論文 Experimental Verification of Availability of An Optimal Shape Design Method

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ABSTRACT: An optimal shape design method was proposed previously. Different from the existing optimization programs, the method is available for many kinds of material, yet not only for some specified material. In order to realize the effectiveness of this proposal on practical application, experimental verification was conducted in this study. In this paper, different strength ratios were under control to investigate whether the effect of load response is indeed considered by this proposal or not.
KEYWORDS: optimal shape design, constitutive equation, equivalent stress, effect of load response, tension test of axially reinforced specimen

1. INTRODUCTION

Up to date, the majority of structural optimization problems has been emphasized on the morphology of the structures without consideration on the characteristics of composed material of structures. With the interest on structural optimization from the viewpoint of material, an optimal shape design method with the consideration on the characteristics of material has been previously proposed [1]. Generally speaking, optimal shape design is termed as " the design for dealing with the optimal morphology of the structure with respect to the design variables, e.g. weight (or volume), stress concentration and strain energy ,etc. There have been established several approaches for finding the optimal shape of a design structure. Among them, in order to evaluate if the design structure is optimized or not, the object function whose formula is based on the relationship of the design variable is often used. If the convergence of a specified object function can be found, the structure under discussion can be regarded optimized.

With the limit of the space of the context, the algorithm of this proposed method is only briefly described in the following : the initial configuration of a design structure can be input by means of a pre-processor. Next, a structural analysis within elastic limit is carried out by FEM (finite element method). As a result, the scatter of the stress within the structure will be acquired. Then, the process of the optimization will be executed in accordance with the execution order shown in Fig.1 until the optimizing criteria is satisfied. The governing equation used in the method is given as eq.1 (where K, Δu and Δg mean stiffness matrix, nodal transformational vectors and the equivalent nodal force vector generated by bulk strain respectively). In the case of a cantilever beam, the optimized structures for steel and concrete-like material are illustrated in Fig.2 respectively. The details of the description can be available in [1]. For the proposed method, the design variable introduced in the object function was the scatter of the stress within the design structure. Due to the good convergence on object function and the deduction of the scatter of inner stress, the effectiveness of the proposed method could be confirmed. However, in order to verify the applicability of the method, this paper was motivated to enact the experiments to check if the performance of the proposal meets the requirement or not.

$$[K]\{\Delta u\} = \{\Delta g\} \qquad \cdots (1)$$

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For evaluating the applicability of an optimized structure, there exist several approaches to achieve the goal, e.g. the observation on the stress concentration, potential energy or toughness. Generally speaking, once if either of them holds, the applicability of the structure can be accepted. In this study, toughness was measured as the index of applicability of the proposed method. In order to reflect the effect of load response of material, the experiments were performed by varying the ratio of elastic limit of compressive and tensile strength with the selection of different material. The material utilized in this research adopted OPC (ordinary Portland cement concrete) and SFRC (steel fiber reinforced concrete), the strength ratio of which were experimentally estimated 8:1 and 2:1. For SFRC used in the research, the small ratio of strength was achieved by adding excessive amount of steel fibers into the mix. According to the result of the experiments, it indicated the validity of the proposed method could be confirmed by effectively increasing the toughness.

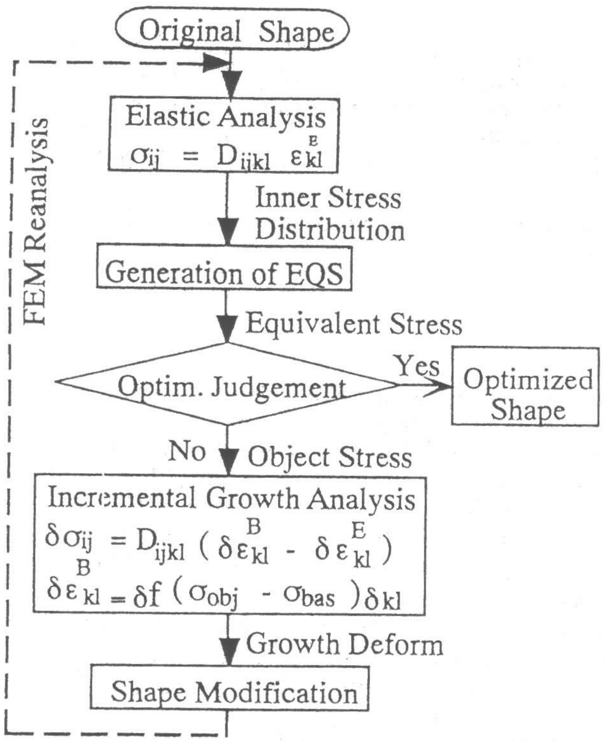

Fig.1 Flow of Optimization with Incremental Growth Analysis

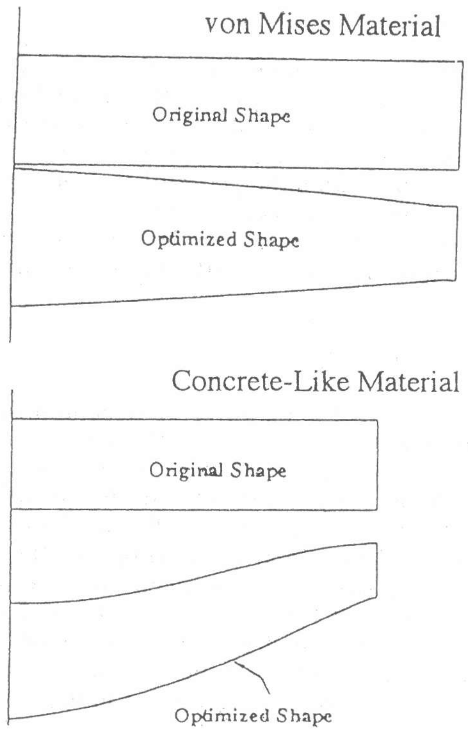

Fig.2 Ilustration of Optimized Result by the Proposed Method

2. EXPERIMENTS

For achieving the goal of this research, the flow of investigation steps is given in Fig.3. To carry out the process of optimal analysis on structures, the experimental parameters of material need to be established in advance by performing the various experiments on material properties. Owing to merely two-dimensional and elastic case considered in the proposed method, the experimental parameters are elastic limit of compressive and tensile strength, elastic modulus, Poisson's ratio and specific weight, which denote as Fc, Ft, E, n and d respectively in the context. With the acquirement of the experimental parameters, the dimensions of specimen were obtained according to the result of the analysis. Then, the verification of the proposal was made by comparing the analytical and experimental data.

2.1 INVESTIGATION OF EXPERIMENTAL PARAMETERS

In order to verify that the effect of load response is included in the algorithm of the proposal, the ratio of strength limit (i.e. Fc : Ft) was considered as experimental variable. There were 2 types of material with significant difference of ratio of strength limit for illustrating the influence of this factor. Here, OPC was selected as one material for its large ratio of Fc:Ft while SFRC was select as the other material for its small ratio of Fc:Ft due to effective uplift on tensile strength and slight restrain on compressive strength. Because the applications discussed in the proposed method were limited in the case of plain stress with homogeneous and elastic material, the material used here was reasonably assumed as homogeneous within their elastic limit. By the observation on the past researches, the increase on the failure strength of the cement-based composite material under biaxial loading can be approximately 19% to 29% as compared with the uniaxial failure strength [2]. However, the difference between elastic limit of uniaxial and biaxial strength can be practically assumed to be ignored. As a result, all the following results for strength parameters were performed on uniaxial tests.

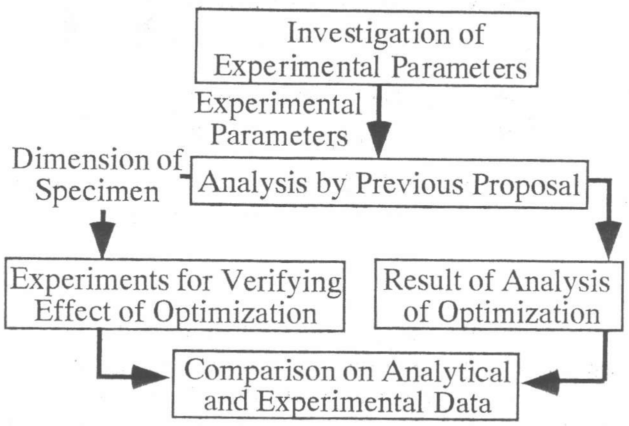

Fig.3 Flow for Verifying the Effect of Optimization by the Proposed Method

Tbl.1 Mix Proportion of OPC & SFRC (unit: kgf/m^3)

Comp / Type	W	C	S	G_{5-13}	G_{13-20}
OPC	189	420	803	491	327
Comp / Type	**W**	**C**	**S**	V_f^*	S_A
SFRC	240	500	1277	392.5	10.0

*: V_f (volume of steel fiber) = 5% of mix patch

(1) Material of specimen

The mix proportions for OPC and SFRC in the experiments were designed as listed in Tbl.1, where W, C, S, G, V_f and S_A represent water, ordinary Portland cement, fine aggregate, coarse aggregate, steel fiber and superplasticizer respectively. The specific weights for C, S, G_{5-13}, G_{13-20}, V_f and S_A are 3.16, 2.65, 2.70, 2.70, 7.85 and 1.07 respectively. The preparation of OPC specimen was made in accordance with JIS A 1132. As for the placing of SFRC specimen, a brief description is given as follows. The type of steel fiber is high-carbon ordinary Duoform steel 0.6 * 30 mm. For conventional SFRC(V_f is not more than 2%), the ratio of strength limit often ranges from 8:1 to 16:1, which differs little from that of OPC. Therefore, to generate a small ratio of strength limit, an unusual volume of steel fibers (V_f = 5 %) was suggested in the mix of SFRC in this research. It is known that, along with the increase on the volume of V_f, the workability of the batch degenerates. Thus, the addition of superplasticizer became necessary for improving the workability of the batch. Due to the excessive volume of fibers, the requirement for adding steel fibers into the fresh mortar within 2 minutes could not be met. Here, the time for adding fibers was experimentally decided, which ranged from 3 to 5 minutes. All the specimen were cured in 20 ± 1°C water for 7 days.

(2) Tests for strength parameters of material

As indicated in Fig.3, the material parameters which needed to be investigated in the first stage were elastic limit for uniaxial compressive and tensile strength, elastic modulus, Poisson's ratio and specific weight. Up to date, the test methods for most of these parameters have been standardized while only the method for measuring the tensile strength for SFRC is still under discussion. The descriptions for these methods are given as follows.

a. Tests for compressive strength, elastic modulus, Poisson's ratio and specific weight

In order to acquire the uniaxial compressive strength, the specifications of JIS A 1108 was followed by the procedures of experiment. Besides, the tests for elastic modulus and Poisson's ratio were performed according to ASTM C 469-65. By the relationship of stress and strain, the elastic limit of compressive strength could be also observed. By dividing the average weight of specimen by the average volume of specimen, the specific weight of specimen was given. The results of these tests were shown in Tbl.2.

Tbl.2 List of Parameters of Material

TYPE	Fc*	Ft*	E(*10^5)*	ν	d(*10^{-3})**
OPC	160	20	1.5	0.2	2.46
SFRC	120	48	2.2	0.2	2.42

(* : unit : kgf/cm^2;** : unit : kgf/cm^3)

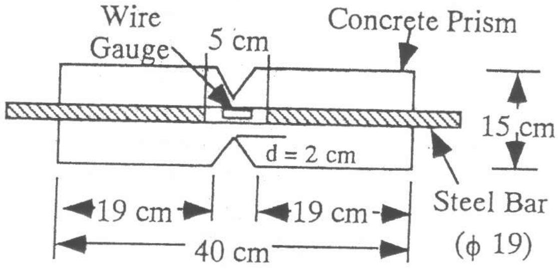

Fig.4 Layout of the Specimen for Tension Test of Axially Reinforced Specimen

b. Test for tensile strength

Test for split tensile strength (JIS A 1113) is generally adopted for finding uniaxial tensile strength of OPC due to its good consistency with true tensile strength. For stresses less than 60% of the uniaxial tensile strength, the creation of new microcracks is negligible. Thus the stress level can correspond to the elastic limit of tensile strength [3]. On the other hand, it was ponited out that the test for split tensile strength of SFRC can not precisely represent the true tensile strength of SFRC in [4]. By [4], it was suggested that the tensile strength for SFRC be investigated by "tension test of axially reinforced specimen". According to the description in [5], the dimensions of specimen for tension test of axially reinforced specimen are illustrated in Fig.4. The tensile strength is able to be estimated by eq.1 in [5]. And the result of the test is concluded in Fig.5.

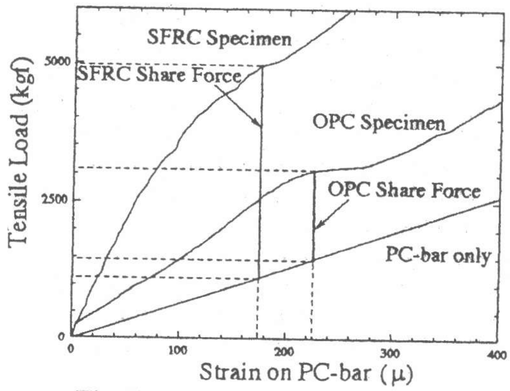

Fig.5 Axially-Reinforced Tensile Strength of OPC and SFRC

For the reason of comparison, Fig.5 also shows the test result on OPC. It indicates that the tensile strength from tension test of axially reinforced specimen of SFRC was 65 kgf/cm^2 while that of OPC was 27 kgf/cm^2. Compared with the experimental results given in [5], the flat curve after initial deflection in this study was relatively short, which might resort to the speed of stretching steel bar and the different section area on the center cross section due to the different depth of notch(d). A good consistence was observed between split tensile strength of OPC (33 kgf/cm^2) and the tensile strength from tension test of axially reinforced specimen of OPC. And Ft (elastic limit) for OPC shown in Tbl.2 was obtained by multiplying 0.6 * split tensile strength according to the description in [3]. As for SFRC, the relationship between limit of elasticity and ultimate strength of SFRC has not yet successfully established. Yet, because the initiation of first crack can be generally assumed as the failure of elasticity, the assumption that the deviation from the initial slope of the load-deflection curve is regarded as an indication of the occurrence of the first crack in the flexural test [6] was adopted for finding out the elastic limit of tensile strength of SFRC. The test for flexural strength followed JIS A 1106, The central deflection could be measured by setting up the apparatus shown in Fig.6. Fig.7 gives the relation between external load and central deflection, which suggested the deflection of load appeared around 1600 kgf. Consequently, the value of elastic limit of tensile strength was computed as 48 kgf/cm^2 while the measured ultimate strength of SFRC was 65 kgf/cm^2. Because the experiment was designed to be performed within the elastic state, the ultimate strength was not adoped in the present research.

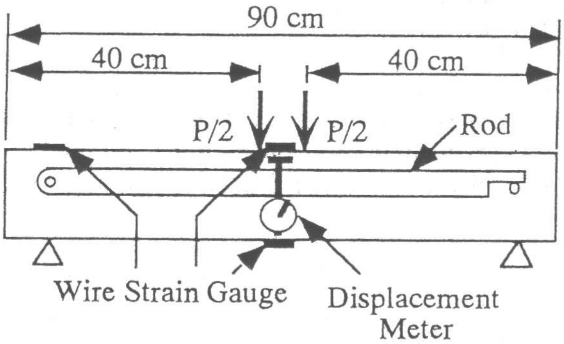

Fig.6 Configuration of the Specimen for Verification(devised by T. NISHIMURA)

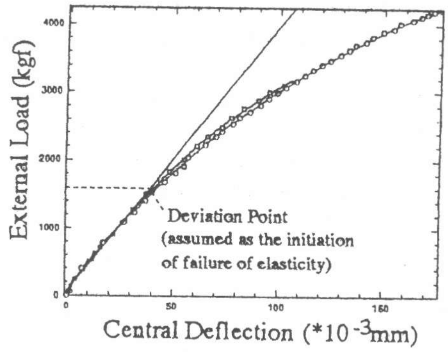

Fig.7 Relationship Between Central Deflection and External Load

2.2 REALIZATION OF TEST BASED ON RESULT OF OPTIMIZATION

After all the essential parameters of material were available, the process of optimization was carried out by the input of the initial data (material parameters , structural configuration and boundary condition). (please refer to [1] for the further details on the analyzer). Then, the dimensions of the optimized structures, inner scatter of stress could be utilized for the following steps. The original structure designed for verification was a straight beam with two hinge ends. The setting for the structure is illustrated in Fig.6. The measured variables included central deflection and strain on the specified points. According to the proposed method, the straight beam was optimized into arch-like beam.

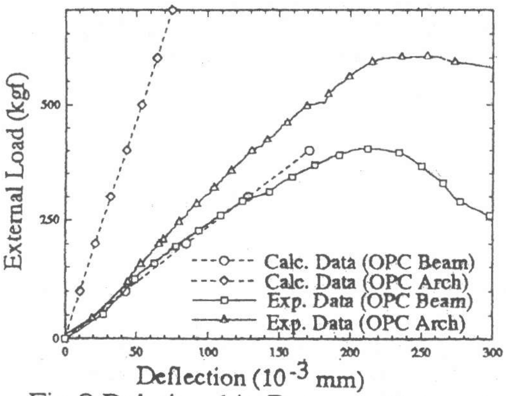

Fig.8 Relationship Between External Load and Deflection for OPC

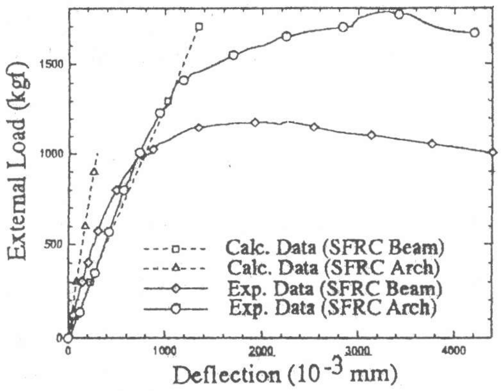

Fig.9 Relationship Between External Load and Deflection for SFRC

3. COMPARISON AND DISCUSSION ON RESULTS OF TEST

In order to verify the validity of the proposed method, the experiments were performed to observe the following relationship: external load and deflection of specimen (i.e. toughness).

The relationship between external load and central deflection for OPC and SFRC were indicated in Fig.8 and Fig.9 respectively. The dash line denotes the analytical curve, which is a straight line owing to its elasticity. The solid line represents the experimental envelope, which displays the elasto-plastic behavior of material. From Fig.8 and Fig.9, the toughness for the structure were indeed promoted by the optimal design. Due to the limit of elasticity, not all the experimental envelopes can be simulated by analytical calculation. However, it is convinced that the optimization of the structure really improve the performance of structure from Fig.8 and Fig.9. In order to apply this method more comprehensively, the process of elasto-plastic simulation offered by this optimal shape design method is under development by the authors.

4. CONCLUSIONS

Based on the above investigation and the comparison between experimental and analytical value, the issues discussed in this study can be concluded as follows:

(1) The effectiveness of the proposed optimal method was verified in this study by observing the following aspect : the optimized structure had higher toughness than the original structure , as indicated in Fig.8 and 9 in spite that the experimental curves were not completely simulated by the present proposal due to its lack of consideration on elasto-plastic behavior of material.

(2) Even with the excessive use of steel fiber (V_f=5%), the availability of the test method suggested in [5] seemed to be supported by the result of the experiment. But due to the limited number of experimental data, the further confirmation is necessary.

(3) Because of no well-established description about the stress-strain relationship of SFRC, the assumption that the initial deflection point represents the failure of elasticity was made to find out the elastic limit of strength of SFRC in this study. As a result, it is claimed that the availability of the assumption needs further investigation.

(4) Due to incompetence for describing the behavior of material after the initiation of plastic strain, the inclusion of inelastic behavior is very essential to be considered in the following development of the proposed method.

ACKNOWLEDGMENT

The authors would like to owe the accomplishment of this paper to the effort of Mr. Yasuyuki SAKADA, who was the former college student of the Shibaura Institute of Technology. With his help, the experiments of this study could be finished as expected.

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