18. Ultimate Strength of Composite Steel–Concrete Structure of Sandwich System

Masakasu MATSUISHI*, *Member*, Yoichi HATTORI**, *Member*,
Setsuo IWATA*, *Member*, Takaaki ISHIHAMA**, *Member*,
Takao YAMAMOTO**, *Member*, Masumi KITAZONO**, *Member*

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Summary

Recently, various kinds of Arctic offshore structures have been constructed. In designing such structures, designers have to pay particular attention to how to overcome ice loads acting on the structures. The use of the composite steel–concrete structure of sandwich system appears to be viable solution for offshore structures in the Arctic.

In this paper, theoretical and experimental studies were carried out to study elastic–plastic behavior and ultimate strength of composite steel–concrete structure of sandwich system where concrete was placed in between steel plates. The theoretical analysis was performed using the finite element method which was newly developed to incorporate nonlinear characteristics of concrete and interaction between steel and concrete. Experiments were carried out to study reserved ultimate strength of the composite structure which had been exposed to thermal cycles, i.e. recurrence of freezing and thawing of concrete.

The following information was obtained through the investigation:

1) Newly developed computer program can accurately predict the elastic plastic behavior and ultimate strength of the composite structure,
2) Simplified method of analysis based upon the truss theory could predict the ultimate strength of the composite structure.
3) The freezing and thawing cycles did not give an appreciable adverse effect on the strength of the composite structure.

1. Introduction

Various kinds of offshore structures have been constructed, with the new oil exploration and production developments in the Arctic and sub–Arctic waters. The use of composite steel–concrete structure of sandwich system appeares to be viable solution for offshore structures, because it enhances their load–carrying capacity in the severe arctic environment.

A huge offshore structure, if made of steel, necessitates a great deal of dead load to offset its big buoyancy. The concrete may be used as ballast and strength members in such an offshore structures.

Drawbacks of concrete associate with low tensile strength and low ductility. It is difficult to secure watertightness, once concrete cracking develops in an offshore structure. The drawbacks of concrete require a design with an absurdly excessive margin.

The authors have developed a new composite steel–concrete structure of sandwich system to eliminate as much as possible the various drawbacks of both concrete and steel. The new composite structure endures large deformation and absorbs a great deal of energy until failure occurs, because the steel plate, having high

* Hitachi Zosen Technical Research Laboratory, Inc.
** Hitachi Zosen Corporation

strength and ductility, suppresses the development of surface cracks. Thus, the safety of offshore structure is ensured if the composite structure is used at ice–resistant wall which has to withstand excessive ice loading.

In the previous paper the authors carried out investigations into the strength of composite structures of sandwich system and developed a method of an analysis of ultimate strength[1)2)]. The method is applicable to the composite structure with a relatively large ratio of span to depth. While structural memberes of ice–resistant wall will have a small ratio of span to depth, say 3, to withstand excessive ice loading.

In this paper, experiments and theoretical analyses were carried out to study ultimate strength of the composite structure with a small ratio of span to depth which will be used as an ice–resistant wall of offshore structures in the Arctic.

2. Model Tests and Results

2.1 Test Models

Two types of two–dimensional test beams of the composite steel–concrete structure shown in Fig. 2 are employed in the model tests. They are approximately one–third scaled model of ice–resistant wall of offshore structures which will be used in the arctic as shown in Fig. 1. Longitudinal stiffeners are furnished at the outer surface of MA–model to increase shear strength, while no stiffeners are furnished to MB–model. Sectional area of the upper steel plate of MB–model is equal to the sum of sectional area of the longitudinal stiffener and upper steel plate of MA–model. The contribution of longitudinal stiffeners to ultimate strength of the composite structure can be examined by comparing test results of the test models. To study the effect of severe weather condition in the Arctic upon the strength of the composite structure, MA–2 and MA–3 are exposed to twenty and forty cycles of freeze and thaw, respectively.

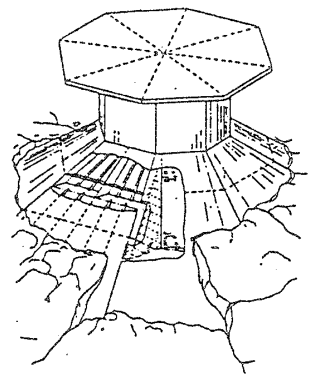

Fig. 1 Ice–resistant wall of Arctic offphore structure

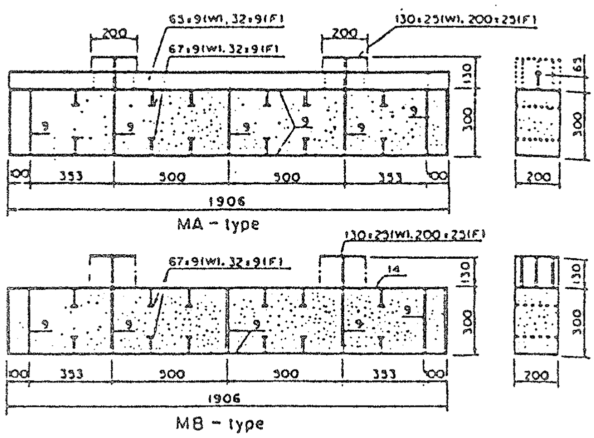

Fig. 2 Test model

The mix proportions of concrete is shown in Table 1. After placing light weight concrete having 28–day design strength of 37.80 N/mm^2, a moisture cure at 55° C was followed for three hours. Yield stress and tensile breaking

Table 1 Mix proportions

max. dia. of coarse aggregate (mm)	slump (cm)	air content (%)	water–cement ratio (%)	ratio of fine aggregate (%)	unit weight (kg/m^3)				
					water W	cement C	fine aggregate S	coarse aggregate G	water reducing admixture
15	7~16	5±1	39	43	176	450	636	660	4.5

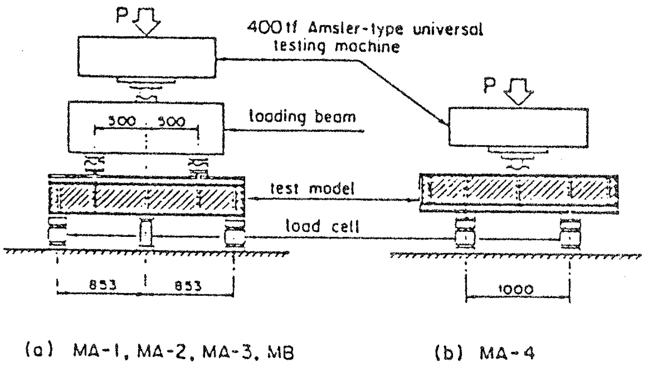

Fig. 3 Experimental set–up

Table 2 Mechanical properties of concrete

kgf/cm² (N/cm²)

cycle of freeze-thaw N	0	20	40
compressive strength σ_c	456 (4471)	332 (3256)	402 (3942)
splitting tensile strength σ_t	54 (530)	31 (304)	28 (275)
bending strength σ_b	29 (284)	31 (304)	27 (265)
initial tangent modulus $E_c \times 10^{-5}$	1.51 (14.8)	1.37 (13.4)	1.33 (13.0)
shear strength τ	110 (1079)	——	——

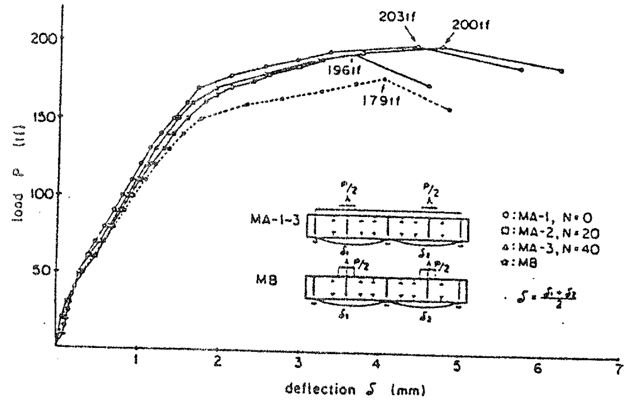

Fig. 4 Measured load–deflection curves

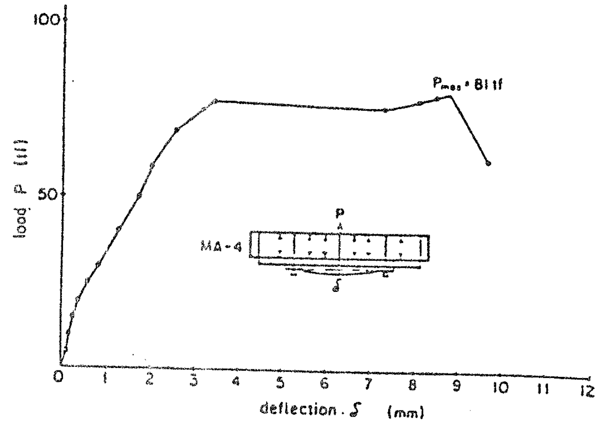

Fig. 5 Measured load–deflection curves (MA–4)

strength of steel plates are 280 N/mm² and 465 N/mm², respectively.

2.2 Experimental Apparatus and Testing Procedure

Test models are loaded to their failure by an Amsler testing machine of 400 tf. Test beams of MA–1, MA–2, MA–3 and MB are supported at three sections and loaded at two sections as shown in Fig. 3 so that bending moment and shearing force distribution of the test beams will be similar to that of ice–resistant wall of Arctic offshore structures exposed to ice loading. The development of concrete cracking is detected by the magnifier.

Test beams of MA–2 and MA–3 are exposed to freeze–thaw cycles in a cold room. Temperature in the cold room is controlled so that the maximum temperature of concrete during thaw period is 10° C and the minimum one during the freezing period is −20° C. The rate of freeze–thaw test is one cycle a day.

2.3 Test Results and Discussion

Mechanical properties of concrete are shown in Table 2. Due to freeze–thaw cycles, the compressive strength and tensile strength decreased by approximately 15 % and 45 %, respectively. Flexural strength remained almost same.

The measured load–displacement curves for MA–1, 2, 3 and MB beams are shown in Figs. 4 and 5 together with the ultimate strength. It is found that the composite structure, which experienced freeze–thaw cycles, did not exhibit appreciable decrease in the ultimate strength and the amount of deformation which the composite structure exhibited before its failure. Its flexural stiffness decreased due to the freeze–thaw cycles. It is a great advantage of the composite structure when used as structural members of the Arctic offshore structures that the freeze–thaw cycles does not deteriorate its load–carrying capacity.

The development of cracks in each model is

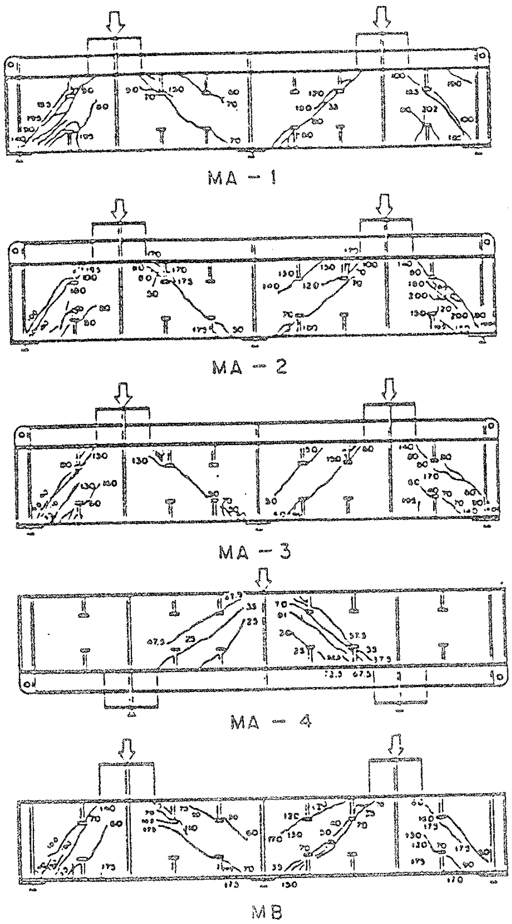

Fig. 6 Crack propagation in concrete

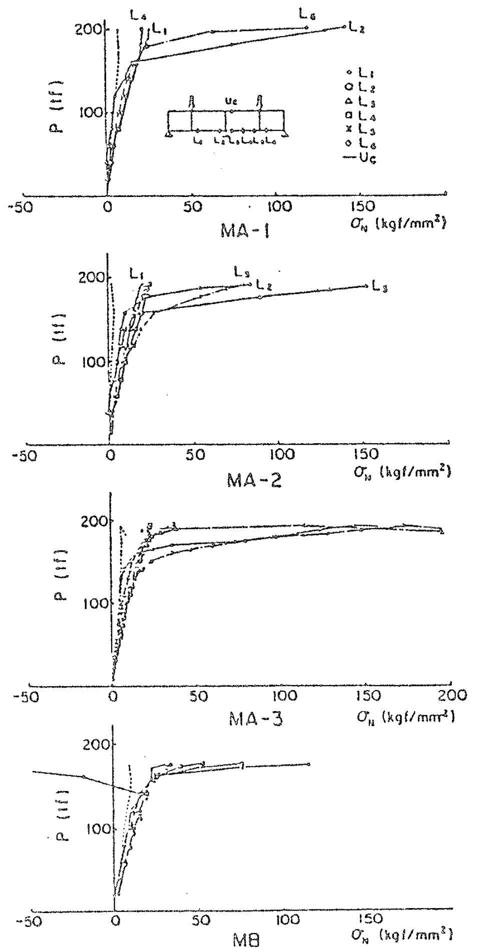

Fig. 7 Measured axial stresses of steel plates

shown in Fig. 6. It is found that concrete cracks start at or very close to a shear connector and a place where loading is applied. The concrete cracking propagates diagonally. This suggests that the cracked concrete transmits diagonal compressive force and carries shearing force.

Both axial stresses and bending stresses induced in lower steel plates are shown in Figs. 7, 8 and 9. It is found from Fig. 8 that tensile stresses in the lower plates are uniform. A slip between concrete and steel plate, and diagonal cracks in concrete make the axial stress distribution somewhat different from the one predicted by the beam theory. The behavior of the composite beam which is different from the one predicted by the beam theory can be analysed by the truss theory as shown in Chapter 4.

The load–axial stress relation is almost linear until the diagonal cracks in concrete propagate all through the concrete and reach both upper and lower steel plates as shown in Fig. 7. Axial stresses near the supports of the test model increase rapidly after the diagonal cracks propagate all through the concrete. As shown in Fig. 9 bending stresses near the supports are large, too. Thus, initial yielding of steel plate starts at supports when the diagonal cracks propagate all through the concrete. As the load increases further, plastic region of steel plate expands gradually. Finally, the failure of test model occurs after exhibiting large deformation.

Reaction forces at the supports of the test beam increase linealy with increasing loading. The rate of increase in the reactions change after the applied load exceeds 150 tf. When the failure of the model occurs, the reactions at

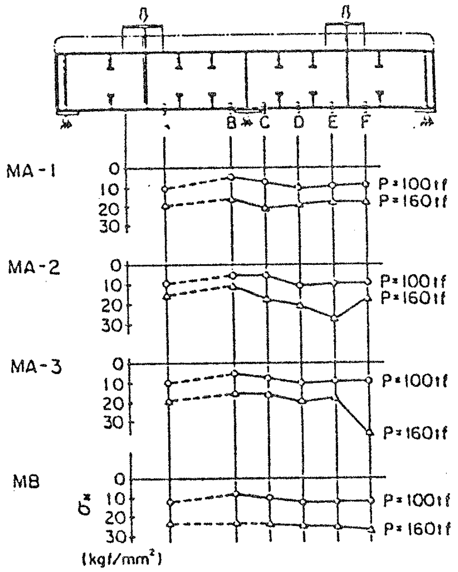

Fig. 8 Measured load–axial stresses of steel plates relaion

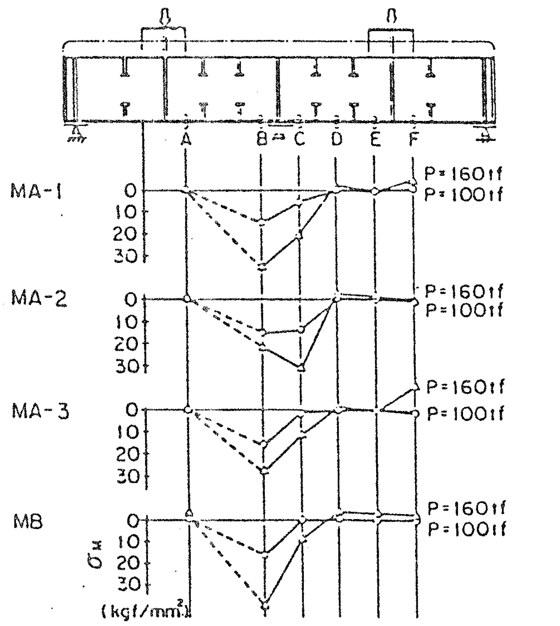

Fig. 9 Measured bending stresses of steel plates

supports are equal to the one calculated by assuming the model to be simply supported at each support.

3. Non–linear Analysis by FEM

When a load, acting upon the composite structure of sandwich system, exceeds its proportional limit, the structure exhibits non-linear behavior and finally reach its ultimate strength. The nonlinear behavior of the structure is caused by the following nonlinearities :

Cracking starts in concrete when the tensile stress reaches the tensile strength. As cracking forms, stress transfer across the crack is reduced to zero. When the compressive stress acting on concrete reaches the yield stress, the plastification of the concrete starts. The concrete crushes when the stress reaches its compressive strength. The steel plate buckles and loses the load carrying capacity when the compressive stress reaches the buckling stress. When the stress of steel plate reaches the yield stress, the steel exhibits plastic deformation. Finally, the steel loses the load–carrying capacity when the stress reaches the tensile breaking strength. A gap occurs between steel plate and concrete when tensile forces act between them. No stresses are transfered

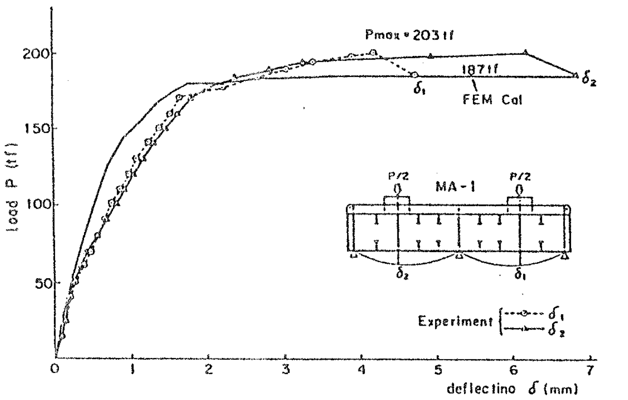

Fig. 10 Comparison of load–deflenction curves (MA–1)

thereafter.

In this section, the finite element method is applied to analyse the nonlinear behavior of the composite structure.

The steel plates and concrete are divided into triangular elements. Linkage elements are incorporated to represent the effect of bond between concrete and steel.

The solution of linear incremental equation is obtained under successive, small increment of loading until failure of the composite structure occurs.

Figs. 10 through 12 summarize the measured and calculated load–deflection curves of the

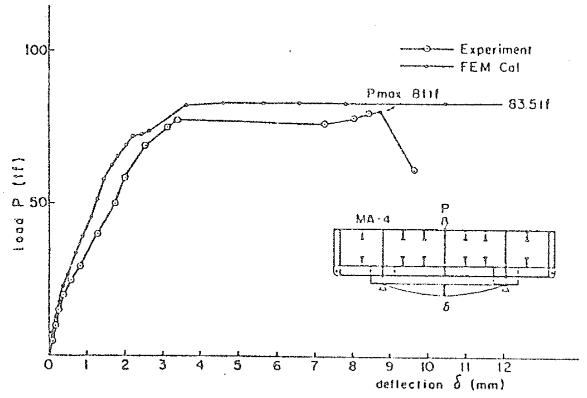

Fig. 11 Comparison of load–deflenction curves (MA–4)

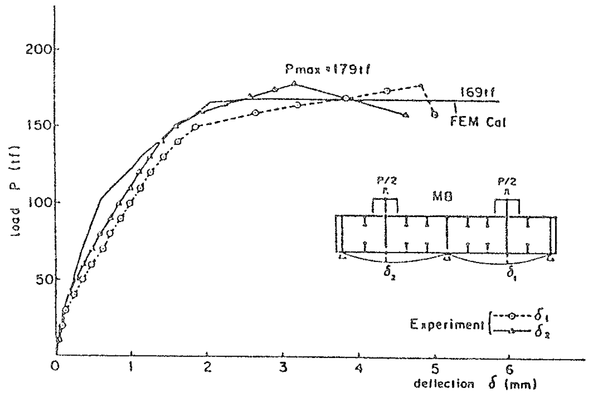

Fig. 12 Comparison of load–deflenction curves (MB)

test models. The calculated ultimate loads are 187, 83.5 and 169 tf for MA–1, MA–4 and MB models, respectively. They are in good agreement with measured results of 203, 81 and 179 tf.

Fig. 13 shows the principal stress distribution and change of element properties in the post elastic region, i.e. cracking, yielding, crushing of concrete and steel. It is found that diagonal compression field develop in concrete after diagonal cracking developed in concrete. Higher stresses are observed at the corner of stiffeners, which contribute to suppress local deformation of concrete and gap between concrete and steel.

The following information is obtained by comparing measured and calculated results ;

(a) Diagonal compression field develops in concrete and carries diagonal compressive force.

(b) The collapse of the composite structure occurs by general yielding of steel plates and local yielding of concrete.

4. Simplified Method of Ultimate Strength Analysis

Nonlinear analysis by the finite element method is costly and time consuming. So a simplified method of of the ultimate strength

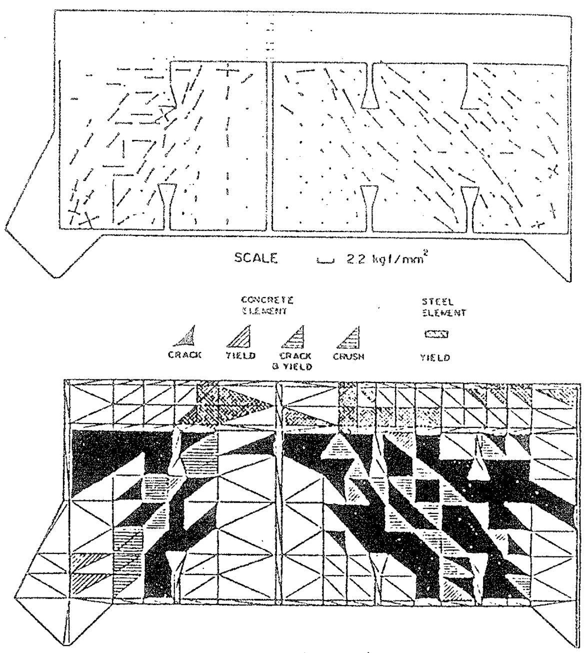

Fig. 13 Calculated principal stresses and variation of element properties (MA–1, P=187tf)

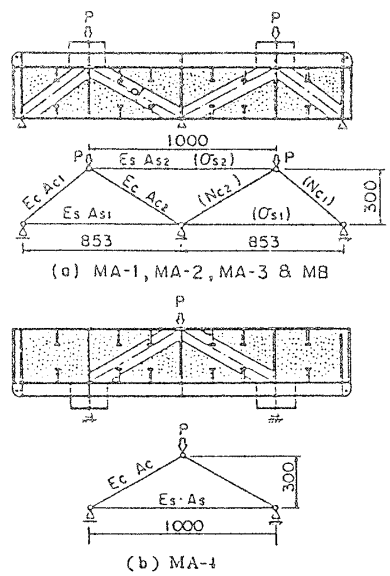

Fig. 14 Simplified model for ultimate strength analysis

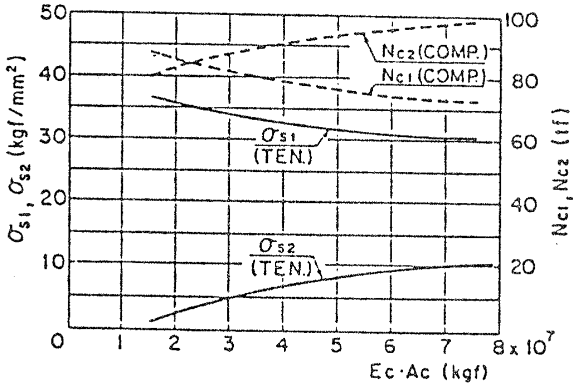

Fig. 15 Effect of axial stiffeness on stresses of steel plate and axial force of concrete

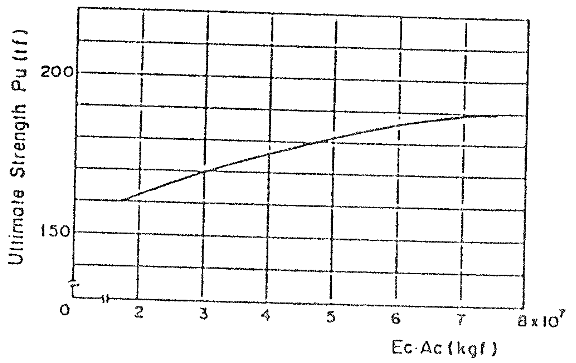

Fig. 16 Relation between ultimate strength and axial stiffeness

analysis of the composite structure with a small ratio of span to depth is developed by the help of the experimental observations described in the preceding section.

An idealized model of truss structure as shown in Fig. 14 is used for analysis, consisting of upper and lower steel plates and concrete. The steel plates carries the horizontal forces and concrete the diagonal compression. Young's modulus and effective sectional area of diagonal compression field of concrete are found through a series of calculations, comparing the results with those obtained by the experiments and the FEM analysis.

Fig. 15 depicts the effect of the compressive stiffness of the diagonal concrete, $E_c A_c$, upon axial stresses of the diagonal concrete. Fig. 16 depicts the ultimate strength of the composite structure when the stress of the lower steel plate reaches the yield stress of 28.7 kgf/mm². It is found that the ultimate strength decreases slightly with decreasing the compressive stiffness of the diagonal concrete; 10% reduction of $E_c A_c$ causes 1–2% reduction of the ultimate strength.

The composite structure, which experienced freeze—thaw cycles, does not show appreciable decrease in their ultimate strength. This is because the failure of the composite structure is not caused by crushing of concrete, but by general yielding of steel plate. Their ultimate strengths decrease slightly due to decrease in their mechanical properties caused by the freeze—thaw cycles.

The ultimate strengths for MA—1, 2, 3 and MB are calculated and they are shown in Table 3 together with the ultimate strengths obtained by the experiments and the FEM analysis. It is clarified that the proposed method of the ultimate strength analysis is accurate.

Table 3 Comparison of ultimate strength

(tf)

	MODEL TEST	FEM ANALYSIS	SIMPLIFIED ANALYSIS
MA-1	203	187	170 ~ 190
MA-2	200		170 ~ 190
MA-3	196		170 ~ 190
MA-4	81	84	92
MB	179	169	170 ~ 190

5. Concluding Remarks

Various excellent properties of the new composite steel—concrete structure with a small ratio of span to depth are clarified through experimental and theoretical investigations. Important information obtained in these investigations is summarized in the following:

(1) A simplified method of ultimate strength analysis is developed. Comparison of the calculated results with the measured ones shows good correlation between them. Thus, the accuracy of the proposed theoretical method is assured.

(2) Although mechanical properties of concrete are deteriorated by cycles of freeze—

thaw, the ultimate strength of the composite structure does not show appreciable decrease. This is because of the fact that the failure is caused by general yielding of steel plates, not by concrete crushing.

References

1) M. Matsuishi, et al.: On The Strength of New Composite Steel–Concrete Material For Offshore Structure, Paper No. 2804, OTC, 1977.
2) M. Matsuishi, et al.: On the Strength of Composite Steel–Concrete Structures of Sandwich System (2nd Report), Jour. of SNAJ, Vol. 142, Dec. 1977 (in Japanese).