FALLING-WEIGHT IMPACT TESTS AND IMPACT RESPONSE ANALYSES OF TWO-LAYERED ABSORBING SYSTEM

Takashi Satoh[1], Kenji Ikeda[2], Norimitsu Kishi[3], Ryoji Kawase[4], and Takeshi Chiyoda[5]

ABSTRACT

In order to upgrade the impact-resistance of rockfall retaining wall against falling and/or tumbling rocks, two-layered absorbing system is developed which is composed of 10 – 15 cm thick RC slab for top layer and 125 – 250 mm thick Expanded Poly-Styrol block for bottom layer. Here, in order to investigate its absorbing performance, a falling-weight impact test is conducted and elasto-plastic dynamic response analysis is also performed to discuss an applicability of a proposed FEM analysis technique on this type of impact problem. The results obtained from this study are as: 1) applying a proposed absorbing system, maximum weight impact force can be decreased to one-ninth that occurred due to direct impact loading; 2) transmitted impact stress can be widely spread with small amplitude less than 0.3 MPa; and 3) numerical results obtained from the proposed FEM technique are in good agreement with experimental ones.

Key Words : rockfall retaining wall, two-layered absorbing system, falling-weight impact test, FEM

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[1] Researcher , Structures Division, Civil Engineering Research Institute of Hokkaido
(Address: 1-3 Hiragishi, Toyohira Ward, Sapporo, 062-8602 Japan,
Tel: +81-11-841-1698, Fax: +81-11-820-2714, E-mail: taka4@ceri.go.jp)
[2] Head , Structures Division, Civil Engineering Research Institute of Hokkaido
[3] Professor, Department of Civil Engineering, Muroran Institute of Technology, Ph. D
[4] General manager, disaster prevention division, Koken Engineering Co. Ltd.
[5] General manager, Mitsubishi Chemical Foamplastic Co.Ltd.

1. INTRODUCTION

In Japan, many rockfall retaining walls (hereinafter, walls) constructed along the national roads near mountainous area to protect people's lives and vehicles from falling and/or tumbling rocks. Now, the walls are designed assuming that they behave as rigid bodies and can resist against the impact force with their gravity (Japan Road Association 1993). Then the walls are basically constructed using plain concrete. However, in practice, due to falling and/or tumbling rocks, the walls suffered severe damage that cracks in both transverse and vertical directions and shear cracks along the direction in the wall thickness are developed. And also, it is recognized that the walls fall into the ultimate state under half the design input energy.

Generally, in order to let the walls resist against the impact force, two basic concepts can be acceptable which are: 1) to let the wall resist with the whole system including foundation by increasing mass with enlarging in size and/or reinforcing concrete with steel bars; and 2) to let load intensity decrease and to let the loading time prolong by using absorbing system to be possible to design under quasi-static condition.

On the other hand, authors developed three-layered absorbing system (Kishi et al. 1993, 1995) for applying onto the roof of rock-shed structure to decrease the impact force generated due to falling rocks, which is composed of 50 cm thick sand cushion for top layer, 20 – 30 cm thick RC core slab, and 50 – 100 cm thick Expanded Poly-Styrol (hereinafter, EPS) block for bottom layer. The applicability and absorbing performance for practical use have been made sure conducting many prototype field tests.

In this paper, in order to upgrade the impact-resistance of rockfall retaining walls, two-layered absorbing system for setting in front of the walls is developed based on the second concept mentioned above and its absorbing performance is experimentally discussed conducting falling-weight impact test. And three-dimensional nonlinear Finite Element Method (hereinafter, FEM) analysis is also performed and its validity and practical applicability are discussed comparing with the experimental results on weight impact force, transmitted impact stress/force onto the basement, and crack pattern developed in the RC slab.

2. EXPERIMENTAL OVERVIEW

Figure 1 shows the experimental overview in which an absorbing system is laid onto the RC foundation and a steel-weight is dropped onto the system to precisely control an loading point and impact speed of steel-weight. Absorbing system tested in this study is for applying to 2 m high type rockfall retaining wall and its dimensions are of l = 2 m long (corresponding to height H for the wall) and B = 1.7 m wide. One side corresponding to the bottom of wall is anchored to the RC foundation keeping the total thickness of RC slab and EPS block by using three steel bars (ϕ = 32 mm) to protect rebound of the whole RC slab occurring due to steel-weight impacting.

In this study, a 400 kg cylindrical steel-weight is singly dropped from the predetermined height, in which RC slab and EPS block are discarded after a single use. A nose part of steel-weight is of cylinder with 150 mm in diameter and spherical shape with 1400 mm in radius to prevent an eccentric impact. And the upper part of weight is of cylindrical shape with 230 mm in diameter to fit the mass of weight with 400 kg. Then, a diameter of penetrated area into RC slab may be more than 230 mm.

The measurement items are weight impact force through load-cell installed in the steel-weight and transmitted impact stresses through load-cells embedded in the RC foundation, in which total sixteen load-cells are embedded at minimum intervals of 10 cm on the transverse and longitudinal lines through loading point as shown in **Fig. 2**.

The test cases conducted in this study are listed in **Table 1**. Nominal names are designated hyphenating thickness of EPS block *hc* (mm) and impact velocity of steel-weight *V* (m/s). In this table, impact velocity V = 3.2, 4.7, 6.3, 7.9 and 9.5 m/s correspond to the velocity *V* = 2, 3, 4, 5, and 6 m/s, respectively, for equivalent impact energy at a 1,000 kg rock impacting.

All RC slabs used for top layer are reinforced by orthogonal single arrangement with 1 % rebar ratio in both directions and are of *l* = 2 m long, *B* = 1.7 m wide, and 100 mm thick as shown in **Fig. 3**. EPS blocks are formed cutting out 50 x 50 x 100 cm blocks with density $\rho = 20$ kg/m^3 into a predetermined thickness. Here, two cases for thickness of EPS block are examined: *he* = 125 mm and 250 mm. The material properties of concrete and rebar used in this study are listed in **Table 2**.

3. ANALYTICAL OVERVIEW

3.1 Analytical Model for Absorbing System

In this paper, LS-DYNA code (Hallquist 2000) is used to analyze the impact behavior of two-layered absorbing system under a steel-weight impacting. **Figure 4** shows a analytical model for the case of E250, in which total number of nodal points and elements are almost 8,000 and 10,000, respectively, for half model. The bottom of RC foundation is perfectly fixed following experimental setup.

Slide interface model is applied in two contact surfaces between the bottom surface of RC slab and the top surface of EPS layer, and between the top surface of RC slab and the bottom face of steel-weight to precisely estimate the rotation of the RC slab and rebound of steel-weight, respectively.

3.2 Analytical Model for Absorbing System

Material models installed in the code are applied for representing constitutive law of concrete, rebar, and EPS composing the absorbing system. **Figure 5** indicates stress-strain relations used in this analysis for each material.

The constitutive model shown in **Fig. 5(a)** is for concrete element, in which stress-strain relation in the compression region is assumed as perfect elasto-plastic material (bi-linear model) with von Mises yield criterion and in the tension region, tensile stress is abruptly decreased to zero level and can not be transmitted in any direction when average normal stress (negative pressure) reaches a cutoff value. Here, it is assumed that concrete is yielded at 1,500 μ strain when stress reaches compressive strength and tension cutoff stress is equal to one-tenth the compressive strength.

Figure 5(b) shows stress-strain relation for rebar element which is isotropic elasto-plastic model considering strain hardening modulus $H' = Es/10$ (Es: Young's modulus) following isotropic hardening rule with von Mises yield criterion.

Figure 5(c) shows stress-strain relation for EPS block, in which the compression region is assumed as tri-linear type isotropic crushable material with reference to the static characteristics and cutoff stress in tension side is assumed to be zero level.

A system damping factor h depending upon the mass of system is assumed to be $h = 0.02$ for fundamental natural vibration.

4. COMPARISON BETWEEN EXPERIMENTAL AND ANALYTICAL RESULTS

4.1 Weight impact force

Figure 6 shows the comparison between experimental and analytical results on weight impact force wave in cases of E125 and E250. In this figure, from the experimental results, it is seen that all waves are composed of a half sine wave with a high amplitude and 5 ms duration time at beginning of impact and following another half sine wave having an amplitude with half that of the first wave and long duration time of 35 – 55 ms. The first wave is excited due to steel-weight impacting onto RC slab and second one is mainly affected by plastic deformation of EPS block. Total duration times for E125-V6.3 and E250-V9.5 are 40 ms and 60 ms, respectively, and the latter case is 20 ms longer in time than the former case. This is because impact energy for latter cases can be effectively absorbed due to damage of RC slab and a thicker EPS block.

The authors conducted another field impact test (Kishi et al. 2000) for prototype 2 m high type rockfall retaining wall without absorbing system using a 1,000 kg steel-weight. **Figure 7** shows the weight impact force wave when impact velocity is V = 6.16 m/s, in which the impact energy of this case is almost the same with hat in case of E250-9.5. Here, comparing between these two cases for the characteristics of weight impact force. The maximum impact force and duration time are 203.6 kN and about 60 ms for E25-V9.5 and 1.8 MN and about 2 ms for the case of directly impacting to the wall, respectively. Then it is make sure that the maximum weight impact force can be decrease to one-ninth and duration time can be prolonged to more than 20 times due to applying two-layered absorbing system.

Comparing with analytical and experimental results shown in **Fig. 6**, it is observed that wave configuration, maximum response value, and duration time obtained from numerical analysis are in good agreement with those of experimental results for all cases except E250-V9.5. In case of E250-V9.5, characteristics of wave distribution obtained from analytical results are almost similar to those of experimental ones but the former wave intends to little overestimate maximum response value comparing with the latter wave. This means that 1) the intensity of impact force from experimental results may be decreased by letting impact energy severely absorb due to steel-weight perforating RC slab because of high impact velocity, but 2) numerical analysis can not precisely follow from beginning of impact to the response of perforation phenomena of steel-weight. However, applying this proposed analytical procedure, a maximum weight impact force can be estimate in the safety side for design.

4.2 Transmitted impact stresses

Figure 8 shows the comparison between experimental and analytical results on transmitted impact stresses onto the RC foundation in transverse and longitudinal directions of the system for the cases of E125-V4.7 and E250-V6.3. In this figure, the distance in both transverse and/or longitudinal direction from the impacting point is taken as abscissa, and time axis and stress intensity are taken on oblique and longitudinal direction, respectively. From the experimental results shown in this figure, it is observed that 1) transmitted impact force is spread in the wide area of both transverse and longitudinal directions; 2) maximum impact stress distributes around 0.3 MPa; and also, 3) duration time of wave is prolonged at least 20 ms.

Comparing analytical results with experimental ones, it is seen that analytical results regarding wave configuration, stress distribution along the distance from loading point, and duration time of wave better correspond to the experimental ones. Then, it is confirmed that a proposed FEM analytical procedure can be applied to practically estimate distribution of the transmitted impact stress of two-layered absorbing system.

4.3 Crack Pattern

Based on the assumption of soil and crushable form model applied as the material constitutive law of concrete, when a negative pressure in a element reaches cutoff level, it is defined that the crack is occurred in the element and the stress is decreased to zero. It implies that if the maximum principal stress occurred in an element is equal to zero value, a crack may have been developed in the element. Here, it is tried to evaluate the crack pattern developed in the RC slab by using this concept.

Figure 9 shows a comparison between experimental results on crack pattern developed in the upper surface of RC slab and analytical results on the gray-scaled contour of the first principal stress around zero level in case of E125. The stress contour for the RC slab is at the time when weight impact force starts unloading and maximum displacement is excited. The time is about 20 ms after beginning of impact. The elements with the maximum principal stress being zero are drawn with white-color in gray-scaled contour. In this figure, two results for the absorbing system model are shown which are for the cases of minimum and maximum impact energy. From this figure, in both cases of minimum and maximum impact energy, it is observed that the distribution of white-color contour from numerical analysis corresponds very well to the crack pattern developed with concentric circle.

Then, it is seen that distribution of crack pattern developed in RC slab can be predicted qualitatively by using a proposed FEM analytical procedure.

5. CONCLUSIONS

In order to upgrade the impact-resistance of rockfall retaining wall, two-layered absorbing system is developed which will be set in front of the wall. This system is composed of 10 cm thick RC slab as the top layer and 125 – 250 mm thick EPS block as the bottom layer.

In this paper, absorbing performance of this system is confirmed performing falling-weight impact test using a 400 kg steel-weight. And nonlinear three-dimensional FEM analysis is performed using LS-DYNA code to discuss applicability of the proposed analytical procedure to this type of impact problem comparing with the experimental results. The results obtained from this study are as:

1) When impact energy is same level, applying proposed absorbing system, maximum weight impact force can be decreased to one-ninth and duration time of wave can be prolonged to more than twenty times comparing with those in case of a steel-weight directly impacting to the wall;
2) Transmitted impact stress can be controlled around 0.3 MPa due to the absorbing effect of EPS block as the bottom layer; and
3) Then, proposed FEM analysis procedure can be practically applied to analyze rockfall retaining wall with two–layered absorbing system.

REFERENCES

Japan Road Association (1993), “Manual for impact resistant design of structures against falling rocks”

Kishi, N., Nakano, O., Mikami, H., Matsuoka, K.G., and Sugata, N. (1993), “Field test on shock-absorbing effect of three-layered absorbing system”, Proceedings of the 12th International Conference on SMiRT, JH13/6, pp. 357-362

Kishi, N., Sato, M., and Nakano, O (1995), “Prototype impact test on absorbing capacity of three-layered absorbing systems”, Journal of Structural Engineering, JSCE, Vol. 41A, pp. 1257-1265, in Japanese.

Hallquist, John, O. (2000), “LS-DYNA user’s Manual”, Version 950 Livermore Software Technology Corporation

Kishi, N., Ikeda, K., Konno, H., and Kawase, R. (2000), “Prototype impact test on rockfall retraining walls and its numerical simulation”, Proceedings of Structures Under Shock and Impact VI, pp. 351-362

Table 1 List of test cases

Test case	Thickness of EPS *hc* (cm)	Impact velocity *V* (m/s)	Steel weight *M* (kg)
E125-V3.2	125	3.2	400
E125-V4.7		4.7	
E125-V6.3		6.3	
E250-V4.7	250	4.7	
E250-V6.3		6.3	
E250-V7.9		7.9	
E250-V9.5		9.5	

Table 2 Material properties of concrete

Material	Young's modulus (GPa)	Poisson's ratio	Compressive strength (MPa)	Yielding stress (MPa)
Concrete	17	0.18	26	-
Steel	206	0.3	-	355

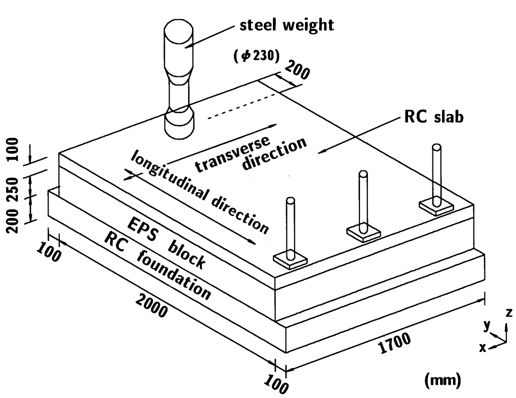


Fig. 1 Experimental setup

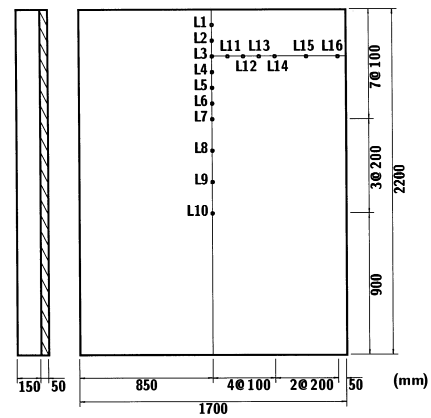


Fig. 2 Locations of load-cells for measuring

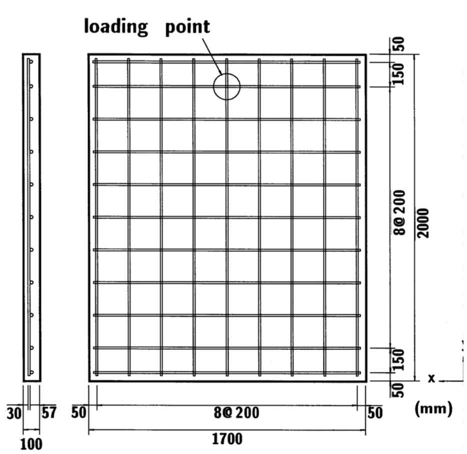


Fig. 3 Dimensions of RC slab and rebar arrangement

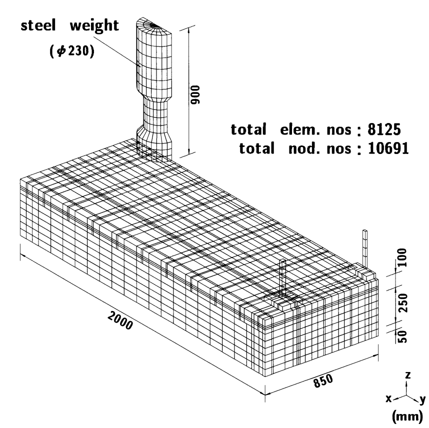
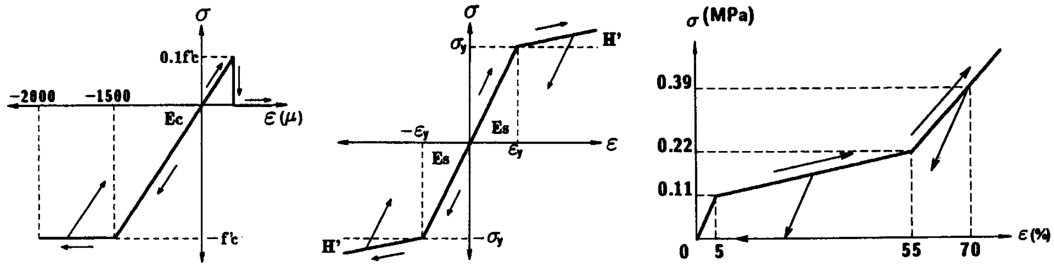


Fig. 4 An example of analytical model (E250)



(a) Concrete (b) Rebar (c) EPS

Fig. 5 Constitutive model for each material

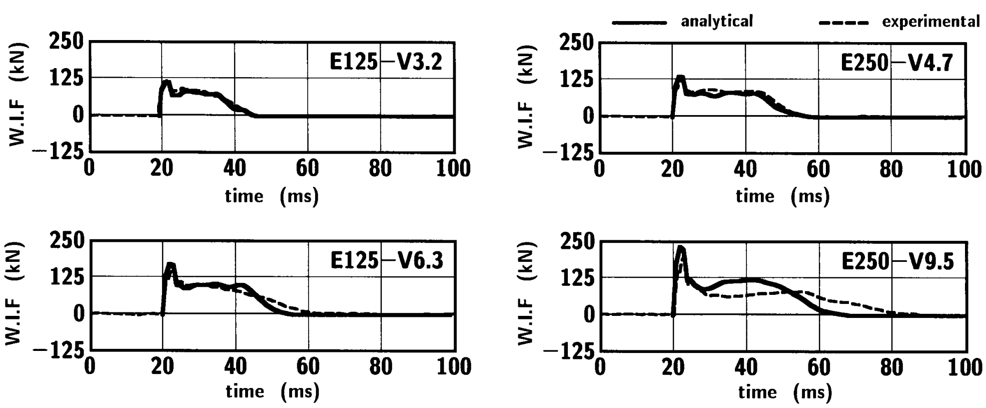


Fig. 6 Comparison of weight impact force (W.I.F.) between analytical and experimental results

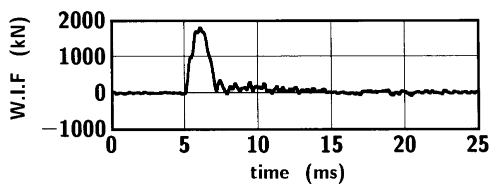
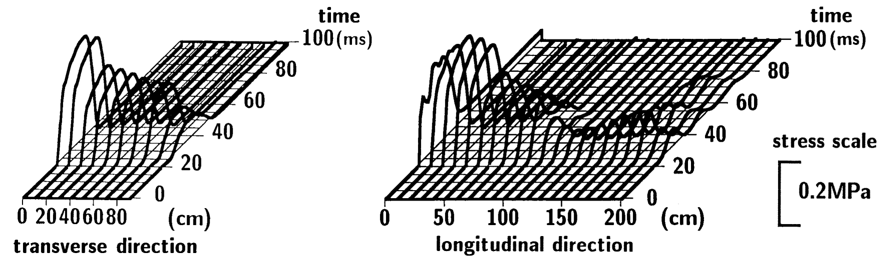
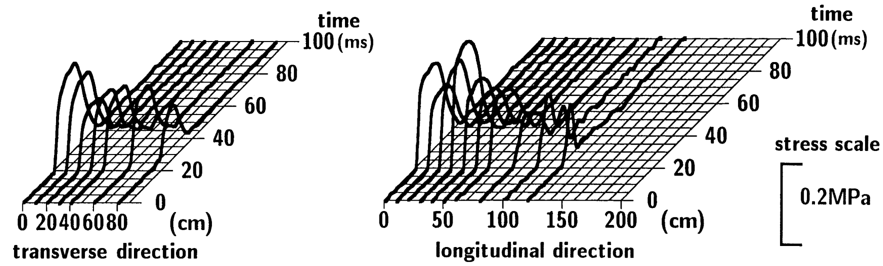


Fig. 7 Weight impact force at directly impacting to the wall (M=1,000kg, V=6.16m/s)

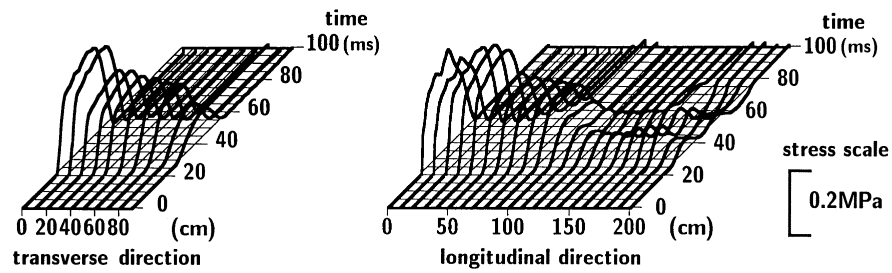


Analytical results

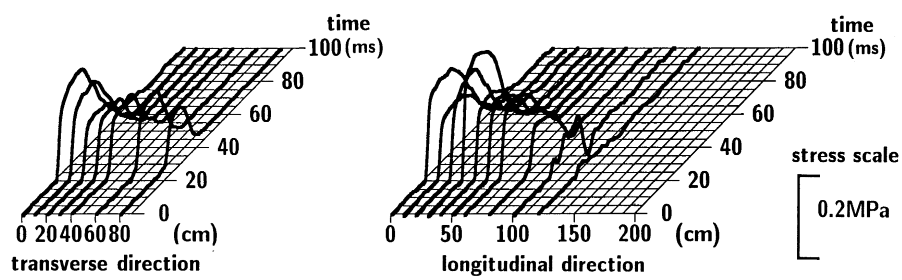


Experimental results

(a) E125-V4.7



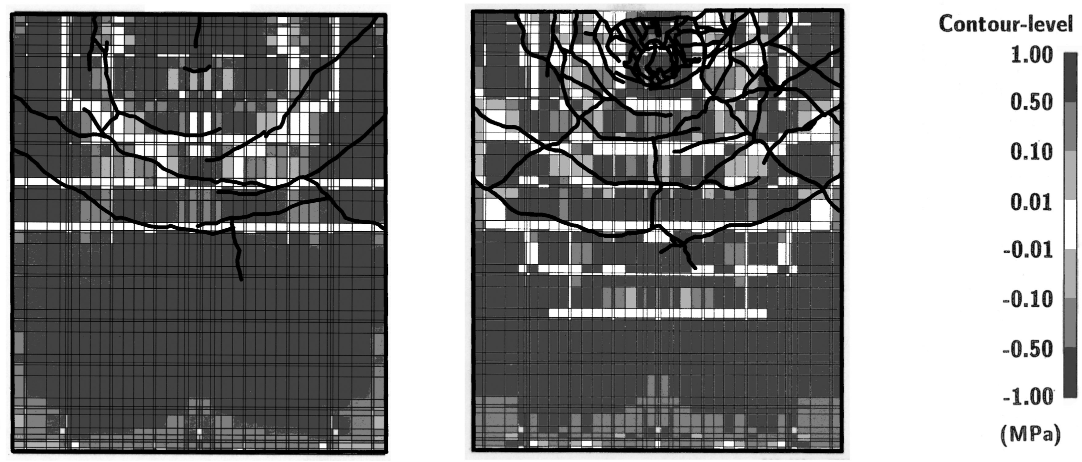
Analytical results



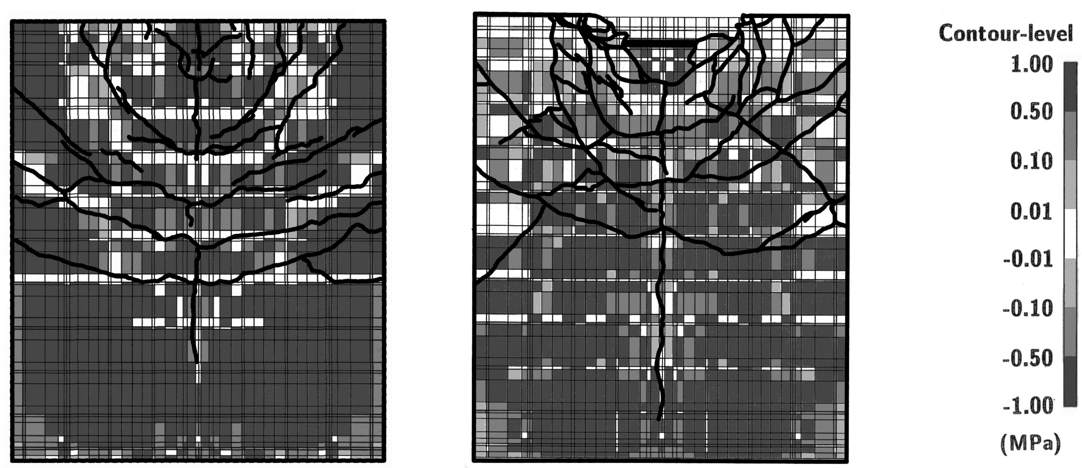
Experimental results

(b) E250-V6.3

Fig. 8 Comparison between analytical and experimental results for transmitted impact stress



(a) E125-V3.2 **(b) E125-V6.3**



(c) E250-V4.7 **(d) E250-V9.5**

Fig. 9 Comparison between crack pattern after experiment and max. principal stress distribution near zero level just after max. response.