures 4.2 (a) and (b). As the rejection ratio (*RR*) increases, those relatively

inefficient connection elements are removed from candidate locations. Figures 4.2 (d), (e), and (f) show that the major number of inefficient connection elements eliminated are allocated at the lower right corner of the connection region. There are only eleven connection elements left at sixteenth iteration, and reduced to six when twentieth iteration is reached as shown in Figures 4.2 (i) and (k) respectively. It is found that the optimal connection pattern at ESO steady state is achieved at $SS = 17$, and there are only four connection elements left as illustrated in Figure 4.2 (l). This result could be argued to be some form of validation of the ESO process implemented in connection optimization problem.

Again, the evolution process can be monitored by plotting a graph of strain energy levels against number of connection elements as shown in Figure 3.3. From the evolution history curves, the point of the highest strain energy approaches to the lowest strain energy during optimization process. The highest and the lowest strain energy in the surviving connection elements become smaller and smaller with the evolution process, which reflects a path approaching a fully strain energy design.
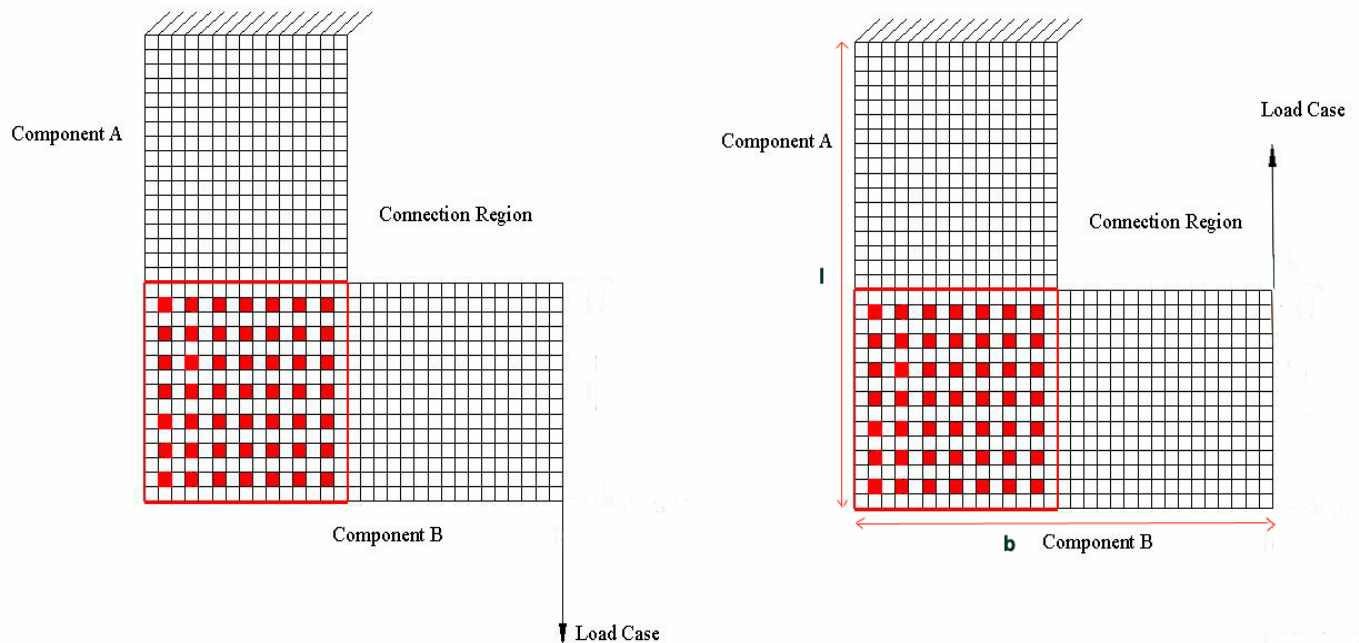
(a) Load case acted in the lower direction   (b) Load case acted in the upper direction

Figure 4.1 The initial models of L-shaped joint
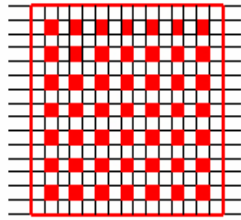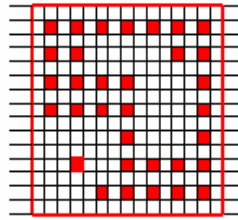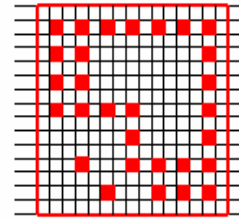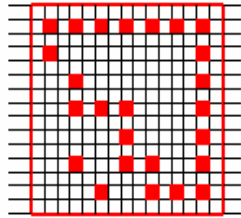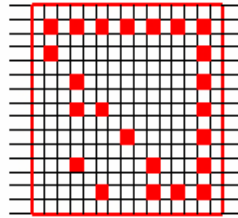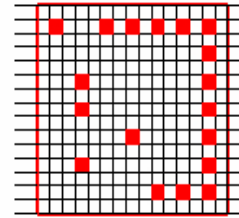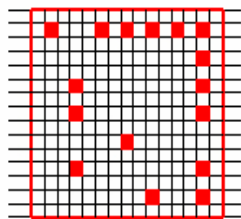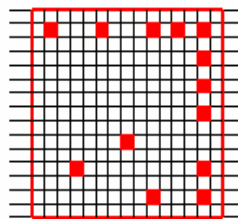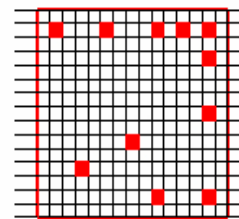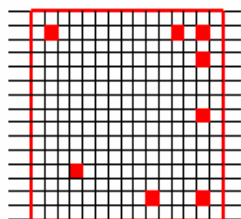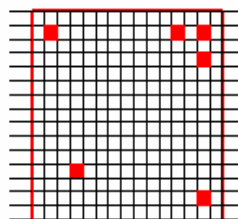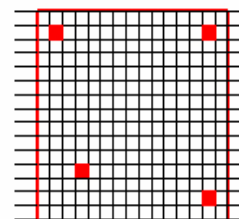
Figure 4.2 ESO solutions for L-shaped connection patterns

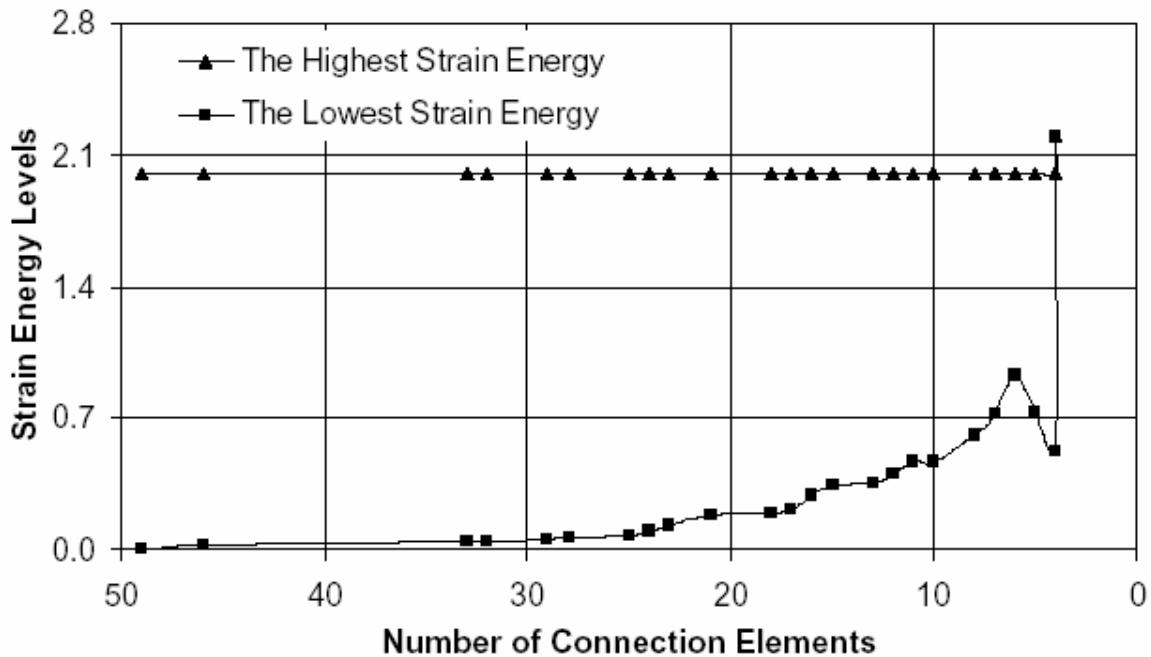## A Graph of Strain Energy Levels Against Number of Connection Elements

Figure 4.3 The evolution history of strain energy levels of the L-shaped joint optimization

4.5.2 T-Shaped Connection Case

The second design example has been investigated is the T-shaped connection case, and it is one of the most useful engineering design structures. It consists of two plates A and B, in which the modeled region reflects a transverse support joint that can be typical for a frame structure as illustrated in Figure 4.4. There are two load cases applied on this design structure, in which one of the load case is applied at the left corner of the free end, and another is applied at the right corner of the free end of the component A as shown in Figures 4.4 (a) and (b). The entire design structure is supported at the lower end of the short vertical plate which is component B. Figure 4.5 illustrates the evolutionary connection patterns at different steady states. At first iteration, there are eleven inefficient connection elements have been eliminated as shown in Figure 4.5(b). All the inefficient connection elements allocated at the center position have been removed gradually. Figure 4.5 (g) shows the evolutionary connection pattern at sixth iteration and it consists of seventeen connection elements.

There is only eight connection elements left at eleventh steady state as in Figure 4.5 (l). It demonstrates that when the steady state is increased more and more, the number of connection elements will be eliminated. However, the optimal connection pattern is achieved at the twelfth iteration, which the last survived connection elements locate at the four outmost corners of the overlapping square as shown in Figure 4.5 (m). It is found that the allocation of eight connection elements around the edges of the connection domain does not offer the optimum in the connection pattern.

From the evolution histories of strain energy deviation, one can identify the optimal connection patterns. It can readily find out that the minimum difference between the highest and the lowest strain energy points occur at four interconnections from Figure 4.6. This explores that the connection pattern M is the best strength efficiency performance compared with the performances of eight and ten connection elements.
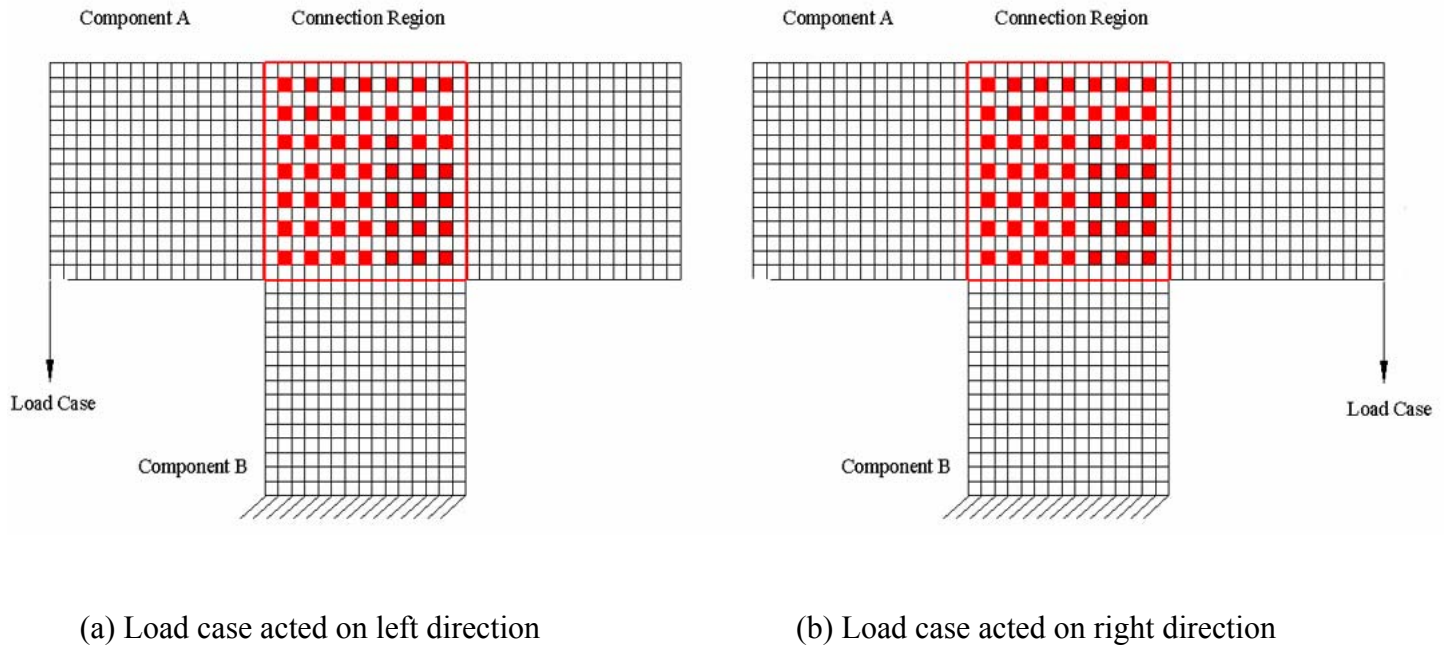

(a) Load case acted on left direction   (b) Load case acted on right direction

Figure 4.4 The initial models of T-shaped joint
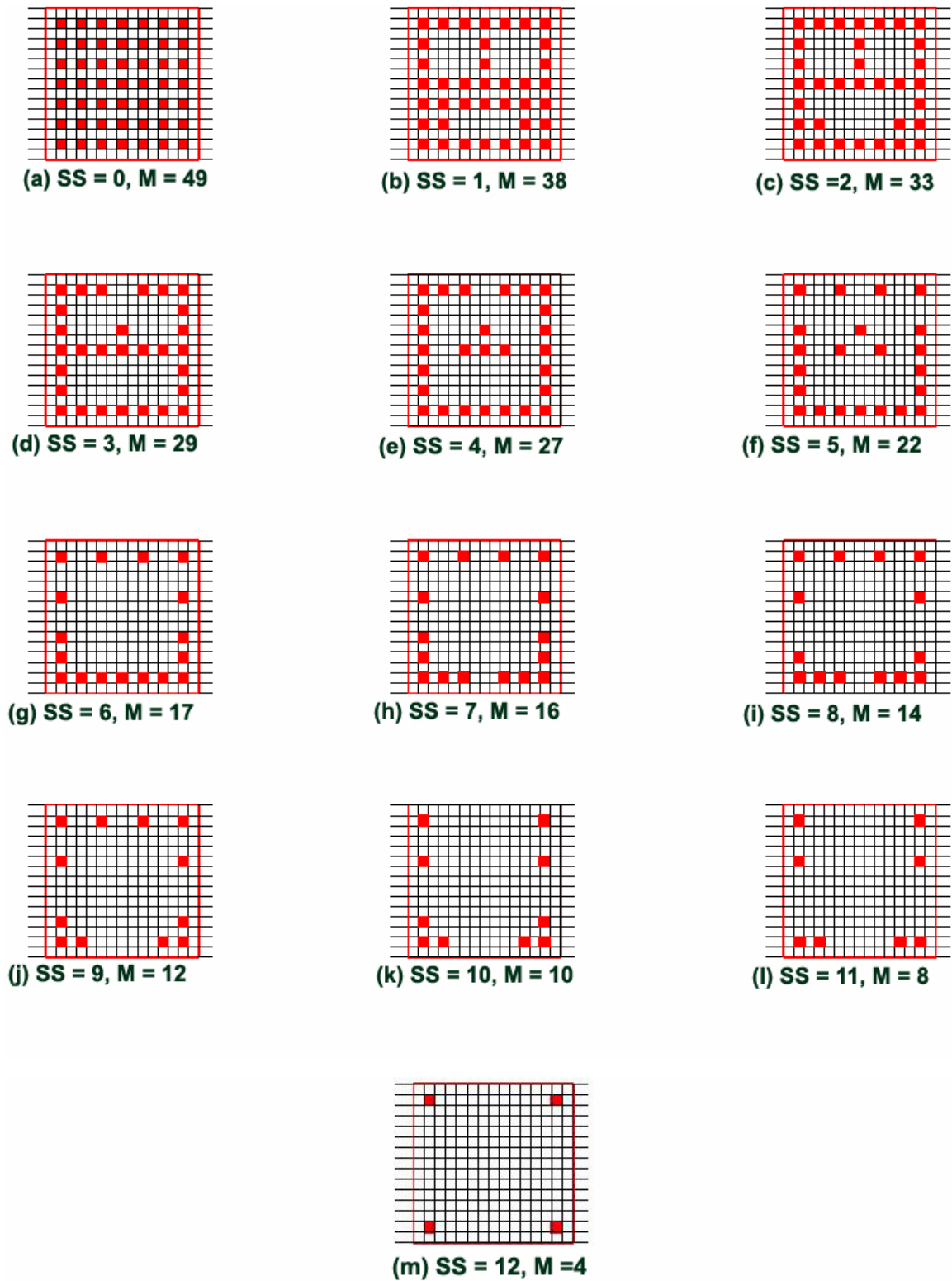
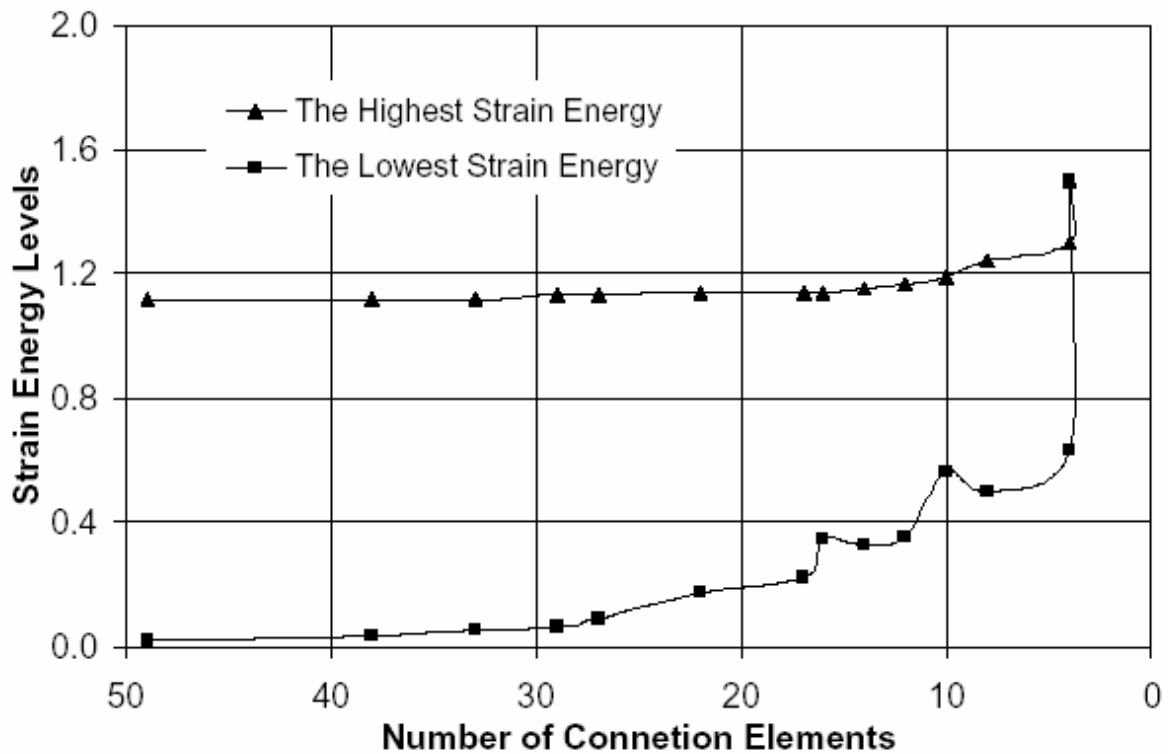Figure 4.5 ESO solutions for T-shaped connection patterns

Figure 4.6 The evolution history of strain energy levels of the T-shaped joint optimization

4.5.3 U-Shaped Connection Case

The third design example is a U-shaped connection case. This connection case consists of three plates A, B and C as illustrated in Figure 4.7, in which two connection regions are optimized simultaneously. Basically, this design example is similar to L-shaped connection case; the only difference is that another connection region is added ($M_1 = M_2 = 49$). Two different load cases are applied on each connection case as shown in Figures 4.7 (a) and (b), in which one of the load cases is applied to right direction on the free end of component C, and another is applied to left direction on the free end of component C.
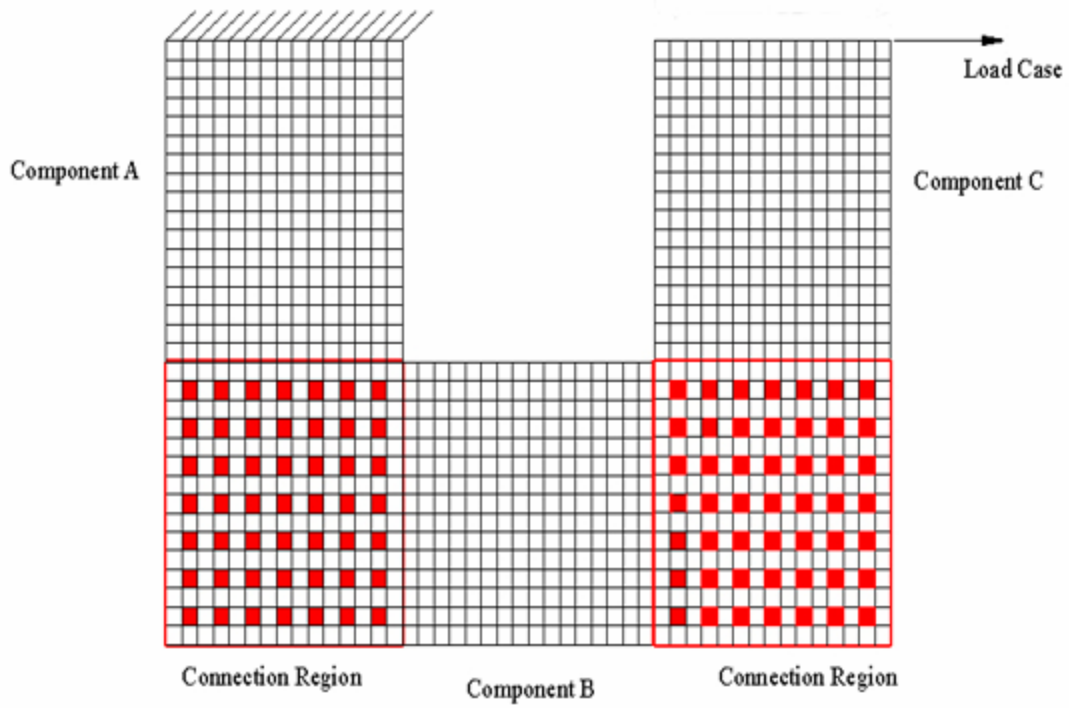
(a) Load case acted on right direction
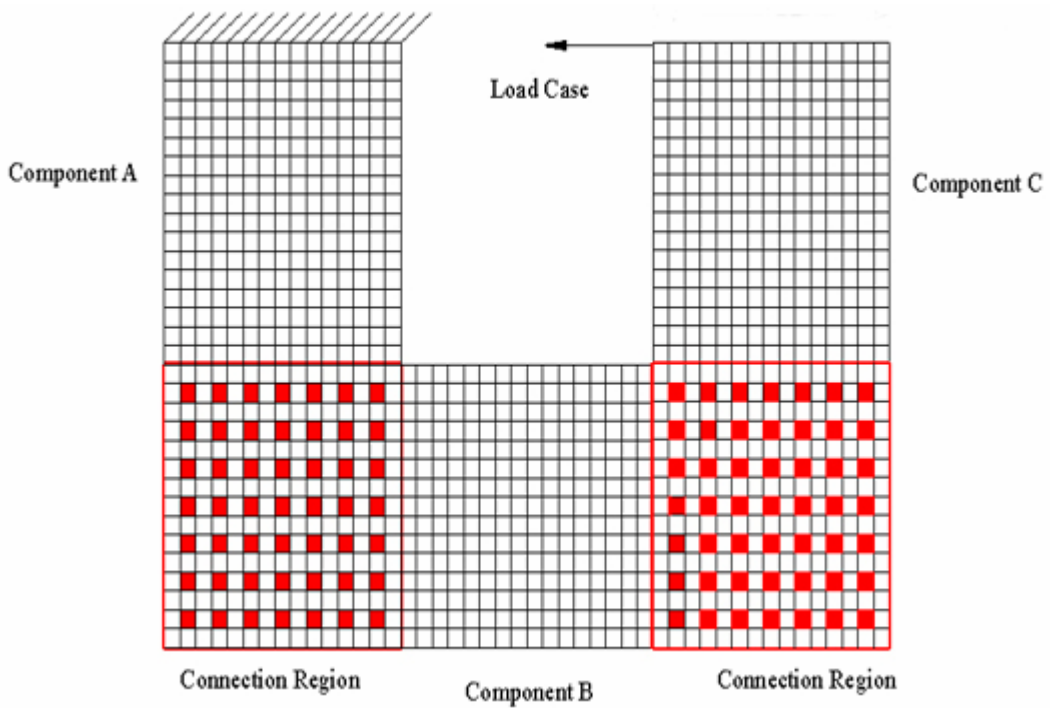

(b) Load case acted on left direction

Figure 4.7 The initial models of U-shaped joint

Figure 4.8 shows the ESO solution connection patterns at different steady states. At the first iteration, it could be seen there is more inefficient connection elements are eliminated start from the end corner of each connection region as in Figure 4.8 (b). To due with multi-load cases, the inefficient connection elements in both connection regions removed simultaneously. In Figure 4.8 (d), twenty one connection elements are removed in each connection regions at the sixth iteration. When the ESO steady state reached the twelfth, more inefficient connection elements have been eliminated, in which only seventeen connection elements are left in each connection regions as shown in Figure 4.8 (f). There are only six connection elements left in both connection regions when the ESO steady state increases to twenty-first as shown in Figure 4.8 (i). The optimal connection pattern for the U shaped connection case is shown in Figure 4.8 (j), in which the number of last survived connection elements equal to four in each connection regions. This indicates the surviving interconnections have both higher extreme efficiency and the higher over all efficiency for these two load cases.

The evolution history curves also provide the quantitative indication of the design optimization. From the Figure 4.9, it can be found that the highest and the lowest strain energy curves cross with each other at M equal to four. This obvious result could be indicated that the best stiffness-efficiency performance occurs at the connection pattern at M equals to four as in Figure 4.8 (j).
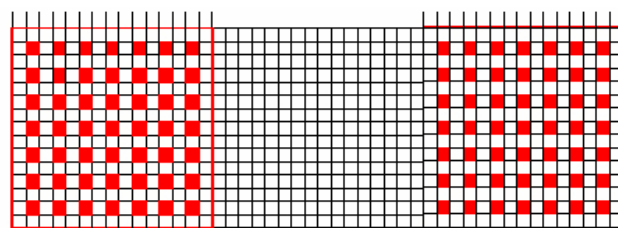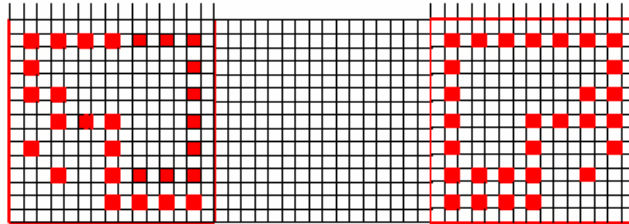

(a) SS = 0, M1 =49, M2 = 49
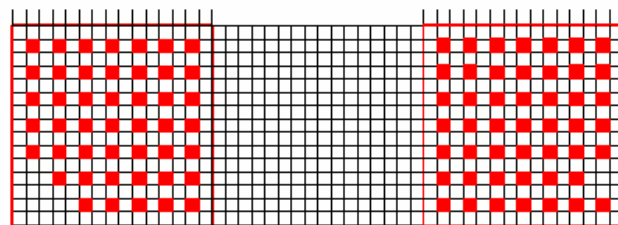
(b) SS = 1, M1 = 46, M2 = 48
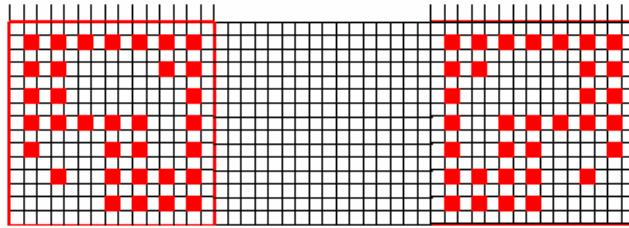
(c) SS = 3, M1 = 33, M2 =33

(d) SS = 6, M1 = 28, M2 =28
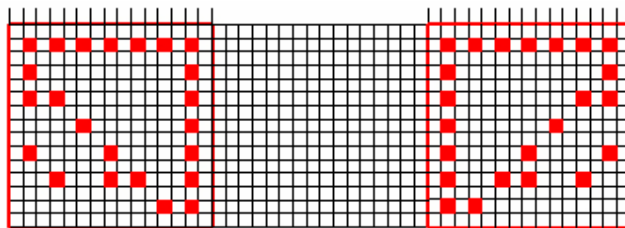
(e) SS = 9, M1 = 23, M2 = 23
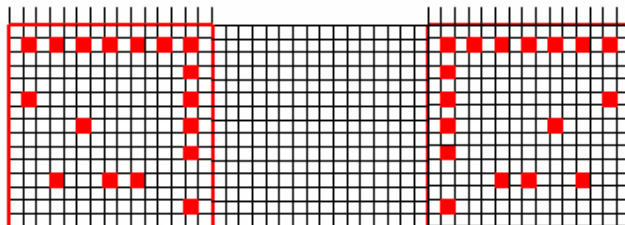
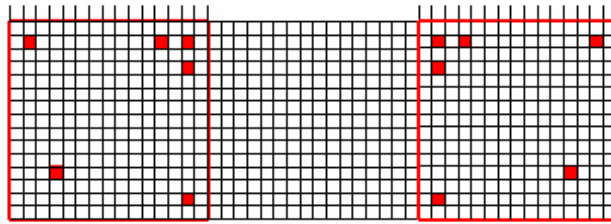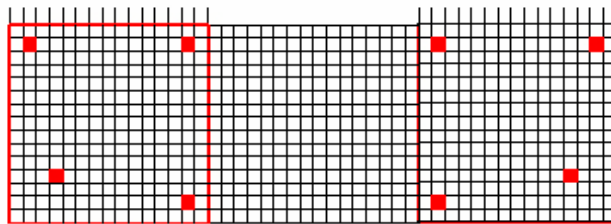
(f) SS = 12, M1 = 17, M2 =17
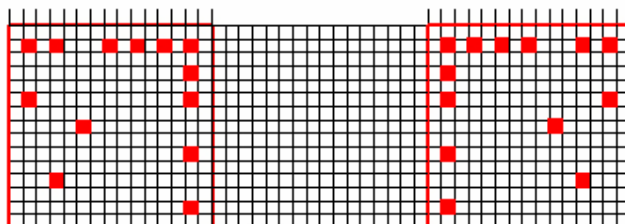
(g) SS = 15, M1 =13, M2 = 13

43
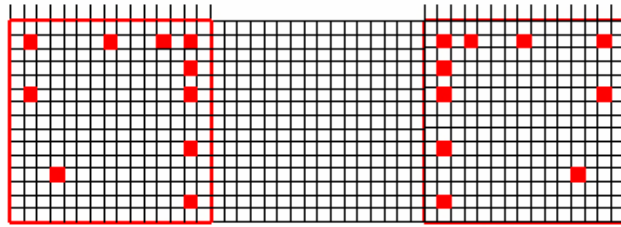
(h) SS = 18, M1 = 10 , M2 = 10

(i) SS = 21 , M1 = 6 , M2 = 6

(j) SS = 23 , M1 = 4 , M2 = 4

Figure 4.8 ESO solutions for U-shaped connection patterns

A Graph of Strain Energy Levels Against Number of Connection Elements
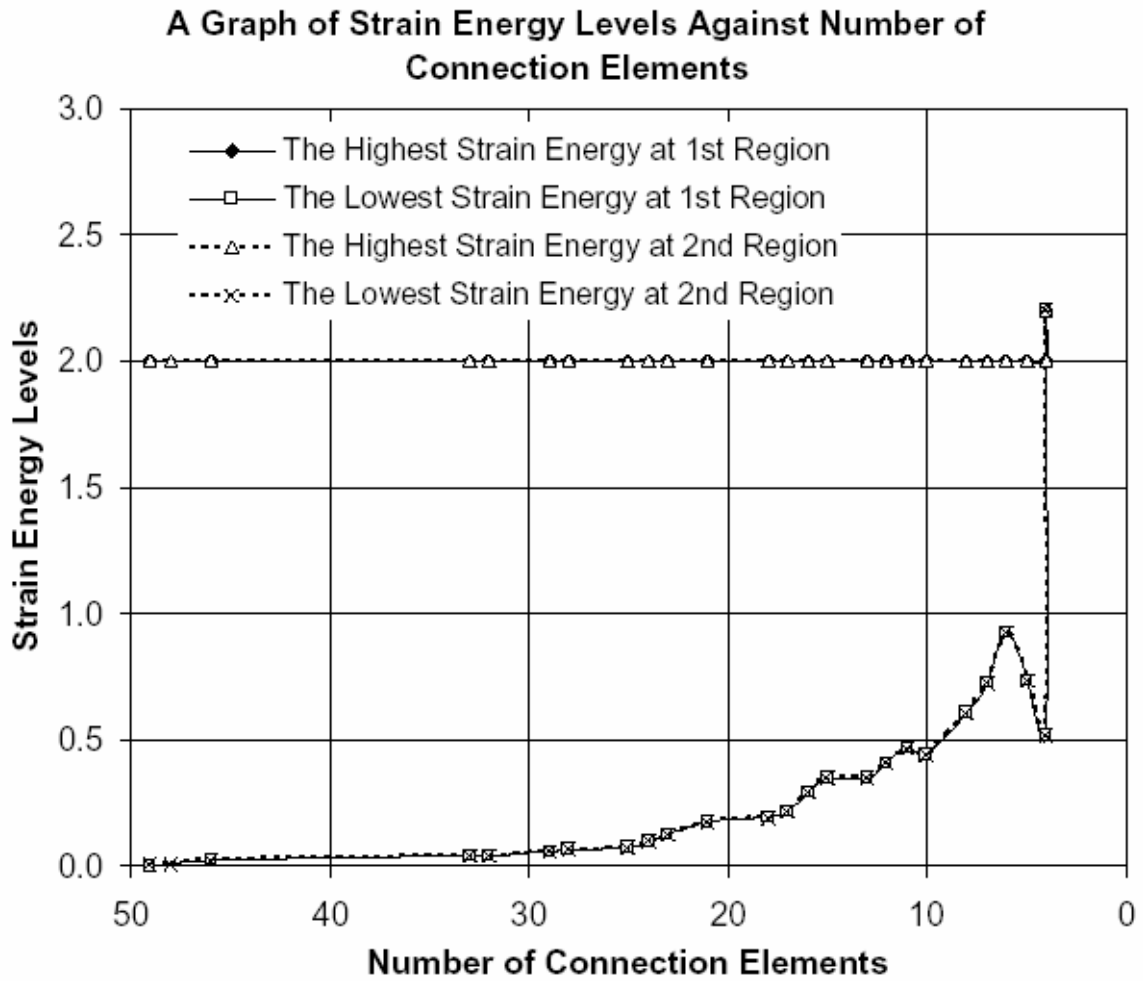
Figure 4.9 The evolution history of strain energy levels of the U-shaped joint optimization

Chapter 5 Conclusion

Up to this stage of the analysis, results show that the importance of Evolutionary Structural Optimization in the industrial area and every engineering discipline. By following the ESO procedure, the inefficient elements are gradually removed from the regions which are in lower stress and it will be improve by distributing the strain energy as uniform as possible at the region of the interconnection. From the strain energy deviation graph which is showing the history of evolution of strain energy levels of the every joint optimization. The result of the deviation graph is able to tell whether the solution that obtained is accepted.

 In the analysis of optimization, highest strain energy has been adopted as the design criterion as what has been discussed in the earlier chapter. There are several researches on the Evolutionary Structural Optimization where the stress level of the interconnection has been assigned as the design criterion. In comparing these two methods of optimization, these two methods give more or less the same results for the interconnections that analyzed in this project.

This paper extends the evolutionary structural optimization method to the design of multi-component systems, which involves both single load cases and multiple load cases. To have the interconnection elements carry as uniform strain energy as possible, strain energy levels of all candidate connection elements are employed to estimate the relative performance. The absence and presence of an interconnection is determined in terms of its relative performance of stiffness by complying with this concept. In the optimization process, those inefficient connection elements are gradually removed from the structural system by following the evolutionary structural optimization procedures. This significantly simplifies the optimization process and makes the algorithm easy to be applied into different design problems.

To deal with multiple load cases, the overall efficiency schemes are presented in the previous chapters. This emphasizes the average extent of use under various load cases. The choices of the schemes depend on the design requirements. The definition of the connection can be as broad as possible herein, in which can include various fasteners such as rivets, bolts, spot-welds, pins, that depend on the areas of application.

REFERENCES AND FURTHER READING

1. Bendsoe, M.P., Kikuchi, N. (1998). Generating optimal topologies in structural design using a homogenization method. *Computer Methods in Applied Mechanics and Engineering* 71:197-224.

2. Chickermane, H. and Gea, H.C. (1997), *Design of multi-component structural systems for optimal layout topology and joint locations*, Engineering with Computers, Vol. 13, pp. 235-43.

3. Chickermane, H., Gea, H.C., Yang, R.J. and Chung, C.H. (1999), *Optimal fastener pattern design considering bearing loads*, Structural Optimization, Vol. 17 pp. 140-6

4. David Roylance. (2001), Finite Element Analysis, Department of Materials Science and Engineering, Massachusetts Institute of Technology Cambridge, MA 02139

5. E. Cervera, J. Trevelyan. (2005), *Evolutionary structural optimization based on boundary representation of NURBS. Part I: 2D algorithms,* Computers and Structures 83 1902–1916

6. E. Cervera, J. Trevelyan. (2005), *Evolutionary structural optimization based on boundary representation of NURBS. Part II: 3D algorithms,* Computers and Structures 83 1917–1929

7. Jiang, T. and Chirehdast, M. (1997, *A system approach to structural topology optimization: designing optimal connections*, ASME Transactions: Journal of Mechanical Design, Vol.119, pp.40-7.

8. John Barlow. (2000), *Structural Design Optimization In The Real Engineering World,* PTC.

9. L. Fryba and J. Naprstek (Eds.); A.A. Balkema, Rotterdam. (1999), *Structural Dynamics EURODYN'99*, Engineering Structure, pp 1224–1226

10. Li, Q., Steven, G.P. and Xie, Y.M. (2001), *Evolutionary structural optimization for connection topology design of multi-component systems, to appear in Structural Optimization.*

11. Pasi Tanskanen, (2002), *The evolutionary structural optimization method: theoretical aspects,* Computer. Methods in Applied in Mechanical and Engineering. pp.5485–5498

12. Rozvany, G.I., Zhou, M., Gollub, M. (1989). Continuum type optimality criteria methods for large finite element systems with a displacement constraint, part 1. *Structural Optimization* 1:47-72.

13. Xie, Y.M. and Steven, G.P. (1994), optimal design of multiple load case structures using an evolutionary procedure, *Engineering Computations*, Vol. 11. pp. 295-302.

14. Xie, Y.M. and Steven, G.P. (1997), *Evolutionary Structural Optimization*, Springer-Verlag, Berlin.

15. Young, V., Querin, O.M., Steven, G.P. and Xie, Y.M. (1999), 3 D and multiple load case bi-directional evolutionary structural optimization (BESO), *Structural Optimization*, Vol. 18, pp. 183-92.

APPENDIX A

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project
PROJECT SPECIFICATION

FOR: Chuah Yew Pin

TOPIC: Evolutionary Structural Optimization for Multi-component
                                  Structural Systems

SUPERVISORS: Dr. Yan Wen Yi
ASSOCIATE SUPERVISOR: Dr. Fok Sai Cheong

ENROLMENT: ENG 4111 – S1, X, 2005
                                  ENG 4112 – S2, X, 2005

PROJECT AIM: This project seeks to prove that efficiency of applying the
                                  Evolutionary Structural Optimization method to the
                                  multi-component structure system.

PROGRAMME: **Issue A, 12 March2005**

1. Review the work on evolutionary structural optimization (ESO) in generic design
   problems associated with connection topology

2. Construct and evaluate the methodologies for the ESO

3. Analyze typical interconnections and their optimizations

4. Case studies of some industry applications like Middle Pillar to Rocker Joint
   Design and Hat section Design.

5. Analyze the optimization of interconnected elements under single load and
   multiple load cases

As time permits:

6. Suggestions for improving the Evolutionary Structural Optimization procedure

7. Evaluate the stiffness design criterion.

AGREEED:

_____(Student) _____ , _____(Supervisor)

18 /3/ 2005   30/0/05   13/ 4 05

APPENDIX B

Appendix

ANSYS GUI Program

To build a structure design: (straight connection case)

Start with new Analysis
        Preferences
                Click Structural
                        OK

Pre-processor
        Element type
                Add/Edit/Delete
                Add
                        (Solid) & (Brick & node 185)
                        CLOSE

        Material Props
                Material Models
                Material Model number 1
                        Structural
                        Linear
                        Elastic
                        Isotropic
                              $EX = 210E9$
                              $PRXY = 0.3$
                              OK

Edit
        Copy
        OK
Material Model number 2
        Linear Isotropic
                $EX = IE + 011$
                $PRXY = 0.3$
                OK
                X Exit

Modelling
        Create
                Volumes
                      Block   By dimensions

$X_1 , X_2 = 0, 0.45$
$Y_1 , Y_2 = 0, 0.15$ - APPLY
$Z_1 , Z_2 = 0, 0.01$

X$_1$, X$_2$ = 0.3 , 0.45
Y$_1$, Y$_2$ = 0 , 0.15   - APPLY
Z$_1$, Z$_2$ = 0.01 , 0.015

X$_1$, X$_2$ = 0.3 , 0.75
Y$_1$, Y$_2$ = 0 , 0.15   - OK
Z$_1$, Z$_2$ = 0.015 , 0.025

Operate
  Booleans
    Glue
      Volumes 9 Pick All

Plot Operate
  Specified Entities
    Volume 1, 4, 1
        OK

  Create
    Volumes
      Block By dimensions

X$_1$, X$_2$= 0.3 , 0.31
Y$_1$, Y$_2$ = 0 , 0.15   - APPLY
Z$_1$, Z$_2$ = 0.01 , 0.015

X$_1$, X$_2$= 0.3 , 0.45
Y$_1$, Y$_2$ = 0.14 , 0.15   - OK
Z$_1$, Z$_2$ = 0.01 , 0.015

    Copy
      Volume Pick horizontal
        OK

   8, 0.02, 0, 0 no. of copies, DX, DY, D
        OK

    Copy
      Volume Pick vertical
        OK
      8, 0,-0.02, 0
        OK

  Operate
    Booleans
    Subtract volumes Pick all the bases $_{st}$V
        OK

Pick all &
   OK

Glue
   Volumes Pick all

Meshing

Mesh tool   Element Atrriutes : Volumes
SET 6 Pick 1&2 plates
   OK

Material number = 1
Apply
   Pick all elements
    OK

Material number = 2
   OK

Mesh tool size controls:
Global SET
Size element = 0.01
No. of element = 0
   OK

Lines SET
Pick DY for 1 & 2 place
   OK

Size element = 0.01
No. of elements =15
Size , NOIV = NO
   APPLY

Pick DX for 1&2 place
   OK

Size element = 0.01
No. of elements = 45
SIZE, NOIV = NO
APPLY

Pick DE for 1 & 2 place
   OK

Size element = 0.01
No. of elements = 1
SIZE, NOIV = NO

Mesh tool
        Mesh : volumes
        Shape : HEX/Wedge :Sweep
        SWEEP
        Pick for 1&2 place
                OK

Plot
        Specified Entities
                Volume 1, 68, 1
        Mesh tool
                Lines SET
                Pick all DX, DY for all elements
                        OK

        Size element = 0.01
        No. of elements = 45
        SIZE, NOIV = NO
                APPLY

        Pick DZ for all element
                OK

        Size element = 0.005
        No. of elements = 1
        SIZE, NOIV = NO
                OK

Mesh tool
        Mesh : volumes
Shape : HEX/Wedge :Sweep
        SWEEP
        Pick all elements
                OK

To apply load cases:
Solutions
    Define loads
        Apply Structural
                Displacement
                On areas Pick boundary condition in 1 place
                        OK

                DOF1 = All DOF
                Displacement Value =0
                        OK

            Force/moment
                On nodes Pick a nodes

OK
Directions = FY
Value = -150
OK

(Warning _ CLOSE)

To solve the structure:
Solve
Current LS
OK 2 Warning ± CLOSE
X exit

General Postproc
Plot results
Contour plot
Item be contoured = stress : Von Mises SEQV
OK

List Results
Element solution
Energy : strain energy SENE
OK

To copy into Excel:
Copy the results from table from 1350 to 1399
Paste in notepad
Open excel

Open the Notepad file
Save in excel _ 2 rows
Next
V space
FINISH

In Excel make ie 3 rows

Si	i	Alfa i
.	.	.
.	.	.

Alfa i = i = $\underline{\text{Si}}$.
$\quad\quad\quad$ Si max

Then using i Ü RRss = 0.0

From table remove 1372
- 1366
- 1384
- 1360
- 1370

Removing elements
Pre-processor
   Meshing Clear
      Volumes Pick the elements that want to be removed
         OK

   Modelling _ Delete
      Volumes only Pick the element that want to be removed
         OK

   PLOT 3 Replot
4)
Solution _ solve
   Currene LS _ warning CLOSE
     X exit

General postproc _ list results
   Element solution _ energy : strain energy SENE
         OK

Repeat for 2nd iteration

FEA diagrams haven been taken using ANSYS program
Single load case design example for Straight Connection Case
At the initial state
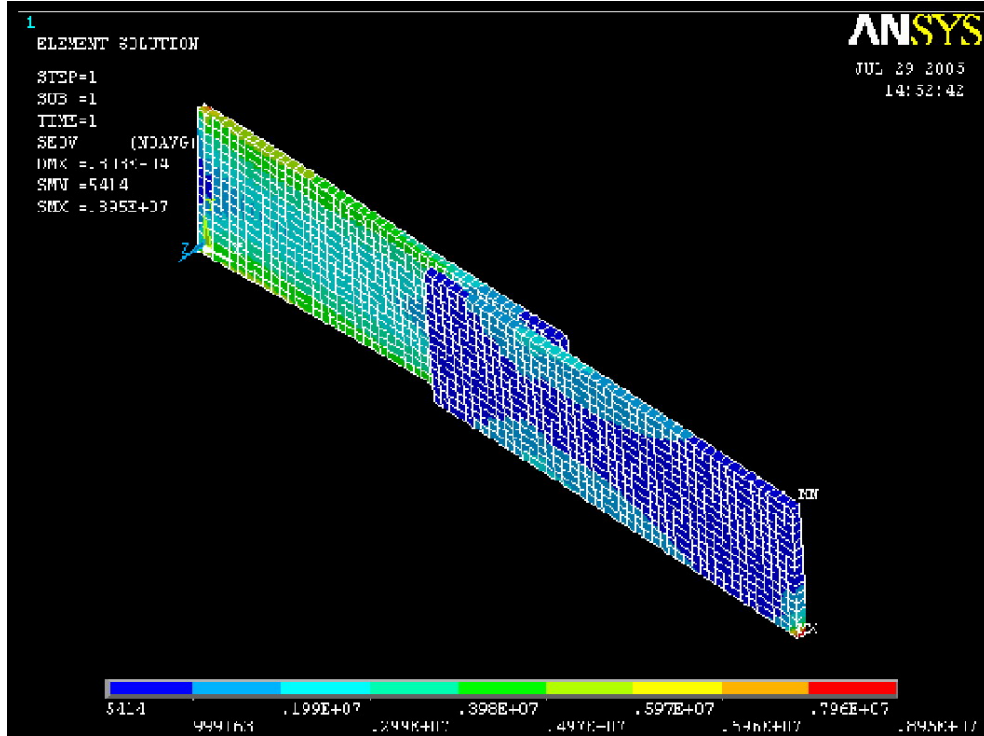
At Isometric View
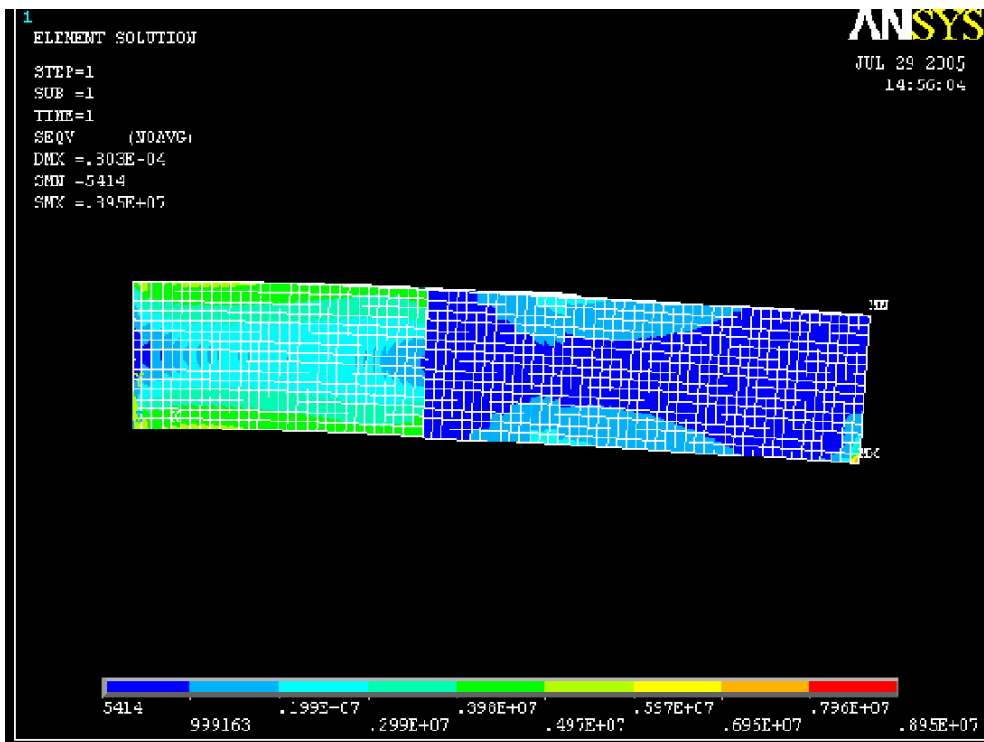
At Front View
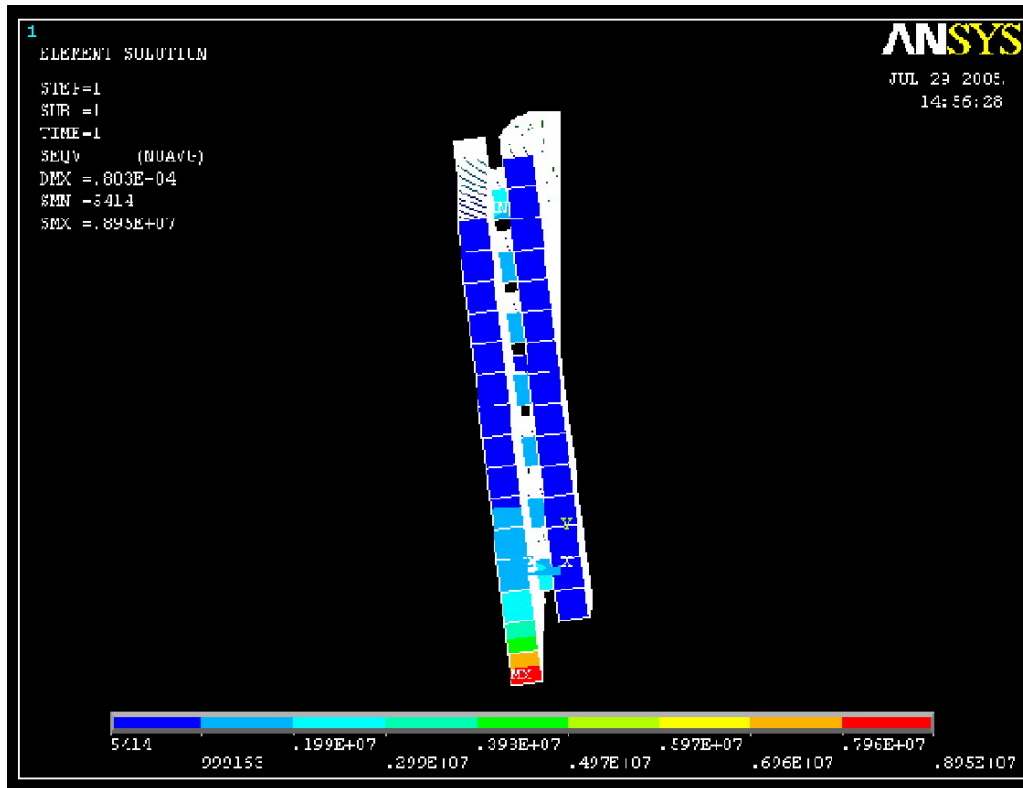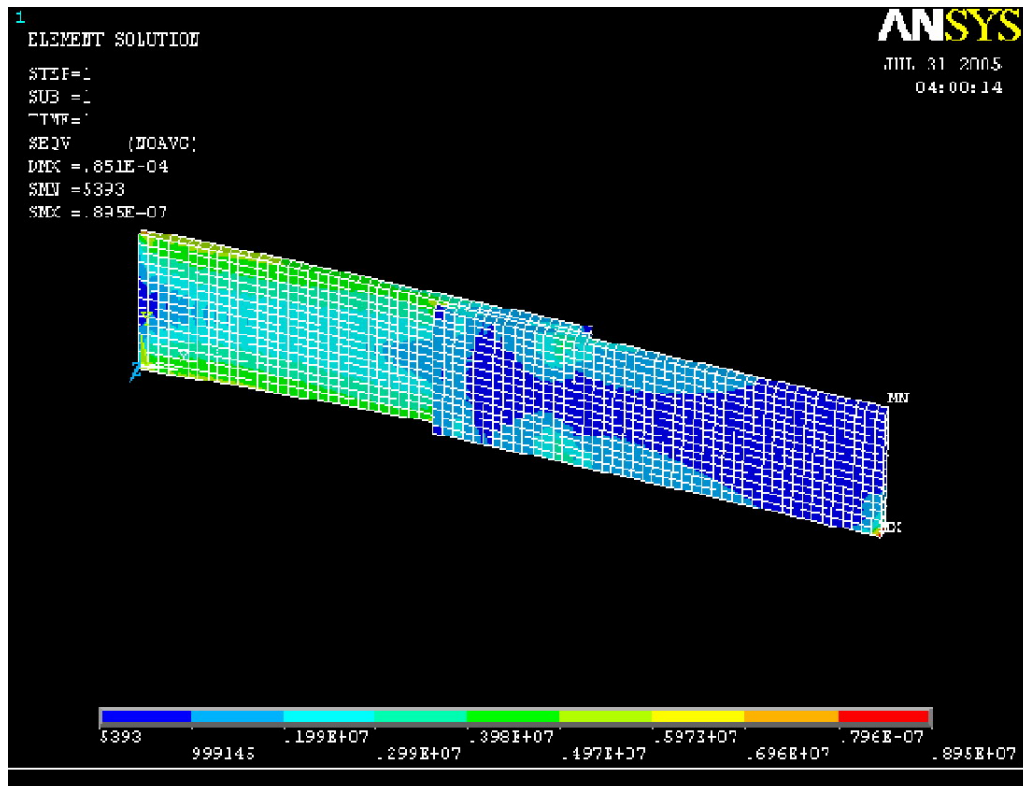
At Right View

At Oblique View
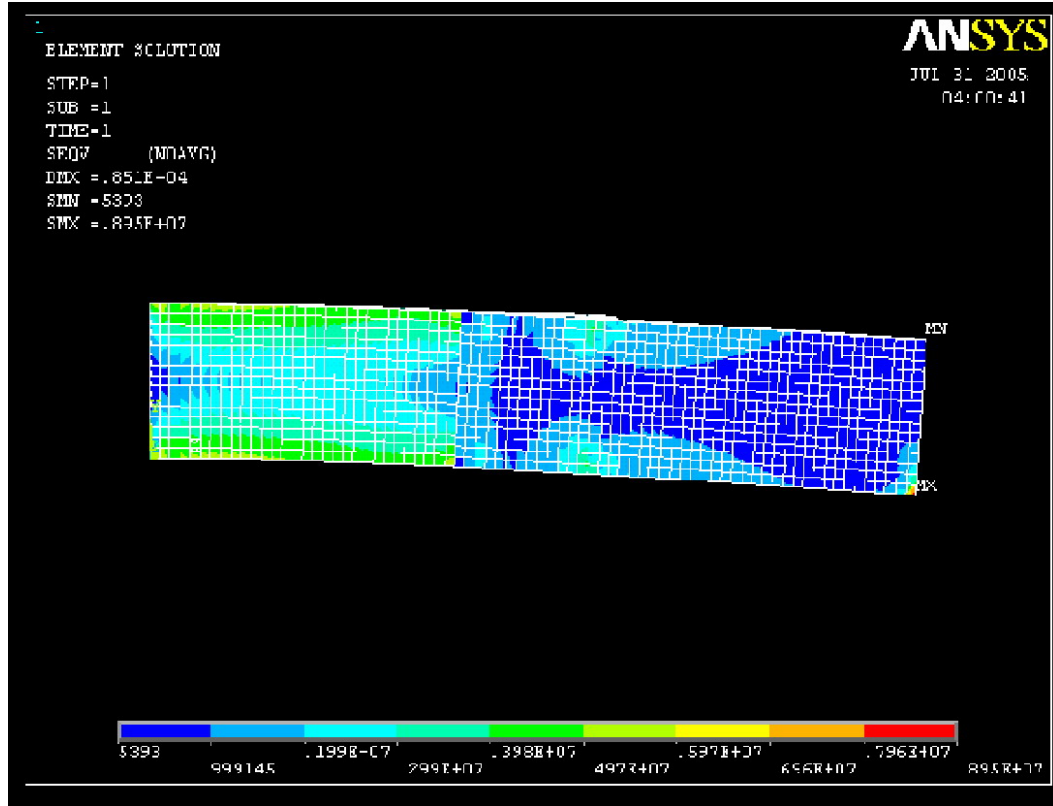
At Front View
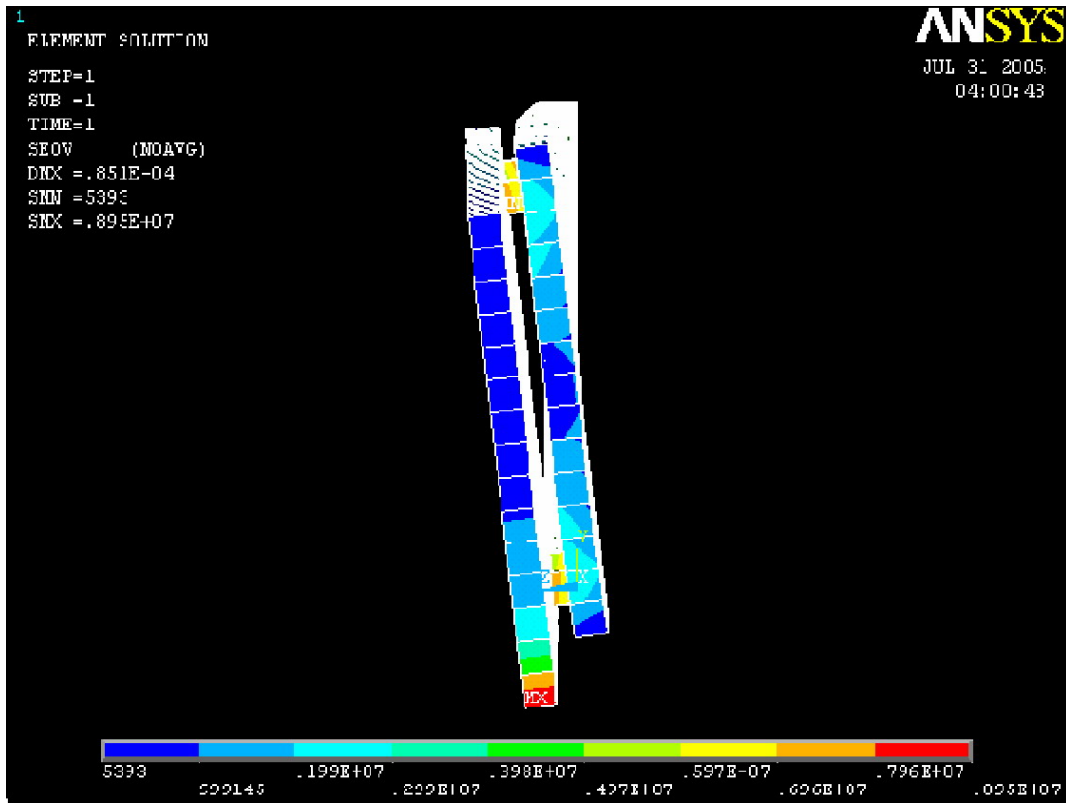
At Right View

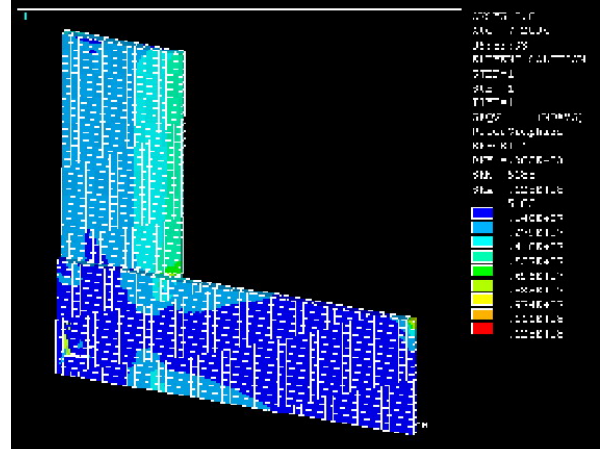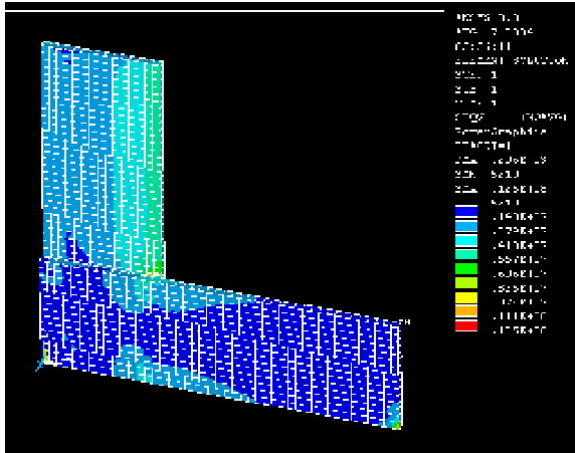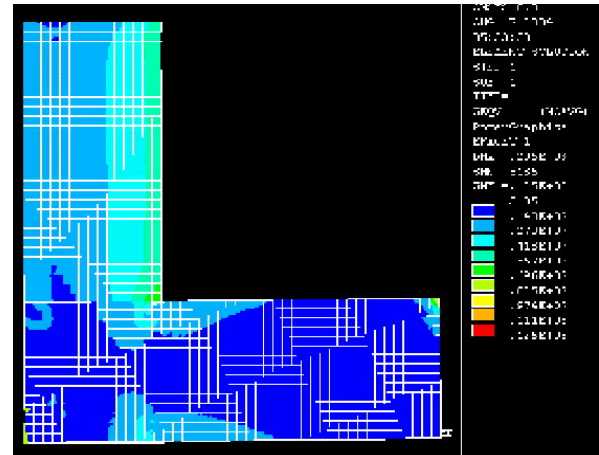**Multiple load cases design example for L-shaped Connection Cases**
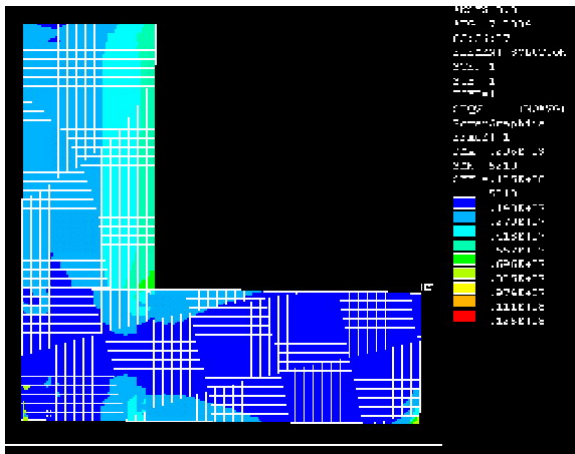**At the initial state**
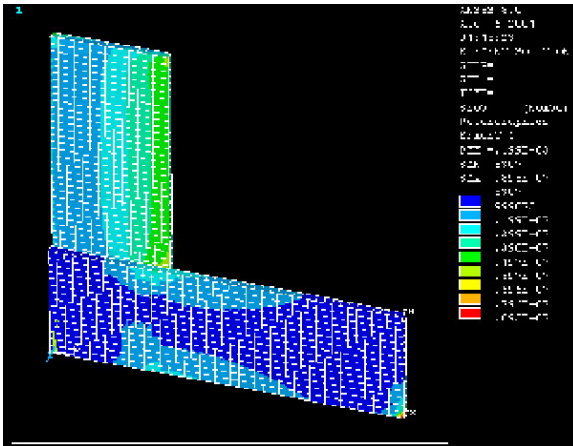
a. The force applied to downward direction
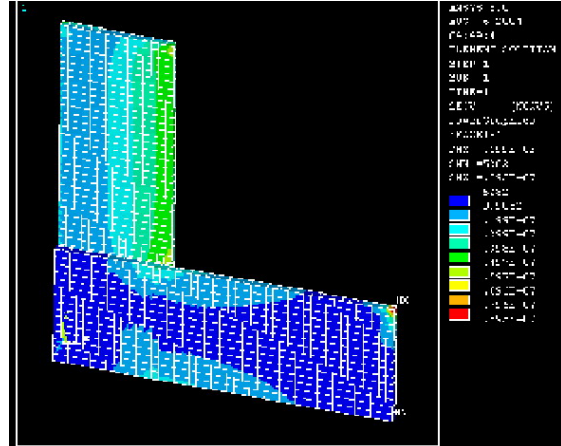
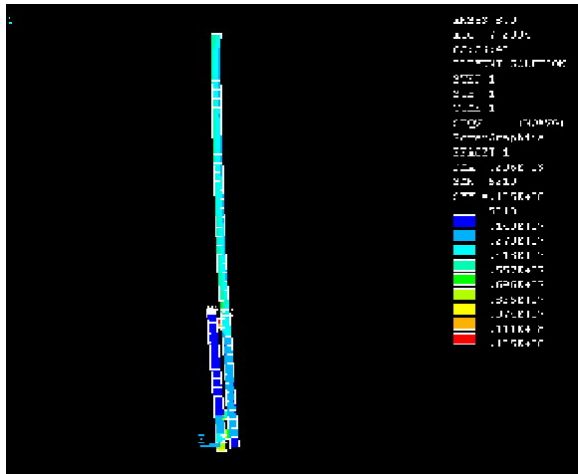b. The force applied to upward direction

At Oblique View
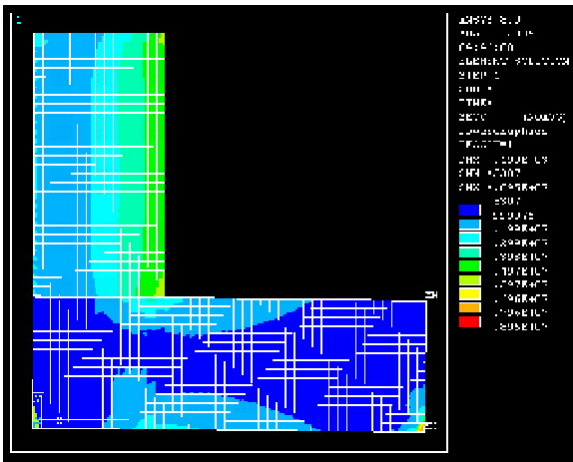
a. The force applied to downward direction
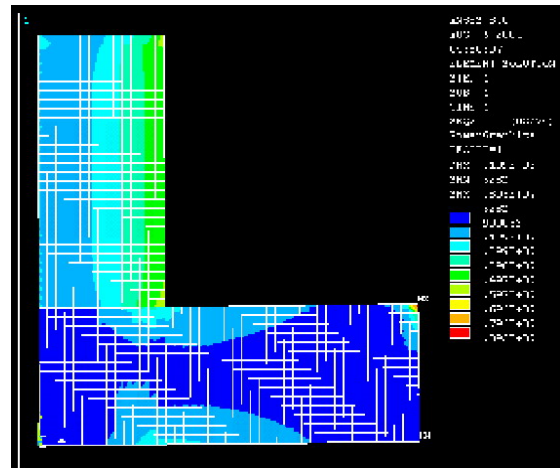
b. The force applied to upward direction

At Front View
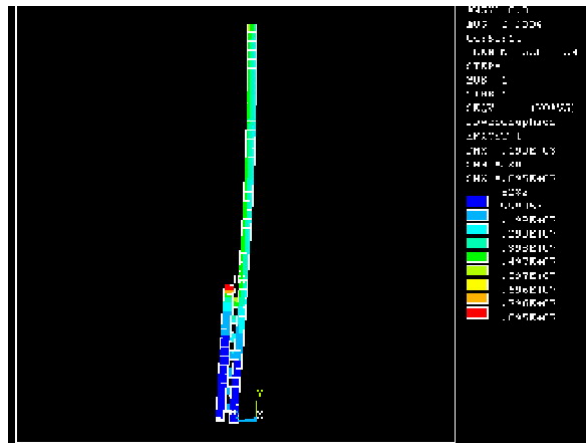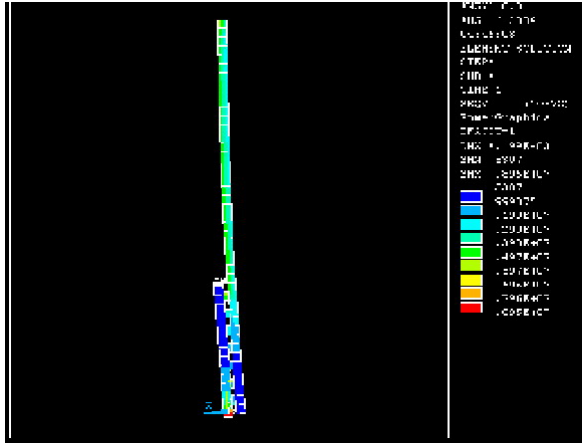
a. The force applied to downward direction b. The force applied to upward direction

At Right View

At the final state

a. The force applied to downward direction   b. The force applied to upward direction
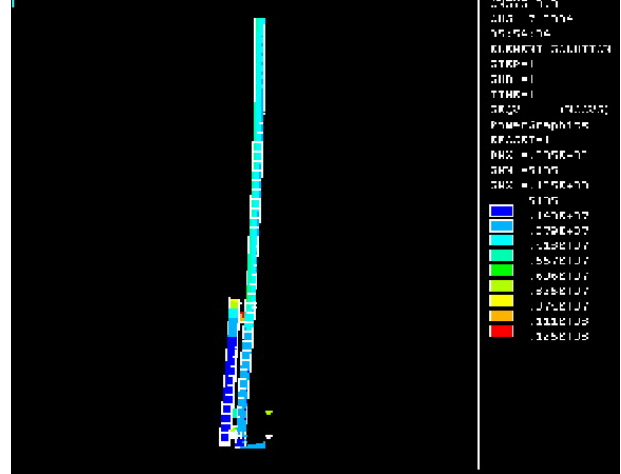
At Oblique View

a. The force applied to downward direction   b. The force applied to upward direction

At Front View

a. The force applied to downward direction   b. The force applied to upward direction

At Right View