

DEVELOPMENT OF A PROTOTYPE DEPLOYABLE BRIDGE BASED ON ORIGAMI SKILL

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ABSTRACT: In recent years, the world has seen many natural disasters such as earthquakes, floods, and tsunamis. In particular, Japan experienced a very bad flood that damaged many bridges in Sayo, Shiso and Mimasaka along several branched rivers of the Chigusa and Ibo rivers in 2009. We need to develop a new rescue structure to survive such disasters. We have to consider how to recover a damaged structure or how to rebuild a new type of rescue system as soon as possible after a disaster occurs because time is of the essence when trying to save lives. To this end, we have created an optimum deployable bridge based on an origami folding structure determined by computer analysis. Such computer analysis based on origami is a skill that is useful for making new designs for light structures or achieving high stiffness in mechanics. We wish to use this computing skill to help people recover from natural disasters. To design a new emergency bridge called Mobilebridge™ we have originally created an optimization truss by computing mechanics. We realize that it is necessary to develop this Mobilebridge as soon as possible to be ready for the next natural disaster.

Keywords: *Structural Optimization, Deployable Bridge, Mobilebridge, Emergency Bridge*

1. INTRODUCTION

In recent years, the world has seen many natural disasters such as earthquakes, floods, and tsunamis. In particular, many bridges were damaged by a very large flood in Sayo, Shiso and Mimasaka along several branches of the Chigusa River and Ibo River in Japan. We need to develop a new rescue structure to survive disasters such as these. We have to consider how to recover a damaged construction or how to build a new type of rescue system as soon as possible after a disaster because time is very important when trying to save lives after an emergency.

A temporary bridge is a structure that allows prompt recovery of a lifeline after a disaster, but currently this kind of bridge has various technical issues that need to be solved. Developing and building a new emergency bridge 1 that an emergency vehicle can quickly cross is essential for a country like Japan which is prone to natural disasters.

On the other hand, often the materials or dimensions of bridges that have conventional designs are adjusted to meet the design specifications, depending on the bridge's purpose or the way it is used. This is done based on the standard

form of the existing structures. And the structural form of the bridge's final shape and cross section is determined.

That is, after the section and shape of the bridge are determined according to a partly experienced design procedure, a stress check on the structural members must be carried out by FEM analysis. However, there are urgent needs to design a light, strong structural form with no unnecessary material to ensure a bridge that can withstand a heavy load and one that has a strong foundation when it is erected. It is also necessary to ensure the bridge has "muscles", or places where it can expand, in the necessary places.

There is a tendency to request mobility when developing a temporary emergency bridge, even though using high-quality materials might increase the material cost of the type of bridge described in the opening. It is also necessary to build up the bridge system lighter and give it high strength. Therefore, we need to come up with a concept and method for deciding the best material shape and optimized design, aiming to ensure that the structural form of a bridge system has high.

¹ The bridge developed in this research is called "Mobilebridge™".



(a) A collapsed bridge on the Ibo River



(b) A collapsed pier on the Chigusa River

Photo 1 Constructions in Sayo, Japan that were damaged in a flood following Typhoon No. 9 which made landfall on 9 August 2009¹⁾.

stiffness. To date, many structural optimization theories have been developed in an attempt to ensure both a lightweight and highly rigid design^{9)~?)}.

In recent years, design approaches such as the grand-structure method, the homogenization method, the genetic algorithm, and the cellular automata have been developed as analytical computing methods to create the layout form of a bridge structure. These approaches tackle an issue known as the problem of optimizing a structural topology. Here, the micro truss technique that relates to this topological optimization is used as a way to decide on the form of a bridge. The design and production of and experimentation on a prototype of the *Mobilebridge*TM, whose structure was determined by looking at the digital optimum structure in the figure, were executed. And the potential application of this bridge was estimated. It seems that a design with a high degree of freedom becomes possible and is useful in terms of structural engineering when using the present analytical method to determine the design and material to use for the structure.

This paper describes a bridge design that was determined using a folding technology^{26),?)} according to an original grand-structure method. This bridge considered compression buckling that occurs when a micro-truss is used on a large scale. In this way, the optimum folding structural form for an emergency bridge was created by using this computing method. A prototype bridge that had this structural form was actually produced. It was experimented on to examine its mechanical behaviour by subjecting it to a nondestructive load (coming from the weight of people). We have carried out a comparative investigation by conducting a basic experiment on this folding structure to examine

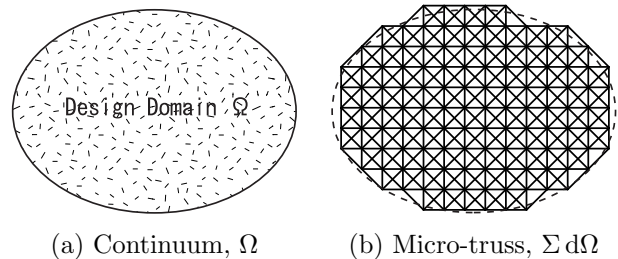


Fig. 1 Discretisation of a Continuum

the design and production of this new bridge.

2. Optimization strategy

We represent the design domain Ω of a continuum by micro-trusses, (2). The discretisation is diagrammatically represented in **Fig.1**, where an example of a continuum **Fig.1(a)** is discretised as **Fig.1(b)**. It is proposed that the behaviour of the domain Ω can be adequately modelled by micro-trusses for a large number of unit cells, m , where each micro-truss member represents a pin-jointed linear extensional spring.

$$\Omega = \int d\Omega = \lim_{d\Omega \rightarrow 0} \sum_{m}^{(1/d\Omega) \in \mathbf{Z}} d\Omega^{(m)} \quad (1)$$

$$\approx \sum_{\substack{m \gg 1 \\ d\Omega \propto 1/m}} d\Omega^{(m)} \propto \sum_{\substack{m \gg 1 \\ x^{(m)} \propto 1/m}} x^{(m)} \quad (2)$$

The design variable is the stiffness of the micro-truss members, x and therefore the non-linear equilibrium equation can be rewritten as (3).

$$\mathbf{F}(\mathbf{u}, p, \mathbf{x}) = \mathbf{0} \quad (3)$$

where $\mathbf{x} = \{\dots, x^{(m)}, \dots\}^T \in \mathbf{R}^m$.

The goal of optimization is to achieve a fully-stressed design represented as (4) in a discrete form. The design modification is based on the local stress response, where the stiffness of a member is updated at each load step according to (5).

$$\begin{aligned} & \text{Min} \sum_{m=1}^M \left(\frac{\sigma^{(m)}}{\sigma_{\text{nom}}} - 1 \right)^2 \\ & \text{Subject to } x_{\min} \leq x^{(m)} \leq x_{\max} \end{aligned} \quad (4)$$

where σ = member stress, σ_{nom} = normal stress and M = total number of micro-cell members. Subscripts, min and max denote the lower and upper bounds, respectively.

$$x_{i+1} = \gamma \frac{|\sigma_i|}{\bar{\sigma}_i} x_i, \quad i = 1, 2, \dots \quad (5)$$

where i = iteration number, γ = optimization rate constant and

$$\bar{\sigma}_i = \frac{1}{M} \sqrt{\sum_{m=1}^M \left(\sigma_i^{(m)} \right)^2}. \quad (6)$$

After one iteration of design modification, the tangent stiffness matrix is updated and the new equilibrium equation is established for the subsequent load step, (14). The design update is applied at each load step.

2.1 Principle of form formation with the iteration method

The change in stiffness is limited to part of the structural system, although a more accurate calculation can be done by carrying out structural analysis directly. Therefore, it is possible for the iteration method to observe “the flow of stress” to arrive at stable solutions for sequential correction of the whole stiffness of the bridge. In this paper, corrections to the stiffness matrix are assumed to be a feed-back system of the stress response for each member. This method is advantageous even though it includes large-scale calculations or singular problems.

Now, it is assumed that the equilibrium points $(\mathbf{u}, p, \mathbf{x}_{(0)})$ are obtained by the method of loading control and/or displacement control with the configuration of the initial design parameters. The stress in each member is defined as

$$\sigma_{\min} \leq \sigma^{(m)} \leq \sigma_{\max}, \quad m = 1, \dots, M, \quad (7)$$

$$\sigma_{(\nu)} = \mathcal{W}(\mathbf{u}_{(\nu)}), \quad \nu = 0, 1, \dots \quad (8)$$

It is the displacement function of each node. Here ν is defined as the number of iterations, and $\sigma_{(\nu)} = (\dots, \sigma_{(\nu)}^{(m)}, \dots)^T$, is defined as $\mathbf{u}_{(\nu)} = (\dots, u_{(\nu)}^{(m)}, \dots)^T$.

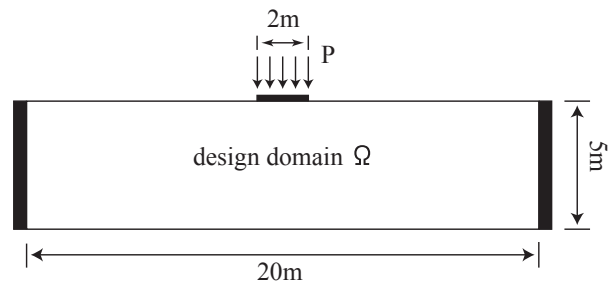


Fig. 2 Initial structure

3. Examples

3.1 A beam model with the clamped supports

Let us consider the problem of optimizing the layout shape when designing a beam which is supported at both of its fixed ends, under part of distribution load P at the center of a member. We can obtain the solution to this problem by using the adaptive-topological optimum method developed by Ramm and Maute^{(15),(16)}. This method employs the calculation iteration procedure, which uses the finite element method, topological optimization and shape optimization based on the distribution of the computing stress of FEM. There are several problems to be solved in this method such as the numerical error of the checker-board instability, non-smoothing shape and high calculation cost. The topological optimization method has a high calculation cost because there are sensitive elements. We apply the grand-structure method as a micro-truss-network to determine a stable solution without any checkerboard error.

This present method produced some successful numerical results compared with the shape optimization example referred to in the paper by E. Ramm *et al.*⁽¹⁷⁾. The process that needs to be followed step by step to produce the optimum shape is shown in **Fig.3**. The figure shows the frame result obtained from the shape optimization analysis used in the present method. It is similar to the topological result produced as a successful frame network in the benchmark model. Finally, the ratio of remaining members to all initial members becomes 19%. You can clearly see the shapes determined when balancing compression (red colour) and tension (blue colour) members with symmetry.

4. Mobilebridge™ based on origami skill as concept for foldable structure

In general, it is known that the upper and lower horizontal members of a truss greatly affect the resistance of bending moment. In this research, however, the

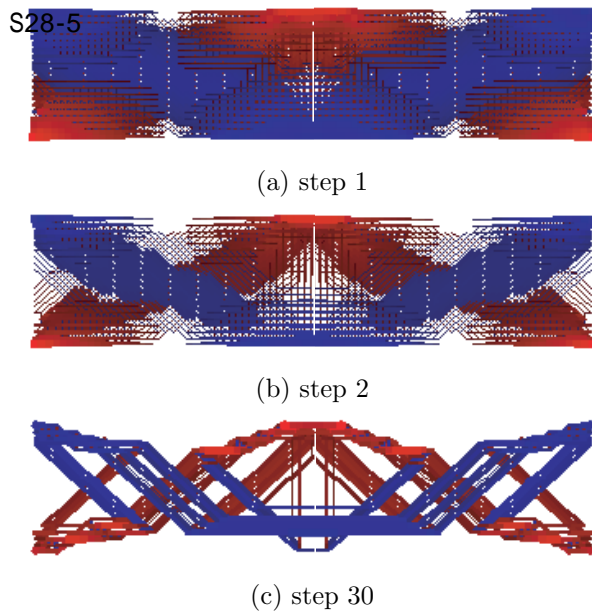


Fig. 3 Analytical results produced by the present method (20×80 meshes)

truss was used in a new type of bridge that has only diagonal members and no upper or lower horizontal members as the main frames. We considered how to develop and apply a new emergency bridge that can be folded up ready for deployment by using a truss system. The aim is to use the bridge to restore infrastructure that has been damaged in a disaster. Therefore, we have tried to develop a *Mobilebridge* based on both the concept of a multi-folding micro-structure and research on structural optimization. To develop a *Mobilebridge* we need to develop a way to expand it from a folded state.

For example, we can examine an expandable truss structure in which we replace a beam with a structure that works like a pair of scissors. This is effective from the viewpoint of structural optimization for Michell's problem. If this scissor structure has enough strength when it is deployed with its own weight, it will not need any horizontal members. However, after it has been expanded it may need to be reinforced to make a completed bridge. In this case, although the horizontal displacement is kept in check owing to both the contact side supports and it keeps its stiffness in a plane, we have to design the bridge so that it has enough stiffness when it moves outside a certain plane without undergoing any large deformation. We believe one effective way to change an unstable structure into a stable structure may be to assemble a three di-

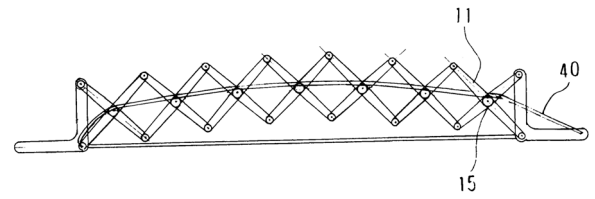


Fig. 4 Concept of *Mobilebridge* as shown in the patent¹¹⁾

mensional truss with a tied cable or tied bar between both of the end supports, as shown in **Fig.4**. This makes it possible to produce an expandable and movable bridge. With the technology used in this bridge system, it is possible to completely and quickly construct a bridge system.

Moreover, if no tied cables are used, this system can form a stable structure if one of the horizontal members is fixed after the system is expanded. To confirm this, we tried to design a new footbridge as a prototype and used patented technology which is based on a combination of the structural optimization method and the foldable design concept. The prototype was made of aluminium A6063-T5 as shown in **Fig.5**. It can stably stand by itself. This developed bridge can easily be expanded by a person.

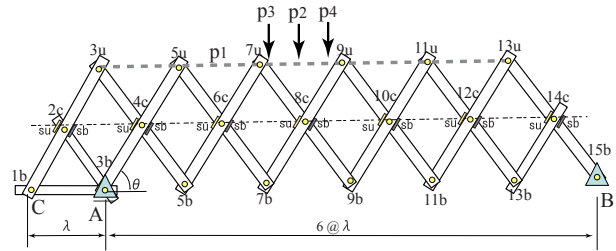


Fig. 5 New prototype of an emergency bridge

5. Static experiments for the prototype of *Mobilebridge*

To understand the mechanical behaviour of a bridge in an attempt to develop a prototype mobile temporary bridge, the following basic static experiment was carried out.

5.1 Experimental conditions and strains

The static experiment placed the prototype under a load equivalent to human's weight, as a nondestructive experiment that examines the prototype within its expected range of use. Here, the basic deformation of the prototype was measured under each loading condi-

Table 1 Measured displacement and strains near S28-5 pivot No. 8 under load cases P_i

Load cases P_i (N)	Disp. (cm)	Strain in theory $ \varepsilon (\mu)$	Strain at upper $\varepsilon_{su}(\mu)$	Strain at bottom $\varepsilon_{sb}(\mu)$
$P_0 = 0$	0.0	0	-34	36
$P_1 = 196$	0.4	77	-172	171
$P_2 = 882$	1.9	556	-476	498
$P_3 = 1499$	2.7	987	-782	809
$P_4 = 2117$	3.8	1414	-1125	1160

tion to obtain an optimal design based on experimental data.

The displacements of the prototype under the loads for a few people were measured. Looking at the bend moment distribution in this experiment, it is apparent that the bridge approximately has a triangular distribution like a simple beam structure. The self-respect is assumed to be a default (0 resets), and the measuremental value of the vertical displacement on the node number 8c in the vicinity of the center of the structure to each state of the load is indicated in **Table 1**. It is clear that they have an almost linear relationship when looking at these measurement results.

5.2 Strains at the pivot of the crossing two members for the loadcases

From the viewpoint of behaviour of the center node No. 8c in this structure, these bending-stresses are shown in **Table 1** and **Fig.6**. The theoretical value of the table inside is a value calculated from the stress-strain relationship and the bend moment based on Hooke's Law. The calculation results show that the theoretical value of the strains was very close to the experimental value. In addition, the experimental value showed that the strain was kept low from the theoretical value². The difference also has increased the strain of both as it almost becomes a linear relation for each load, and the load increases.

6. Concluding remarks

This paper presented a stress-based topology optimization strategy for geometrical non-linearity. We simplified the continuum using a micro-truss representation in order to reduce the computational cost to a realistic level. The modified stiffness iteration method was implemented to analyse multiple bifurcation points. Using the stiffness EA of the micro-truss members as design variables, we systematically modi-

² Theoretical value p_1 is solved by assuming the distributed load.

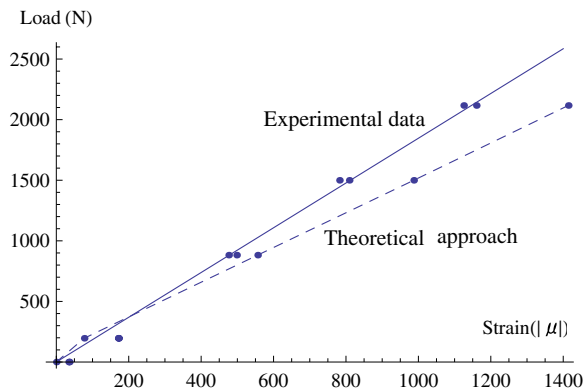


Fig. 6 Experimental strains at the upper and bottom edges of the pivot ($|\varepsilon|$)

fied the stiffness based on the stress ratio at each load step of the load-displacement path. Assuming there is a constant material property, the stiffness EA can be interpreted as the cross-sectional area of micro-truss members, which allows us to understand the optimum solutions. We demonstrated the optimization strategy through two simple examples. As the applied load to a simple cantilevered beam was increased, the local buckling of the truss members encouraged an increasing proportion of the load to be carried in tension. This led to asymmetric solutions, which, unlike the well-known linear solution, were symmetric. We then applied optimization to the problem with varying degrees of initial stiffness. We demonstrated that a constraint diagram could be constructed from the load-displacement paths of the optimization to determine the appropriate initial stiffness value for the design requirements.

When we considered large deformation, strain was more sensitive to the applied load whilst the stress-based optimization continued to eliminate micro-truss members. A similar result may be expected when we consider material non-linearity. Therefore, further investigation would benefit our understanding of stress-based designs versus strain-based designs for optimization with structural non-linearity. The solutions from the second example of an aspect ratio three beam with a central load provided three truss configurations, and we studied these using non-linear finite element analysis. When given elastic material properties, we observed that the post-buckling behaviour was severely unstable, as expected. However, given a simple elastoplastic material property, the material yielded at a fraction of the buckling load and therefore, we did not observe any severe unstable post-buckling. This

seems to indicate that unstable post-buckling behaviour which is often observed in optimum designs, may be avoided by using some elasto-plastic material.

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