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Multidisciplinary Structural Truss Topology Optimization for Reconfigurability

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This paper proposes structural topology optimization that considers design reconfigurability. The ability of a structural system to be reconfigured allows it to perform well under different considered loading conditions. Performance is measured in this paper as manufacturing cost, subject to structural constraints. The manufacturing process of abrasive waterjet (AWJ) cutting is used to estimate manufacturing cost. Potential penalties, such as additional mass, resulting from the embedment of reconfigurability into a structural design are discussed. The advantages and disadvantages of design for reconfigurability are also discussed in the context of structural topology optimization.

Nomenclature

C = Abrasive waterjet (AWJ) cutting speed estimation constant
C_{man} = Total manufacturing cost, [$]
d_m = Mixing tube diameter of the AWJ cutting machine, [in]
d_o = AWJ cutter orifice diameter, [in]
f_a = Abrasive factor for abrasive used in AWJ cutter
h = Thickness of material machined by AWJ, [cm]
l_i = Curve length of each constant cutting speed section along the cutting curve of the part, [in]
M_a = AWJ abrasive flow rate, [lb/min]
n = Number of modules
n_{max} = Loading case number with maximum vertical deflection constraint value
n_{lc} = Number of loading cases considered
N_m = Machinability number
OC = Overhead cost for machine shop, [$/hr]
P_i = AWJ cutting perimeter for i^{th} structural element, [cm]
P_w = AWJ water pressure, [ksi]
q = AWJ cutting quality
u_{max} = AWJ maximum linear cutting speed approximation, [cm/min]
$x^{(j)}$ = Vector of element cross-sectional areas of j^{th} length, [cm^2]
X = Vector of design variables, [cm^2]
Y = Configuration of structural elements

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δ = Deflection [cm]
σ = Stress [Pa]

I. Introduction

TYPICALLY, structural design optimization is performed by only considering the structural performance of the design in the optimization process for a single load case. Conventional structural performance metrics are stress, mass, deformation, or natural frequencies. Another important aspect to be considered in structural optimization is loading condition variation. In this work, we propose a new design optimization framework that deals with structural optimization considering many different loading conditions. These loading conditions are assumed to never be applied simultaneously to the structure. The goal is not to make the system insensitive, but to make it reconfigurable such that it can deal with these various loading conditions well. While robust design is a passive response to different loading conditions, design for reconfigurability is an active response. The incorporation of this reconfigurability into structural design can lead to significant benefits such as reduced manufacturing cost.

An overview depicting the procedure used to produce an optimal reconfigurable design introduced in this paper is shown in Fig. 1. This illustrative example is of a truss structure subject to various loading conditions. The solution to be obtained is not a single optimum solution, but an optimum set of optimum parts that can be reconfigured to form several different designs.

In this procedure, a reconfigurable two-dimensional truss structure is designed based on structural performance and the reconfigurability of the structure. The result of the optimization routine is an optimum set of optimum parts based on the requirements defined in the problem statement.

The motivation for incorporating reconfigurability into structural design in this paper is to account for various loading conditions experienced in the application of a specific structural design. More specifically, in this work design reconfigurability allows for a structural design to accommodate loading variation.

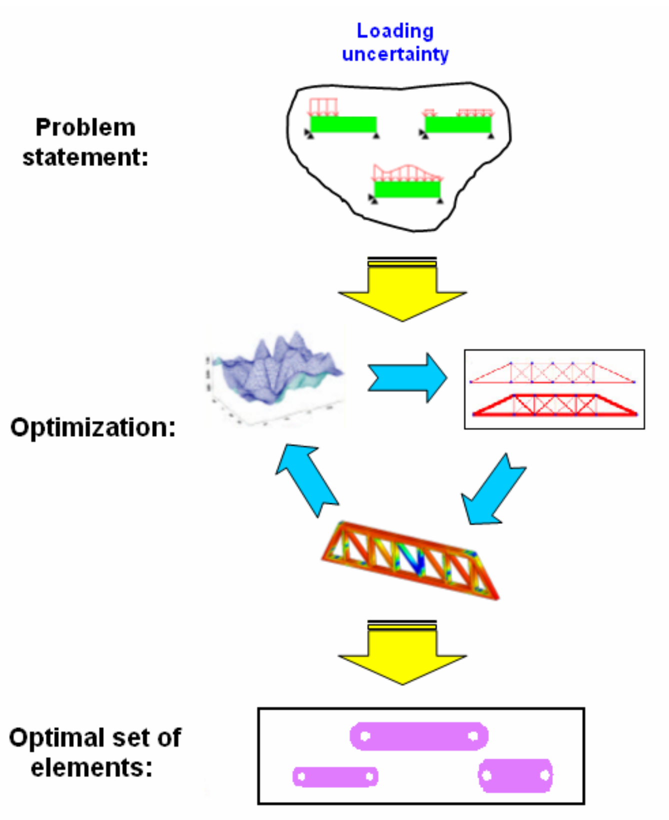


Figure 1: Optimization for reconfigurability procedure.

Structural design optimization is typically done by considering one set of requirements to create a customized structural design. In this paper, this is referred to as "Method I" optimization. Another method of performing structural optimization is to consider several sets of requirements and design a structure which performs well for the set of requirements considered, a design envelope. In this paper, this method of structural design optimization is referred to as "Method II" optimization. Structural design optimization for reconfigurability, in which a single set of components is designed to be reconfigured for various structural requirements, is referred to as "Method III" optimization. These structural design optimization methods are illustrated in Fig. 2. In the figure, custom designs are created for each considered load case, an enveloping design is created for both load cases, and a set of structural components are created which can be reconfigured into feasible structural designs for each load case considered. The magnitudes of the cross-sectional areas of the truss structure elements are depicted as the thickness of the lines in Fig. 2.

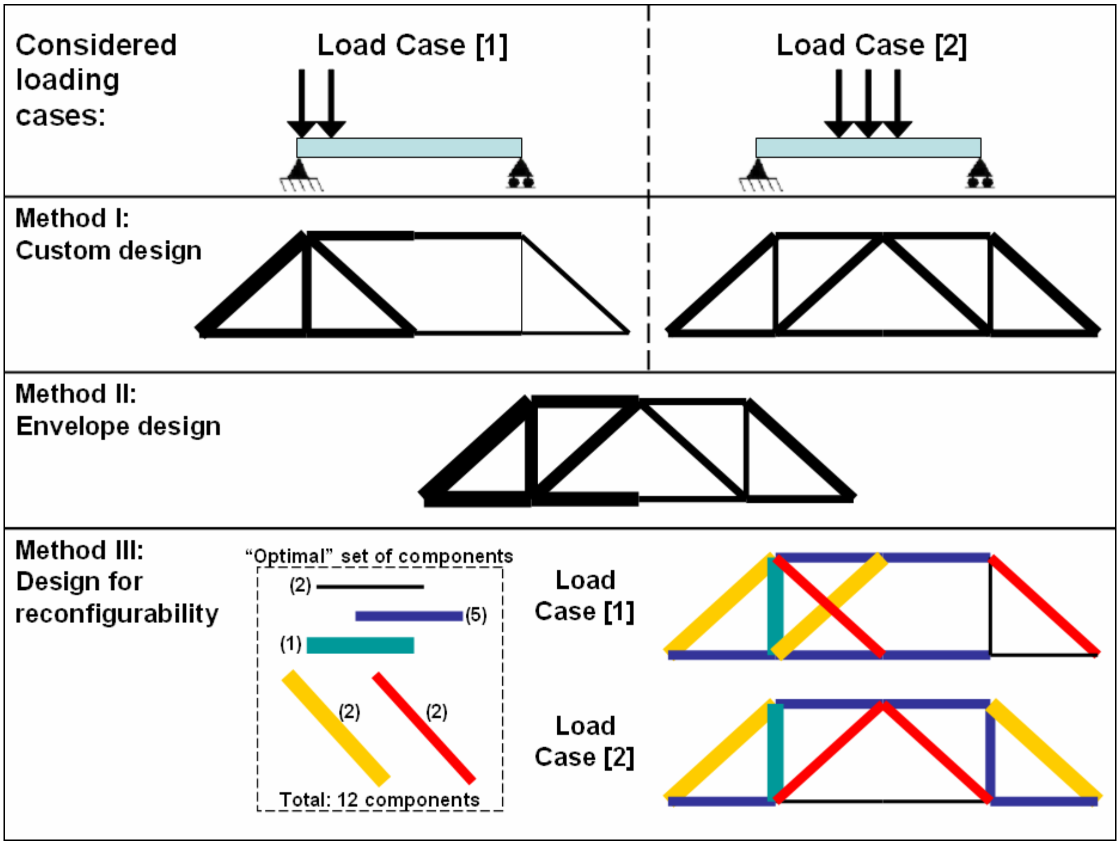


Figure 2: Three structural design optimization methods considering different loading conditions.

The goal is to design a set of parts that can be reconfigured to form various structural designs which can each accommodate different loading requirements. The set of optimum parts used to build these varying structural designs is obtained through designing considering reconfigurability. We consider an important metric to represent the performance of the structural design: manufacturing cost.

Manufacturing cost is chosen to be the metric for this project because the structural designs being optimized are assumed to be used in the private sector. The goal sought by the private sector is to improve profit margin. The consideration of reconfigurability in design allows for a reduction in costs. This reduction in costs is made possible because the manufacturer can mass-produce one set of components which can satisfy many different customer requirements rather than manufacturing a custom-designed structure for each customer need. This ability to manufacture few custom designs and satisfy many customer requirements allows the manufacturer to reduce costs. This in turn improves the profit margin of the manufacturer and is integral to the health of a private business. Design for reconfigurability can help private industry reduce costs by reducing manufacturing costs for a structure by designing a reconfigurable structure that can handle various loading conditions.

A more general definition for design reconfigurability presented in this paper is discussed here. A reconfigurable structure is composed of modules that are interchangeable and can be configured to create various structural designs. Structural reconfigurability is the ability of the structure to be modified in order to respond to

Figure 3: The Medium Girder Bridge being used by the Swiss Army. From Swiss Military website, http://zem.dev.imagefinder.ch.

different loading conditions. In the case of the truss structure elements considered in this paper, a module is an element in the "optimal" set of structural elements. Reconfiguration can be done between modules of the same length.

An example of structural reconfigurability comes from the Swiss Army. The Swiss Army uses a modular, reconfigurable bridge called the Medium Girder Bridge[1] for supporting the transport of military vehicles. This bridge can be assembled quickly for various spans and loading conditions resulting from vehicles such as jeeps or tanks. A picture of this bridge design is shown in Fig. 3.

A. Literature Survey

The goal of structural topology optimization is to determine an optimal layout in order to minimize an objective function of a structure while satisfying given constraints.

Pantelides and Ganzerli[2] performed truss structure design optimization for uncertain loading conditions. Loading uncertainties of magnitude and direction were considered and optimization objectives of structural volume and displacement were minimized.

Bendsøe and Kikuchi[3] first proposed the homogenization method for structural topology optimization, where a number of microstructures represent a structure. An optimality criterion method is used in the homogenization method, and it has been applied to a variety of problems.[4] Yang *et al.* proposed artificial material and used mathematical programming for topology optimization.[5] This method is easy to formulate and use. All the topology optimization method assumed a fixed number of design variables or a fixed design domain. Kim and Kwak[6] proposed a concept of variable number of design variables, which results in a variable design domain. The generalized optimization, which is called as a design space optimization, was applied to structural topology optimization and plate optimization.

One major component of flexible design, modularity, has been studied as a component of structural design. This work has been performed Cetin, Saitou, Nishigaki, Nishiwaki, Amago, and Kikuchi.[7] In their research, Cetin *et. al.* performed a two-step optimization process in which an optimal structural topology design was decomposed into optimal modular components. Structural strength, assemblability, and modularity were considered in the decomposition optimization problem.

It can be seen in the literature survey that while research has been done on structural topology optimization as well as topics such as modularity, no research has been done on structural topology optimization considering design reconfigurability.

The goal of this research is to investigate the manufacturing cost benefits resulting from the incorporation of reconfigurability into structural design by studying the effects of design reconfigurability on two dimensional truss structure designs.

II. Problem Statement

In this section, a multidisciplinary optimization problem statement is presented. This is followed by a description of the optimization methods used to facilitate the solution of the optimization problem.

$$\min f(X) = C_{man} \tag{1}$$

where

$$X \equiv \left(\left\{x^{(1)}\right\}, \left\{x^{(2)}\right\}, \ldots, \left\{x^{(m)}\right\}\right) \tag{2}$$

subject to

$$\delta^{[n_{\max}]}(X, Y) \le \delta_c \tag{3}$$

$$\sigma^{[n_{\max}]}(X, Y) \le \sigma_c \tag{4}$$

where

$$\delta^{[n_{\max}]}(X,Y) = \max[\delta^{[1]}(X,Y)\cdots\delta^{[n_{lc}]}(X,Y)] \tag{5}$$

with

$$x_{LB} \le x_i \le x_{UB} \quad (i = 1,\dots,n) \tag{6}$$

where f is the objective function, X is the design vector composed of cross-sectional areas of each truss structure element, Y is the configuration of the truss structure elements, and $x^{(j)}$ is a vector of cross-sectional areas of j^{th} length. In addition, $\sigma^{[i]}$ is the vector of element stresses in the truss structure exposed to the i^{th} loading condition, $\delta^{[i]}$ is the maximum vertical nodal deflection in the truss structure while exposed to the i^{th} loading condition, C_{man} is the total estimated manufacturing cost of the structure, and x_{LB} and x_{UB} are the side constraints for the design vector variables. In addition, n_{lc} is the total number of loading cases considered, n_{max} is the loading case in which the maximum vertical nodal deflection constraint is maximum, m is the number of unique truss element lengths, and n is the total number of truss elements being optimized in the truss structure.

III. Theory

A. Optimization Method

The optimal reconfigurable structural design for the given range of design requirements driven by various loading conditions is determined using an optimization approach shown in Fig. 4. The outer loop optimizes the cross-sectional areas of the structural elements. An inner loop for each considered loading condition performs a random search reconfiguration of the structural elements to find a feasible configuration.

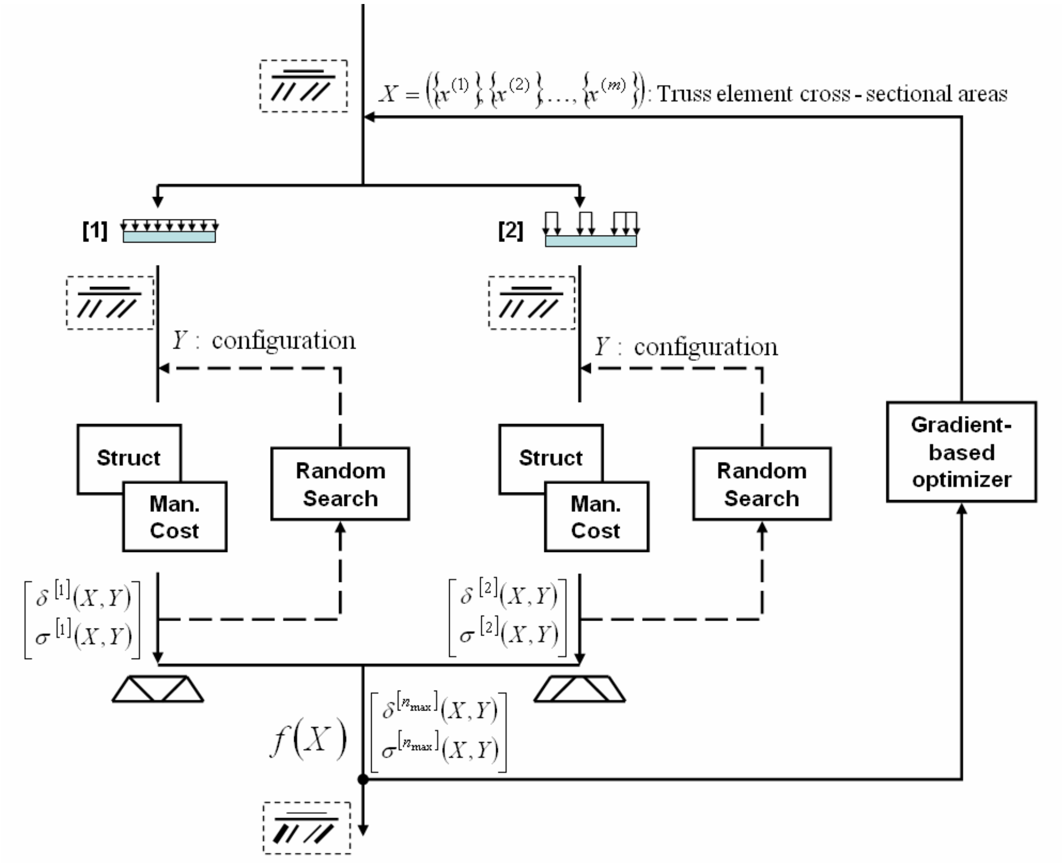


Figure 4: Method III optimization flow chart.

1. Outer loop: size optimization

The outer loop of the optimization procedure, used to optimize the cross-sectional areas of the set of truss structure elements, is performed using a gradient-based optimization algorithm. MATLAB function *fmincon*, a sequential quadratic programming-based optimizer, is used. The relative ease with which fmincon was incorporated with the system model modules, also written in MATLAB, made the algorithm a suitable choice for this problem. A second reason for the selection of a gradient-based optimization algorithm for the outer loop was the fact that all outer loop design variables are continuous.

2. Inner loop: reconfiguration

The inner loops of Method III optimization perform a random search for a feasible structural configuration. One inner loop is required for each loading condition considered. The goal is to find a structural configuration which satisfies the design constraints. This procedure is illustrated in Fig. 5. The random search is performed by perturbing the structural design and performing structural analysis of the perturbed design to check if it satisfies the stress and deflection constraints. Each perturbation in the random search interchanges one pair of truss elements of the same length at a time in the design vector. Optimization is not necessary in the inner loop because the structural configuration is independent of the objective function.

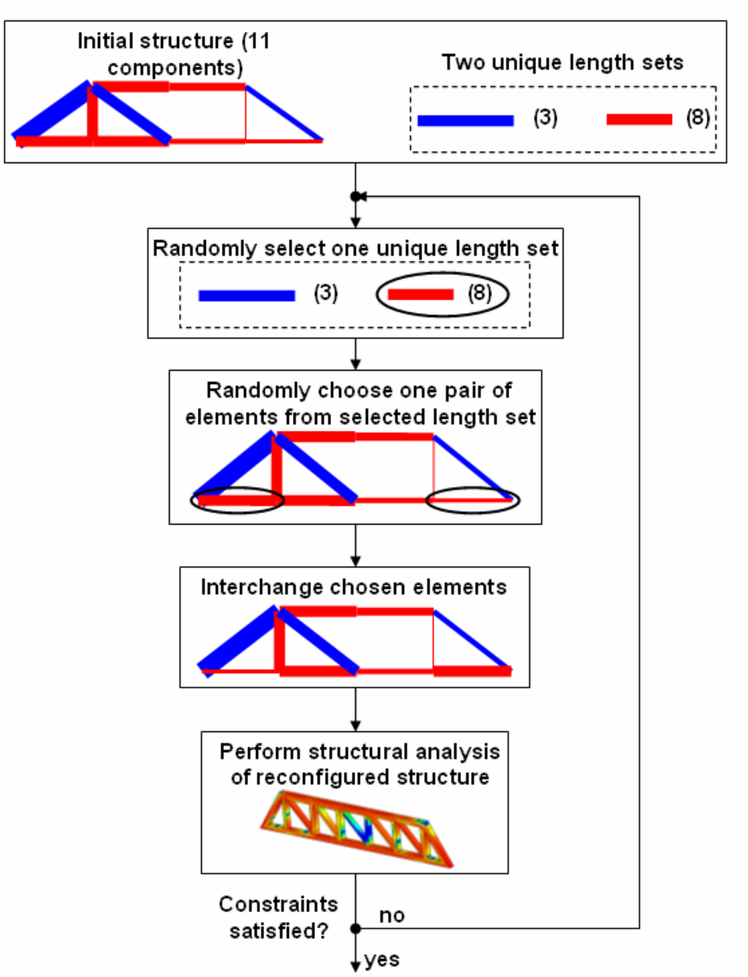


Figure 5: Method III inner loop reconfiguration procedure.

B. Manufacturing Cost Estimation

The manufacturing method used to estimate manufacturing cost for the bridge structural components is abrasive water jet (AWJ) cutting. This manufacturing method uses a powerful jet of a mixture of water and abrasive and a sophisticated control system combined with Computer-Aided Machining (CAM) software. This allows for accurate movement of the cutting nozzle. The end result is a machined part with possible tolerances ranging from ±0.001 to

±0.005 inches. It is possible for AWJ cutting machines to cut a wide range of materials including metals and plastics.[8]

The inputs to this AWJ manufacturing cost estimation module include the design vector variables and parameters such as element lengths, cross-sectional areas, material properties, and material thickness. The output of this module is the manufacturing cost of each bridge structural element.

Based on the material thickness and material properties, a maximum cutting speed is determined for the AWJ cutter. An important assumption made in this module is that the cutting speed of the waterjet cutter is constant throughout the cutting operation. In reality, the cutting speed of waterjet will slow if any sharp corners or curves with small arc radii lie in the cutting path. A visualization for a generic truss element to be machined using the AWJ process is shown in Fig. 6. The cutting path is denoted by the dashed line.

L_i is the length of element i, w_i is the width of element i, h is the user-defined material thickness, and x_i is the cross-sectional area of element i.

The important factors used in determining the manufacturing cost are the cutting length, P_i, the maximum linear cutting speed, u_{max}, the overhead cost associated with using the AWJ cutting machine, OC, the cross-sectional areas of each element, x_i, and the material thickness, h. The equations for the first three of these factors are detailed below in Equations (7), (8), and (9).

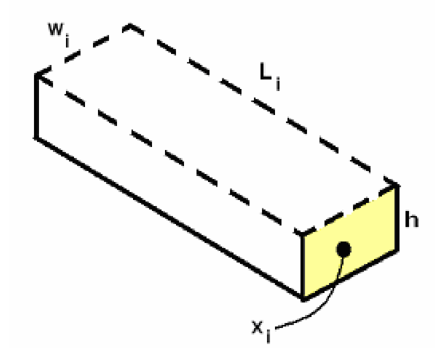


Figure 6: Example truss structure element to be machined using AWJ cutting.

$$P_i = 2L_i + 2w_i \tag{7}$$

$$u_{\max} = \left(\frac{f_a N_m P_w^{1.594} d_o^{1.374} M_a^{0.343}}{Cqhd_m^{0.618}} \right)^{1.15} \tag{8}$$

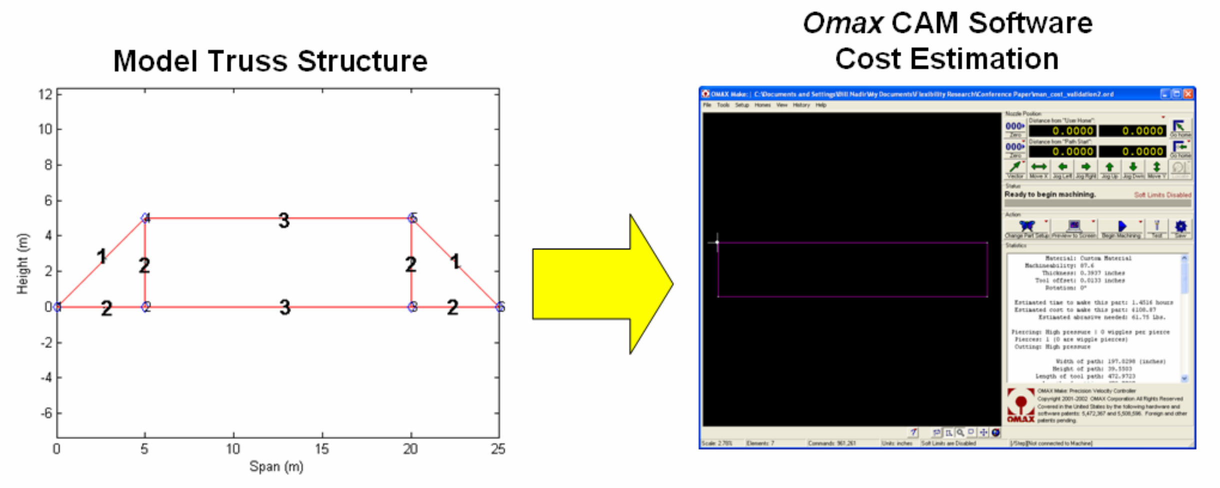
$$OC = \$75 / hr \tag{9}$$

where f_a is an abrasive factor, N_m is the machinability number of the material being machined, P_w is the water pressure, d_o is the orifice diameter, M_a is the abrasive flow rate, q is the user-specified cutting quality, h is the material thickness, d_m is the mixing tube diameter, and C is a system constant that varies depending on whether metric or Imperial units are used.[9]

Total manufacturing cost is estimated using Equation (10).

$$C_{man} = \sum_{i=1}^{n} \left(\frac{P_i}{u_{\max}} * OC \right) \tag{10}$$

In order to validate this module, a simple truss structure is created and manufacturing cost results from the cost estimation module are compared to hand calculations. The truss structure used to perform this validation is shown in Fig. 7. Note that the numbers near the elements will be used to define the manufacturing cost associated with those truss elements.



Ready to begin machining.

```
        Material: Custom Material
   Machineability: 87.6
       Thickness: 0.3937 inches
     Tool offset: 0.0133 inches
        Rotation: 0°

 Estimated time to make this part: 1.4516 hours
 Estimated cost to make this part: $108.87
       Estimated abrasive needed: 61.75 lbs.

Piercing: High pressure | 0 wiggles per pierce
 Pierces: 1 (0 are wiggle pierces)
 Cutting: High pressure

             Width of path: 197.0298 (inches)
            Height of path: 39.5503
       Length of tool path: 472.9723
```

OMAX Make: Precision Velocity Controller
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Covered in the United States by the following hardware and software patents: 5,472,367 and 5,508,596. Foreign and other patents pending.

Figure 7: Manufacturing cost model validation procedure.

In order to estimate the manufacturing cost, the cross-sectional areas for all of the truss structure elements are assumed to be equal to 100 cm^2, the material thickness is assumed to be 1 cm, and the structure material is selected to be A36 steel. Using these inputs, the manufacturing cost of each element was estimated using the manufacturing cost estimation module and compared with the corresponding manufacturing cost using Omax AWJ computer-aided manufacturing (CAM) software.[10,11] These results are shown in Table 1.

The manufacturing cost estimates from the cost estimation model overestimate the cost by roughly 25% when compared with the Omax CAM waterjet manufacturing cost estimation. This is due to the fact that the cost model is based on a theoretical maximum linear cutting speed while the Omax CAM software allows for increased cutting speed. Although the discrepancy in the cost estimation is somewhat large, the difference is fairly consistent and should not negatively affect the results of this project.

Table 1: Manufacturing cost estimation module results.

Element Design	Omax Manufacturing Cost ($)	Cost Model Manufacturing Cost ($)
1	146.31	182.88
2	108.87	135.97
3	289.74	362.59
Totals	544.92	681.44

IV. Results

A. Structural Optimization Example

The concept of structural design optimization for reconfigurability is now applied to a two-dimensional truss structure. The simply-supported truss structure design and the loading conditions considered are shown in Fig. 8. The assumed load for each load case is 6200 kN. All nodes are free in the XY plane except for the constrained nodes depicted in the figure. The two considered loading conditions for this example, denoted by [1] and [2], are also shown in Fig. 8. The material selected for this example is A36 Steel with a Young's modulus of 200 GPa, a Poisson's ratio of 0.26, and a yield strength of 250 MPa. A factor of safety of 1.5 was also assumed for this example. The maximum and minimum cross-sectional areas of each truss element are assumed to be 1100 cm^2 and 0.001 cm^2, respectively. Realistically, this allows the optimizer to remove truss elements if the cross-sectional areas approach the lower design variable side constraint.

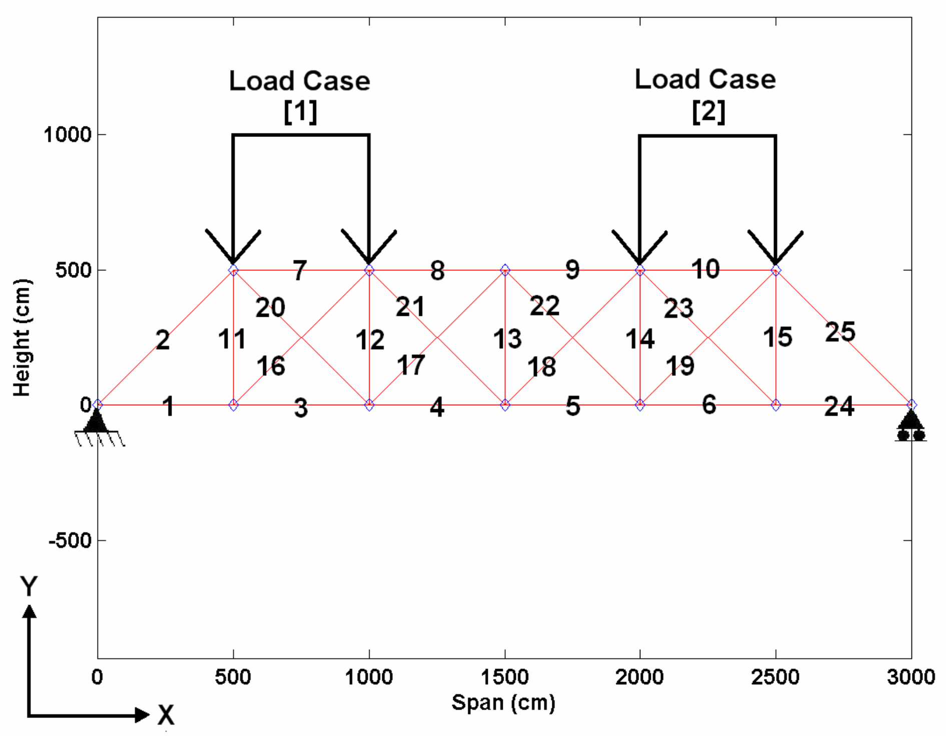
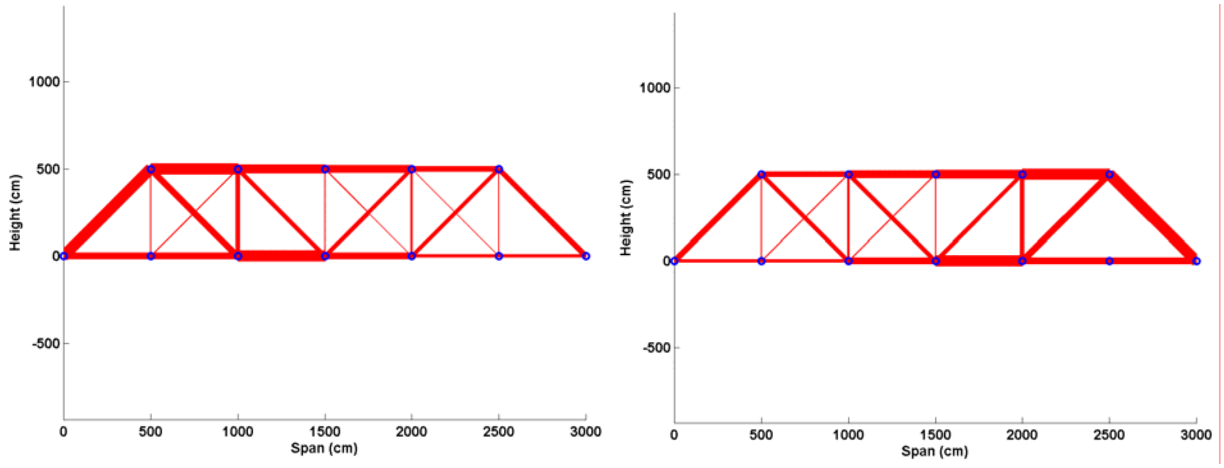


Figure 8: Simply-supported truss structure layout with truss elements labeled and loading conditions considered.

1. Method I Optimization: Custom design

Optimizing the structure for each load case results in unique structural designs for each load case considered. These two custom designs are shown in the following figure. The magnitudes of the cross-sectional areas of each truss structure element are depicted as the thickness of the lines in the following figures.



a) Design for Load Case [1]

b) Design for Load Case [2]

Figure 9: Method I structural design solutions.

It can be seen in Fig. 9 that Method I optimization results in two significantly different structural designs. The “optimal” cross-sectional areas of each structure are different due to the different loading conditions.

2. *Method II Optimization: Design for requirements envelope*

Designing a structure that can accommodate all load cases is another strategy for structural design. If all load cases are at-once considered during structural design optimization, an "optimal" structure shown in Fig. 10 is found.

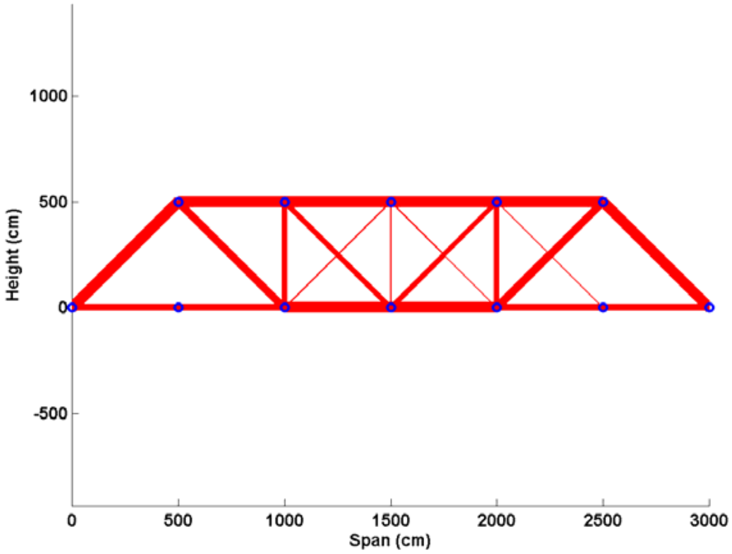
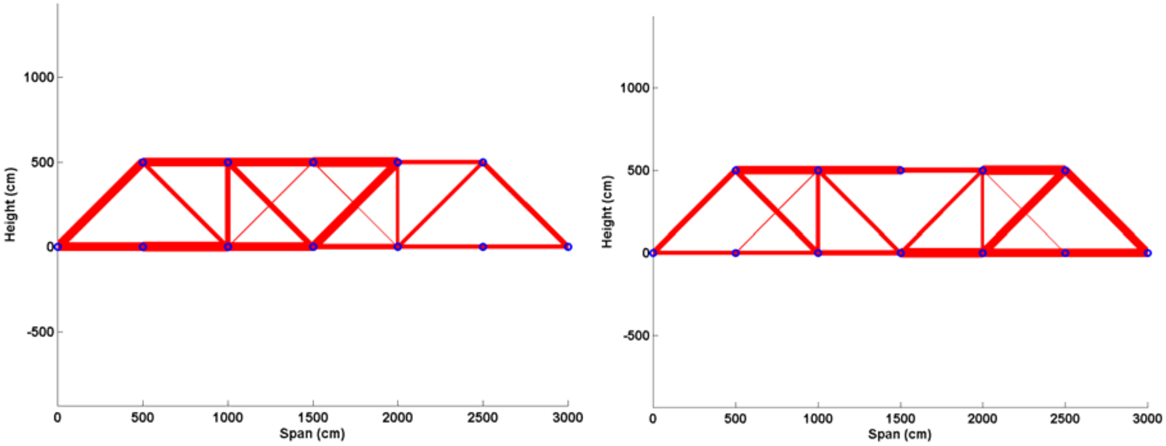


Figure 10: Method II structural optimization results.

Consider Fig. 10. The structural design solution resulting from Method II optimization in which all loading cases are considered at-once is nearly symmetric. This is due to the fact that the two load cases considered are mirror images of each other. This structural design is inefficient since the one structural design must accommodate all loading cases and the assumption is made that both load cases will – in reality – not be applied simultaneously. The above structural design is "over-designed" if it is simply exposed to one of the considered loading conditions.

3. *Method III Optimization: Design for reconfigurability*

A structure designed for reconfigurability can provide the many benefits of a custom design while being able to accommodate all loading cases considered. The results from optimizing the structure for reconfigurability are shown below. This optimization was performed using the optimization method described in Fig. 4. It is important to mention that the best results were obtained by using the Method II structural design result as the initial design topology for Method III structural design optimization. This initial design choice was made so the Method III optimization could start in the feasible region of the design space. This was found to reduce computation time since less time is spent randomly searching the design space for feasible configurations in the inner loop of the Method III optimization approach. The results from Method III optimization are shown in Fig. 11.



a) Design for Load Case [1] **b) Design for Load Case [2]**

Figure 11: Method III structural design results.

In designing for reconfigurability, rather than designing a custom structure for each possible load case or designing one structure to perform adequately for all considered load cases, a single set of components is designed which can be reconfigured to form structures which can perform well for all considered load cases.

4. Discussion and Performance Comparison

The cross-sectional areas of the truss structural elements for the Method I, II, and III configurations are shown below in Table 2. A dash in the table means that no truss element is needed at that location. A comparison of the manufacturing cost objectives for the resulting configurations is presented in Figs. 12 and 13. Fig. 12 compares the manufacturing cost for Methods I, II, and III for customers which only have one of the two loading requirements. Fig. 13 compares the manufacturing cost for the three methods for customers which have both loading condition requirements.

Table 2: Structural element cross-sectional areas for Method I, II, and III solutions (cm^2)

Element Number (see Fig. 8)	Method I, Load Case [1], 24 elements	Method I, Load Case [2], 22 elements	Method II, 22 elements	Method III, Load Case [1], 20 elements	Method III, Load Case [2], 20 elements
1	641	263	510	836	403
2	1081	446	859	821	507
3	638	323	509	895	375
4	1044	568	856	857	479
5	574	1046	856	479	895
6	323	637	511	375	836
7	1031	469	862	869	783
8	788	726	818	783	857
9	740	778	818	924	508
10	471	1047	863	429	924
11	6	57	-	-	-
12	361	149	340	508	429
13	48	48	1	-	-
14	151	371	339	246	246
15	55	-	-	-	-
16	8	104	-	-	78
17	-	81	38	78	-
18	356	439	421	817	333
19	338	618	561	333	817
20	614	337	563	426	455
21	428	364	421	507	426
22	81	-	37	98	-
23	104	-	1	-	98
24	264	643	510	403	869
25	442	1070	857	455	821
Manufacturing cost ($)	5701.56	5700.92	5920.21	5826.67	5826.67

From Table 2, the mass penalty incurred in the Method III design can be seen. Comparing the Method I to Method III solutions for load case [1], structural elements 1, 3, 12, 14, 17, 18, and 24 are significantly larger in cross-sectional area for the reconfigurable, Method III structural design. Many of these members are on the left-hand side of the structure near the nodes being loaded. Making the same comparison for load case [2], structural elements 1, 6, 7, 12, 15, 19, 20, 22, 23, and 24 are significantly larger in cross-sectional area for the reconfigurable, Method III structural design. Many of these structural elements are near the right-hand of the truss near the load case [2] loaded nodes. Overall, the reconfigurable design set of structural elements is more massive than the custom-designed structures.

Method II structural design, which considers all loading conditions, is more massive than all of the other structural designs. This is the result of the Method II design having structural elements nearly sized to the worst-case custom design cross-sectional areas. The philosophy of designing for a requirements envelope allows the Method II design to accommodate both considered loading conditions. While the Method II structure can handle both loading conditions, a mass penalty is incurred for designing for a requirements envelope.

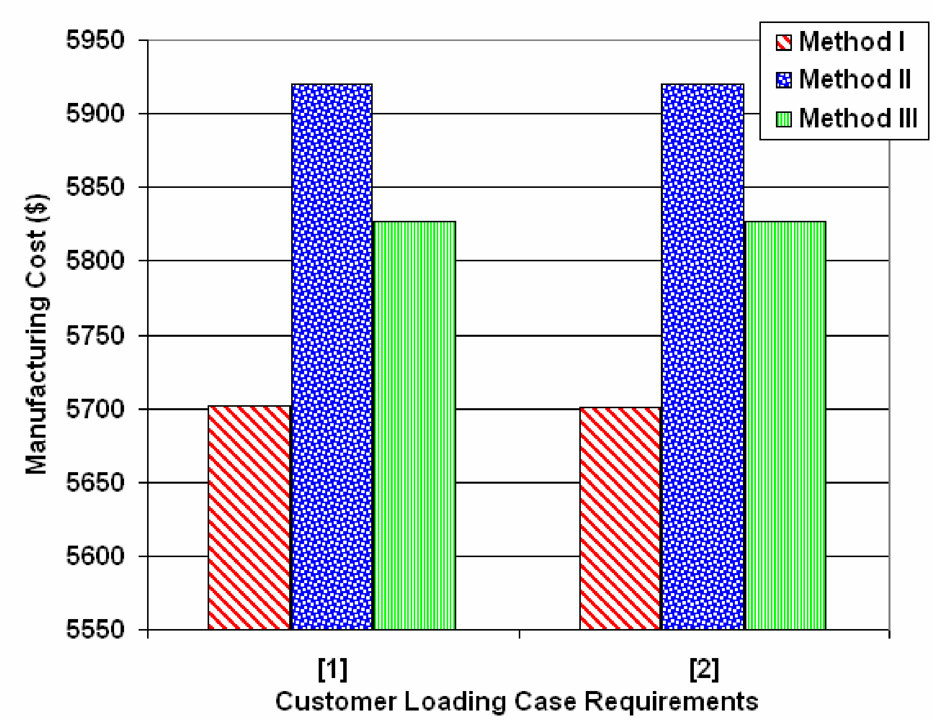


Figure 12: Method I, II, and III manufacturing cost comparison for customers with one loading requirement.

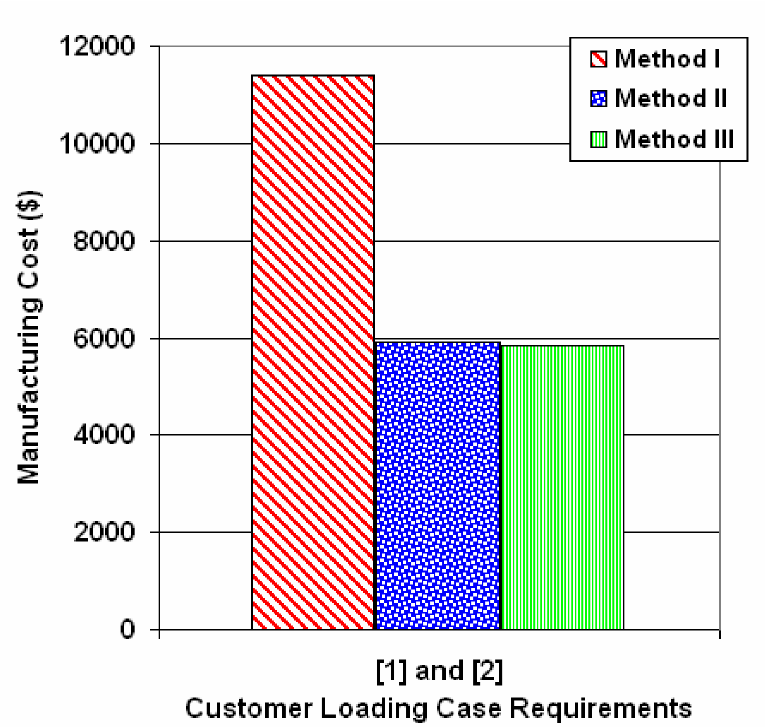


Figure 13: Method I, II, and III manufacturing cost comparison for customers with both loading requirements.

Consider Fig. 12. Compared to the structural design which accommodates all considered loading cases, the reconfigurable structure is 1.6% less expensive. Compared to the custom, Method I designs, the reconfigurable structure is 2.2% more expensive. The result of designing for reconfigurability is a set of structural design elements which, when reconfigured, form structures that perform better than the structure designed to handle all load cases. The results are reasonable because it would not be possible for a reconfigurable set of structural elements to be less massive and therefore less expensive to manufacture than a custom-designed structure. Although reconfiguration allows for good performance, the reconfigurable structural design must still balance the requirements of each load case considered. Therefore, because the reconfigurable set of structural elements must be able to accommodate all load cases considered, the performance of the reconfigurable structural design is limited by this worst case loading condition and a mass penalty is the result. This mass penalty translates directly into a manufacturing cost penalty.

Although it appears from Fig. 12 that Method I structural optimization produces the best results, Method III optimization does have an advantage. This benefit of designing a reconfigurable structure can be seen in Fig. 13. This graph compares the manufacturing cost of providing structures to a customer who has both loading requirements rather than only one as is assumed in Fig. 12. The reconfigurable structure can accommodate both loading requirements and only the single set of elements needs to be manufactured. The Method II structural design, while inefficiently designed for each independent loading condition, can accommodate both loading conditions and only needs to be manufactured once. The custom-designed Method I structural designs both need to be manufactured and sold to the customer in order to satisfy their loading requirements. This requires the manufacturing cost for both Method I structures to be summed together for comparison to the other two structural design approaches. In this case, the Method III solution is the most economical.

The convergence history of the three structural design optimization approaches is shown in Fig. 14.

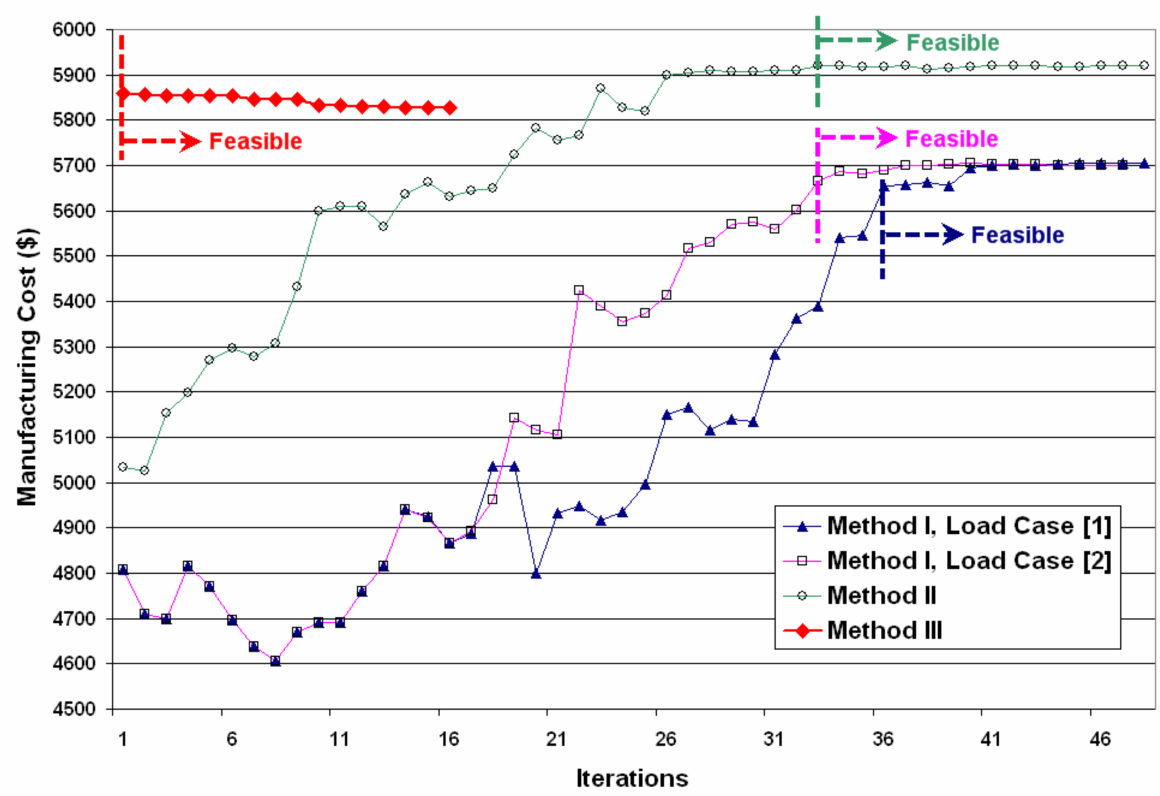


Figure 14: Method I, II, and III optimization convergence histories.

Starting from a feasible design by using the Method II solution, the Method III optimization improves steadily and less dramatically than the Method I and II optimization trials. This is due to the fact that the Method I and II optimizations did not use feasible initial designs. Method I and II optimizations were able to generally handle initial designs which were outside the feasible design space.

The number of function evaluations and CPU time required to converge to an "optimal" feasible solution are shown in Table 3. The results vary significantly between the Method I and II optimizations and the Method III optimization. The large increase in CPU time for Method III optimization results from the time required to reconfigure the set of structural elements in the inner loop. The decrease in the number of function evaluations is a result of the increased CPU time required to perform the random search in the inner loop.

Table 3: Number of function evaluations and CPU time for Methods I, II, and III.

Optimization Method	Function Evaluations	CPU Time (min)
Method I, Load Case [1]	1378	0.4
Method I, Load Case [2]	1349	0.4
Method II	1370	0.7
Method III	702	71.1

V. Conclusion

An optimization method using an inner loop which performs random search structural reconfiguration was used for structural design optimization for reconfigurability. Reconfigurability was incorporated into the design process by the Method III optimization process discussed in the paper. Manufacturing cost benefits were realized due to the embedment of reconfigurability into the structural design optimization process. The manufacturing cost of the reconfigurable structural design is not only less than the structure designed for a requirements envelope, it is cheaper than the custom design structures due to the fact that each set of design requirements can be satisfied with the single reconfigurable set of components rather than two sets of custom-designed structural elements.

The disadvantages of the incorporation of reconfigurability were shown. A mass penalty is incurred by designing reconfigurability into a structure. This mass penalty results in increased manufacturing costs compared to the costs of a custom design. In order to meet the minimum structural performance requirements, a reconfigurable structure may be "over designed" for several of the possible loading scenarios for which it was designed. Designing reconfigurability into a structure reduces manufacturing cost while only incurring a relatively small mass penalty in the structural design.

In addition to the benefits of incorporating reconfigurability into structural design discussed in this paper, other benefits are possible from this design methodology. For example, reconfigurable design will save money for a manufacturer as these reconfigurable component sets are mass produced. Rather than manufacturing many different sets of custom parts for each set of design requirements, one set of components can be manufactured to accommodate all of these considered design requirements. In addition, non-recurring engineering cost benefits will result from having fewer structures to design and test. As an increasing number of different customer requirements is considered in the design of the reconfigurable set of structural elements, the cost benefits compared to designing custom structures will increase. A third benefit of designing for reconfigurability is a cost benefit from inventory. A manufacturer will no longer need to maintain an extensive inventory of each custom design. Instead, a smaller inventory of reconfigurable structural element sets can be maintained which can accommodate all customer requirements as effectively.

The work presented in this paper is at an intermediate stage and the benefits of designing for reconfigurability will be studied in more detail in future work. Although the structural design optimization example presented in the paper considered two loading cases, this optimization method can be used for more complicated structures with as many load cases as is needed for the particular application. A major limitation to the number of load cases considered, however, is the computation time required to perform the optimization.

Future work on this topic will involve applying this structural design optimization methodology to more realistic and more complicated structures. Some structural design applications include military bridges and modular bookshelf structures. A parking structure which can accommodate additional levels is another potential application of this design methodology. Finally, inner loop optimization will be used to create a double-loop optimization method used to improve an objective function such as assembly time which depends on structural configuration.

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