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Dynamic Analysis of Double-Skin Composites

By

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Abstract

Double skin composite (DSC) is the term used to describe a structural system of steel plates connected to a sandwiched concrete core with welded stud shear connectors. In the present paper a non-linear three-dimensional finite element models for Double Skin Composite (DSC) panels subjected to dynamic loading, using a general purpose finite element package ABAQUS version 6.4, is introduced. Pilot model was used to investigate the failure pattern in the composite panel when subjected to Impact loads by rigid penetrator, while the other models were used to analyze the energy absorption capacity of such system when perforated. These models include variation of upper and lower plate thicknesses as well as increasing number of shear connectors in upper or lower plates. Moreover, the last model includes concentrating the distribution density of stud shear connectors in the middle of the upper plate. These models were checked first against quasi static, experimental and finite element results. Results showed that such elements have great ability of absorbing energy when subjected to perforation due to ductility of lower plate skin and vertical stiffness of lower shear studs. Effect of increasing lower plate thickness as well as number of shear connectors, to face impact loading has a great role in controlling the amount of energy absorbed by such structures due to its ability to prevent concrete scabbing from impact rear face which relaxes strain rate of concrete while resisting penetration due to the presence of lower shear studs

KEYWORDS: Double skin composite; Impact; Dynamic loading; Shear studs.

Egyptian Armed Forces

1. Introduction

The field of impact dynamics covers a wide range of situations and is of interest to engineers from a number of different disciplines. Military scientists need to understand the subject in order to design structures that are more efficient for withstanding projectile impact. In the aim of understanding the impact problems and its technical terms, Naik and. Shrirao [1] defined the most important technical terms used in impact problems, as the definition of low velocity impact. The ballistic limit of target is defined as the maximum velocity of a projectile at which complete perforation takes place with zero exit velocity. Perry et al. [2] discussed the factors influencing the response of fiber-reinforced concrete slabs to impact and noted that changing the amount of fiber reinforcement may change the mode of failure of the concrete. The unreinforced concrete tends to fail by shear punching. Steel-fiber reinforced concrete tends to fail by flexure and crushing of the concrete. The response of steel – grout sandwich plates to projectile impact was investigated by Corbett & Reid [3], it was shown that sandwich plates made up of two 1mm thick steel skins separated by grout fillers with thickness ranging from 3 to 40 mm were not efficient enough to withstand projectile impact in terms of energy absorbed per density of steel plates. Corbett et al [4] investigated the resistance of steel-concrete sandwich tubes to penetration from hardened steel indentor. Concrete tubes were claded on their outer and inner diameters with 1mm thick steel skins and subjected to quasi static and dynamic loadings. The tested tubes had an inner diameter of 120 mm, concrete fillers of thickness 10, 20, 38 mm were examined. It was shown that the impact resistance of steel – concrete sandwich structures was less sensitive to projectile mass and nose shape than monolithic steel structures. In addition the resistance of the sandwich structures to projectile penetration was seen to be most effective when the rear face skin was undeformed, which provides substantial support to the filling medium.

In the present paper, a non-linear three-dimensional finite element models for Double Skin Composite (DSC) panels subjected to dynamic loading using a general–purpose finite element package ABAQUS/ Standard/Explicit version 6.4 is introduced. Pilot model was used to investigate the failure pattern in the composite panel when subjected to impact loads by rigid penetrator. The other models were used to analyze the energy absorption capacity of such system when perforated. These models include variation of upper and lower plate thicknesses as well as increasing degree of shear interaction between upper plate and concrete core, increasing degree of shear interaction between lower plate and concrete core. The last model includes concentration of the distribution density of stud shear connectors at the middle of the upper plate. These models were checked first against quasi static, experimental and finite element results [5], [6]. Therefore the purpose of this study is to investigate the change in failure mechanism compared with quasi-static and to investigate absorbed energy by such panels when subjected to impact by conical shape rigid penetrator.

2. Input Data for Dynamic Analysis

The dimensions of the specimens were chosen based on the regulations of detailing of composite steel-concrete structures. All panels were chosen of dimensions (1000 mm x 1000 mm) and have concrete core thickness of 50 mm, except in the pilot specimen, where the concrete core was 80 mm. Table (1) shows the dimensions of all specimens, and Figures (1) and (2) shows the dimensions and studs distribution through the models. The composite Slabs were modeled as non-linear three-dimensional models. The top and bottom steel plates were modeled using four-nodes reduced integration shell elements with large strain formulation; whereas the concrete core was modeled using eight nodes solid element with holes similar to those of shear studs that were embedded in concrete. The shear studs were modeled by using eight nodes solid element. The indentor was modeled as an analytical rigid surface, since it was assumed that no deformation occurs in it. Assembly techniques were used to compose upper plate skin with upper shear connectors and lower plate skin with lower shear connectors. The Concrete core was imposed between the steel plates, while analytical rigid part (indentor) was adjusted in the center of upper steel plate.

Shell elements of upper and lower steel plates were divided into regions of different mesh size, such that the mesh in the two strips-in both directions- at the middle of the shell were refined for a required accuracy in deformations and results of the region around the indentor. Solid elements of shear connectors were finely meshed by approximate element side size of (2.5 mm). Solid elements of concrete core were divided into regions of different mesh sizes, such that the regions of stud holes were the same as those of the steel plates. The core was meshed with the same fine mesh in the two strips (in both directions) at the middle while the rest of core was meshed by mesh size of (35 mm). Figure (3) shows the assembly of indentor with the composite slab after mesh.

2.1 Material Modeling

Steel was assumed to behave as an elasto-plastic material in both tension and compression. The material properties of steel were specified using elastic and plastic options in the ABAQUS/ Standard /Explicit version 6.4. For penetration problems, the finite element package provided an option of using failure model by defining shear failure value for used material. Concrete was treated as anisotropic material. The specification of concrete core was taken as mentioned in BS 8110 [7]. For case of penetration in concrete the shear failure was assumed at a value of 40% of its ultimate strength.

2.2 Loads and Boundary Conditions

Boundary conditions were applied on the models to represent the case of clamped upper and lower steel plate ends. The upper and lower shell edges were prevented from translations and rotations in all directions. These boundary conditions occurs by applying boundary conditions techniques available in ABAQUS/Explicit on nodes from edge of shell to nodes laying at a distance equal 70 mm from edges (angle length of upper and lower frames used to clamp steel plates). As shown in Figure (4). Reference point of analytical rigid part (indentor) was prevented from moving in all directions except in z- direction. The initial velocity was an input given to the reference point of indentor. The energy absorbed during quasi-static experiments [5], were used to obtain the estimated initial value of velocity as follows:-

$$\textbf{Absorbed energy from quasi-static experiments} = \tfrac{1}{2}\, m\, (V_o)^2$$

The mass of indentor used is equal to 58.75 Kg. Table (2) shows the initial velocity values for each panel as calculated from the above relation.

3. Dynamic Analysis

The obtained results were concentrated with the amount of energy absorbed when the panels were subjected to impact by initial velocity, which can cause complete perforation as well as with the investigation of accompanied failure modes that occured. The amount of energy absorbed was calculated by capturing the residual velocity of indentor after perforating the lower plate. The change in initial kinetic energy and residual kinetic energy was the amount of energy absorbed by the panel. Failure phases were described by observing the output of stress contours on panel elements during the running steps. The panels were firstly loaded by initial velocity obtained from Table (2) and the results were observed. It was found that the velocities obtained from quasi static test were very high compared with the required ballistic value. When panels loaded with these initial values, it perforated very fast and residual velocity of the indentor after perforation had very small change. This means that quasi-static results were good in describing shape of deformation during perforation, but they were not valid for estimating the energy absorbed by each panel in dynamic analysis. The Initial value of impact velocity was minimized till a clear difference between initial velocity and residual velocity after perforation was observed. For all specimens the initial velocity was 1000 mm /sec.

3.1 Discussions of Failure Pattern

At first step of impact the upper plate was directly perforated and it moved slightly toward the indentor because of the effect of inertial force. Figure (5) shows effect of the inertial force on upper plate just after impact and failure shape after perforation. The upper studs had a good role that did not appear in quasi-static analysis case Figure (6), since when the inertial force takes place as a reaction after impact, the upper plate move slightly upward and the upper studs played the role of vertical links and increased the stiffness of the plate. The elements of upper face of concrete failed after first step of impact, but they were much localized and high stress values were plotted as shown in Figure (7). No spalling was observed because of the upper skin covering, which keep the resistance of concrete during the post step of penetration. Concrete core lower surface pained much larger than upper surface especially in lower stud places which ensured the great effect of lower studs in resistance of penetration, since they acted as hangers for the lower plate as seen in Figure (8). Failure in lower studs was very obvious and happened faster than quasi-static case, which caused rotation of studs after failure due to absorbing large energy in very small time as shown in Figures (9) and (10). Investigation of panel motion due to impact was done by capturing the velocity in direction and magnitude for the middle point of lower plate, as shown in Figure (11). The lower plate gained the same value of initial impact velocity and moved downward a distance that gave it dynamic stability, then it rebounded upward due to the inertial force gained from getting large energy in small time. As progress of the indentor motion downward, lower plate motion started to increase but with slight vibration.

4. Investigation of Ballistic Limit and Discussion of Results

Ballistic limit is the amount of energy absorbed by the target when subjected to impact by initial velocity and certain mass to have residual velocity equal to zero if succeeded in perforating the total thickness of the target. The initial value of velocity **(V_o)** for all models was taken 1000 mm/sec while, the residual velocity **(V_R)** after perforation was captured. Then the ballistic limit of the studied models was calculated from the following relation:-

$$\textbf{Absorbed energy for computing ballistic limit} = \tfrac{1}{2}\, m\, (V_O)^2 - \tfrac{1}{2}\, m\, (V_R)^2$$

Figures (12, 13, 14, 15 and 16) show the change of the indentor velocity versus time history till complete perforation of panel for all models. The end point of curves is the value of residual velocity V_R of the indentor. All results have the same behavior of parabolic decrease in indentor velocity when the resistances of the panels were faced. All specimens' results were taken in the range of total time history required for perforating the lower plate. In ABAQUS 6.4 time history or total time does not mean real time but it is an indication for required iterations done by ABAQUS solver to reach dynamic stability between elements on contact during the run.

The analysis of results is arranged into three groups (A), (B) and (C). Group (A), which contain DSC-1and DSC-2. The first model DSC-1 study the parameter of increasing the upper plate thickness and the second DSC-2 study the parameter of increasing lower plate thickness.
Group (B), which contain DSC-3 and DSC-4. DSC-3 study the parameter of increasing degree of the upper shear stud interaction while DSC-4 study the parameter of increasing the degree of lower shear stud interaction. Group (C), which contain DSC-3 and DSC-5. DSC-5 study the parameter of verifying the same degree of upper interaction of DSC-3 but with less number of upper shear studs.

Results of group (A) showed that increasing the upper plate thickness from 2 mm to 4 mm did not give a valuable effect compared with increasing the lower plate by the same ratio because impact energy caused rapid failure by the great flip of energy of mass. It has a good effect of preventing any possible spalling of upper concrete face. Increasing lower plate thickness by the same ratio increase the absorbed energy by 15% relative to the energy absorbed in case of DSC-1 as shown in Figure (17).

Results of group (B) shown in Figure (18) explain that, increasing upper degree of interaction has a less valuable effect in enhancing ballistic limit compared with the same increasing ratio of the lower plate degree of interaction. Increasing ratio in lower plate interaction enhanced ballistic limit by 25% relative to the ratio of increasing in upper plate interaction.

Results of group (C), as shown in Figure (19) explain that no change in ballistic velocity value occurs when the shear connectors in the upper plate are concentrated close to the middle of the plate. Change in stress contours plotted for upper plate of DSC-5 is noticed because of the upper plate buckling near supports as shown in Figure (20). Adequate number of upper studs must be verified to ensure that no additional stresses due to buckling deformations may be propagated. Figure (21) shows global comparison of all specimens' results.
For more analysis on the effect of upper and lower plate thickness, the thickness of upper plate of DSC-1 is increased from 4 mm to 6 mm and the thickness of lower plate of DSC-3 is increased from 4 mm to 6 mm. Results showed that an increasing by about 24% of energy absorbed by panel due the change of upper plate thickness as shown in Figure (22). The recorded results of increasing lower plate thickness from 4 mm to 6 mm shows a great effect on energy absorbed which increased by 35% as shown in

Figure (23). These results verified the great role of lower plate skin due to its double effect in preventing any scabbing of concrete lower surface (rear surface of impact) which maximizes the resistance of concrete and provides the ductility required in resisting penetration. Much increase in upper plate stiffness helps slightly in absorbing energy due to its role as casing of concrete front face against impact which prevents spalling. The same increase in the lower plate stiffness will be more effective.

5. Conclusions

Double skin composite steel and concrete panels are good and efficient elements for resisting low velocity impact due to its great toughness and ductility compared to concrete panels. Increasing of the upper plate thickness to face impact loading give less effect on the energy absorbed compared with increasing the lower plate thickness by the same ratio while it represent excellent solution for problem of front face spalling. Effect of increasing the lower plate thickness has a great and main role in controlling the amount of energy absorbed by such structures due to its ability to prevent concrete scabbing from impact rear face which relaxes strain rate of concrete while resisting penetration and due to the presence of lower shear studs. Increasing amount of shear interaction in lower plate enhances the absorbed energy by about 25%. Results showed that such elements have great ability of absorbing energy when subjected to perforation due to the ductility of the lower skin plate and vertical stiffness of lower shear studs. More investigation and experimental work of the proposed models must be extended for this research in future.

6. References

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Table1 Dimensions of all specimens

Specimen	Concrete core thickness (mm)	Upper plate thickness (mm)	Lower plate thickness (mm)	Stud length (mm)	Shank diameter (mm)
Pilot test	80	3	3	35	8
DSC1	50	4	2	35	8
DSC2	50	2	4	35	8
DSC3	50	2	2	35	8
DSC4	50	2	2	35	8
DSC5	50	2	2	35	10

Table2 Calculated initial velocity Vo from quasi static results

Specimen	Quasi-static Absorbed Energy (K Joule)	Estimated initial velocity V_o (m/s)
Pilot- test	25.325	29.30
DSC1	20.809	26.6
DSC2	22.824	27.87
DSC3	11.237	19.55
DSC4	16.555	23.75
DSC5	19.017	25.4

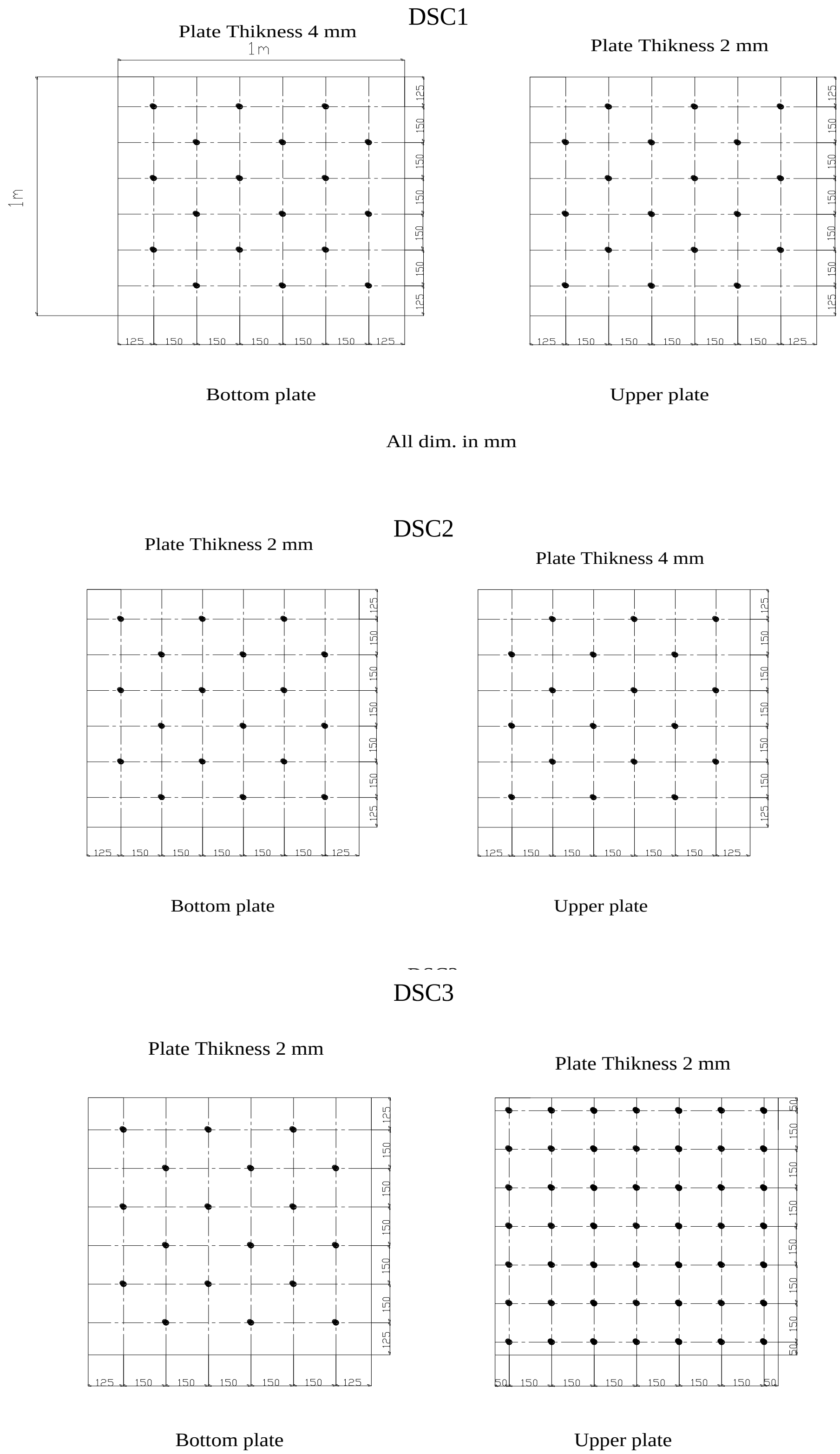

Fig.1 Dimensions and stud distribution across the plates of DSC1, DSC2 and DSC3

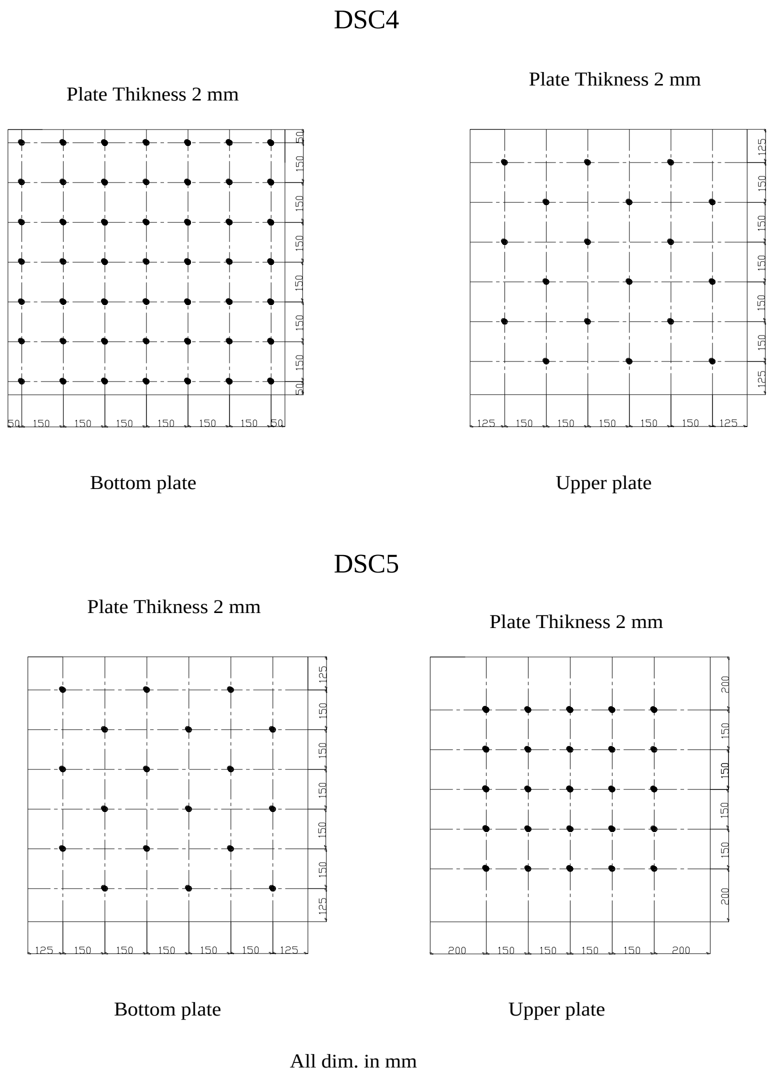

Fig.2 Dimensions and stud distribution across the plates of DSC4 and DSC5

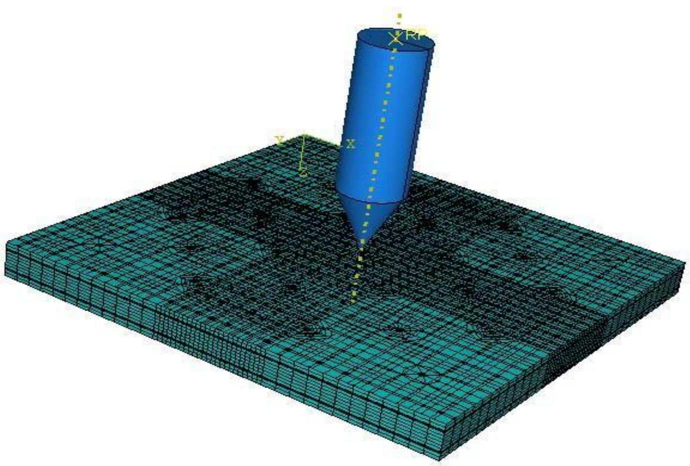

Fig.3 Assembly of indentor with composite slab

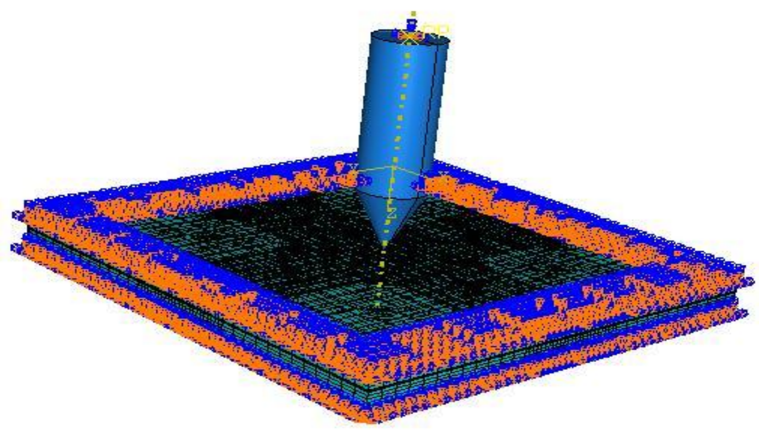

Fig.4 Boundary conditions of composite slab

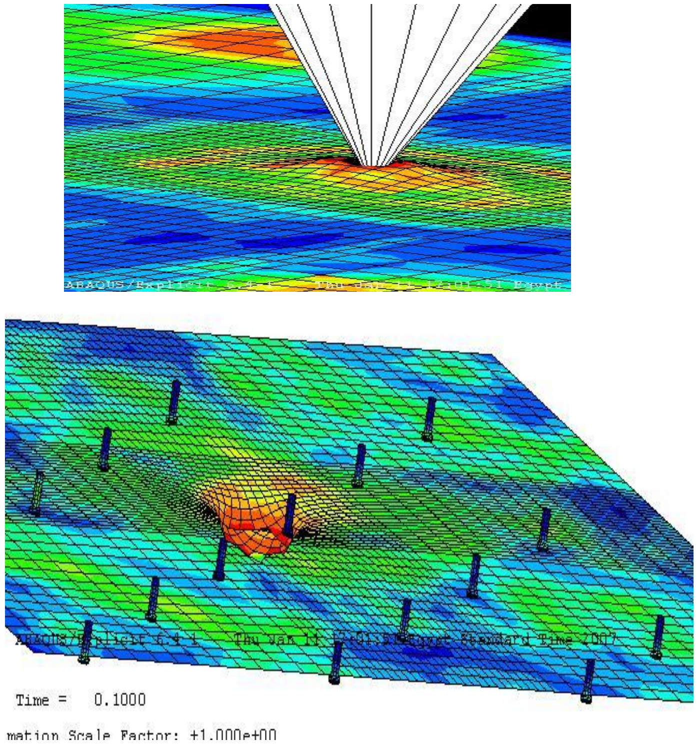

Fig.5 Inertial force effect and failure shape of upper plate (dynamic)

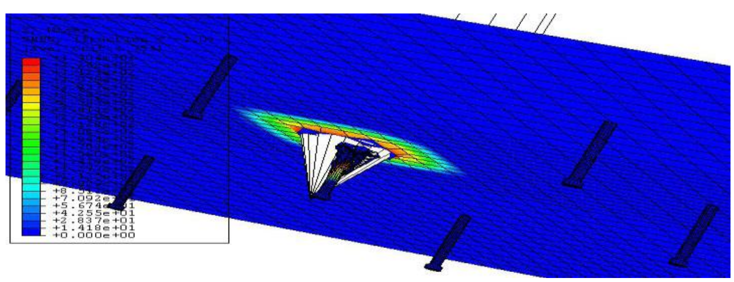

Fig.6 Failure shape of upper plate (quasi-static)

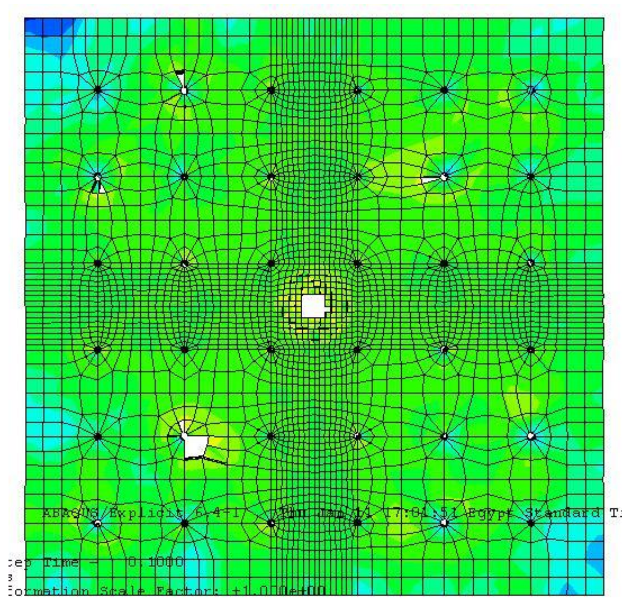

Fig.7 Localized failure of upper concrete face

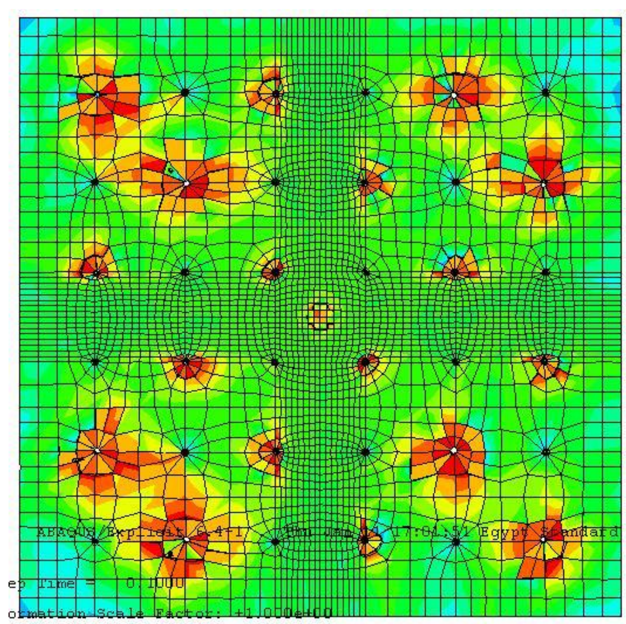

Fig.8 High stress contours in places of Lower studs in Concrete

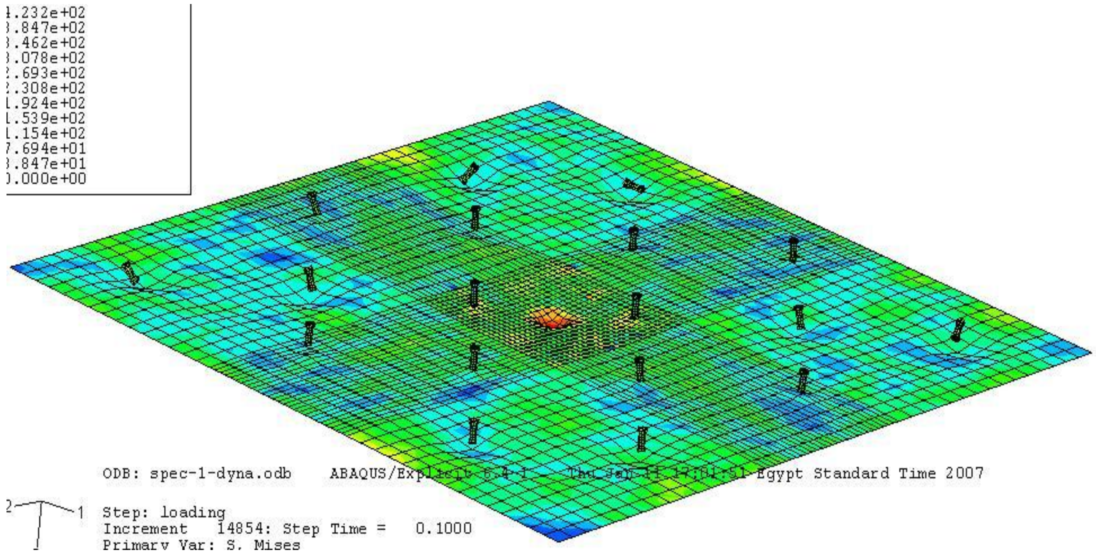

Fig.9 Failure of lower studs (dynamic)

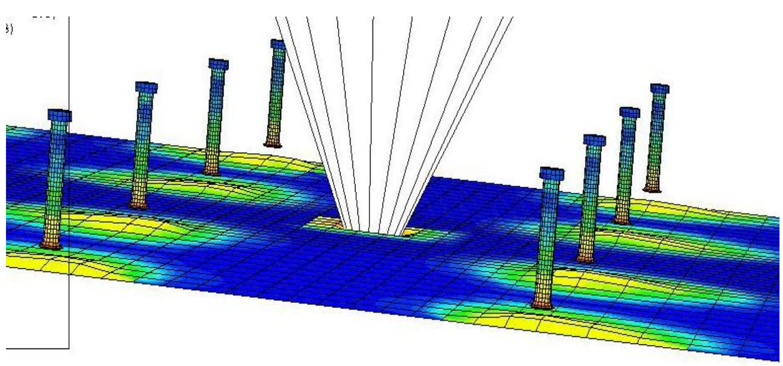

Fig.10 Failure of base element of lower stud (Quasi-static)

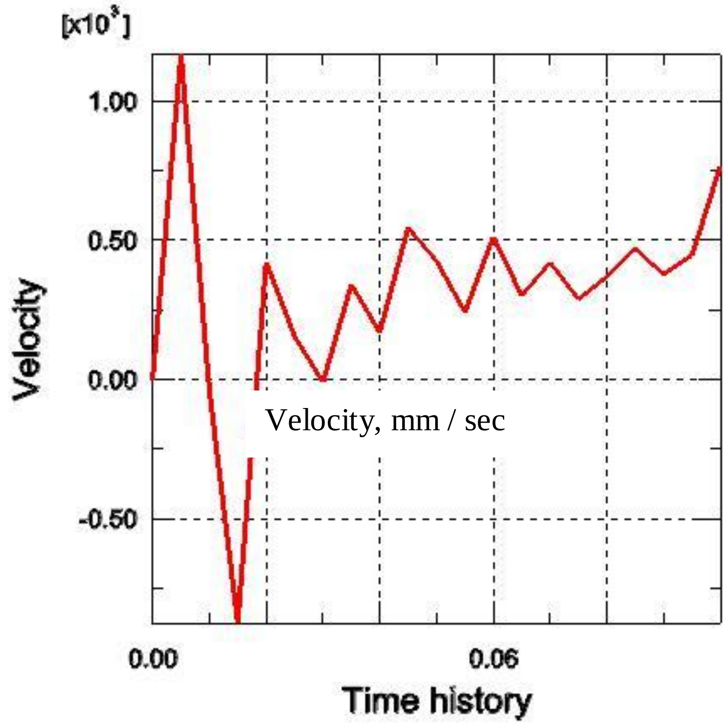

Fig.11 Velocity – Time history of middle point in lower plate

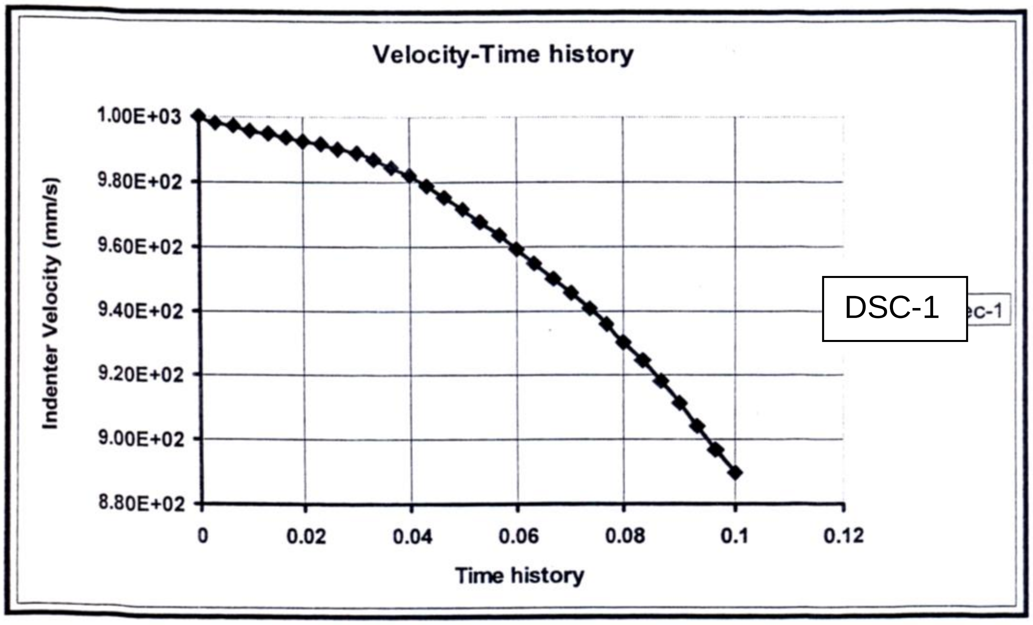

Fig.12 Velocity Time history of DSC- 1

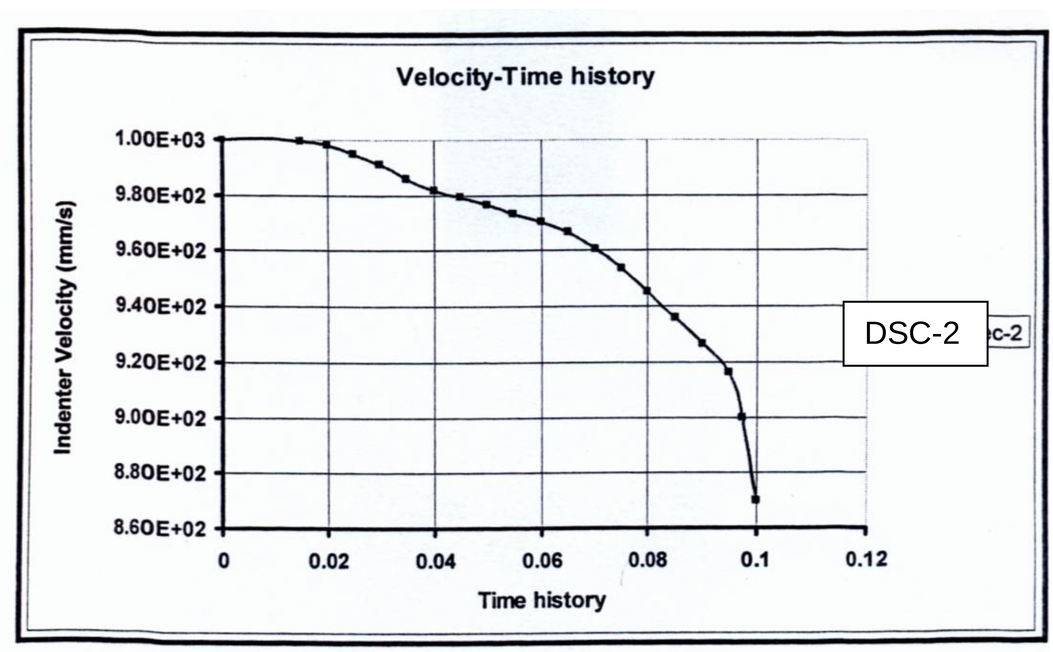

Fig.13 Velocity Time history of DSC- 2

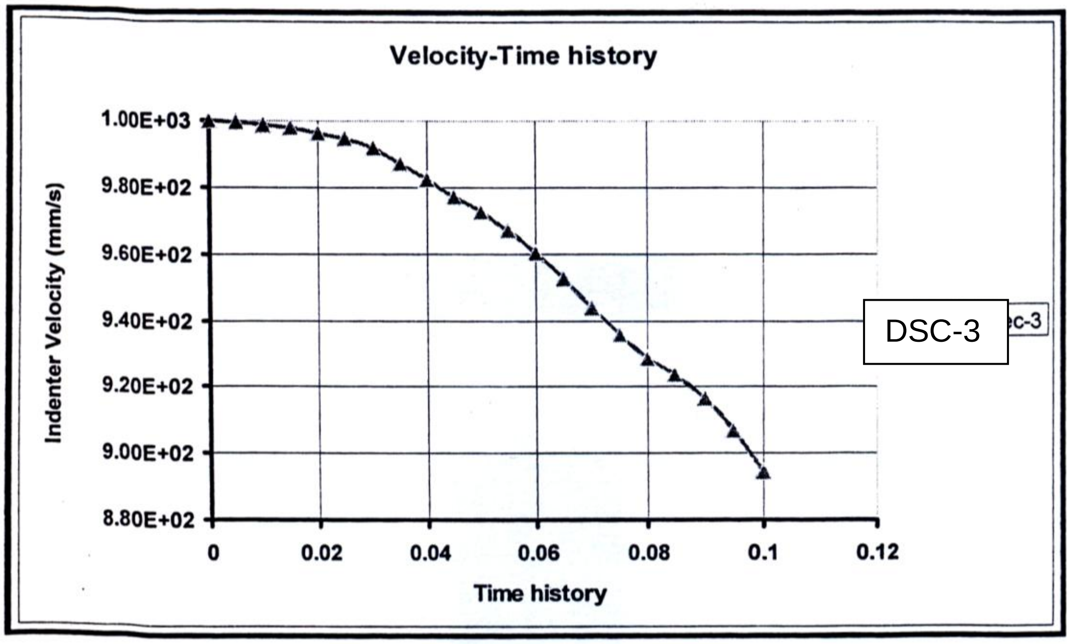

Fig.14 Velocity Time history of DSC- 3

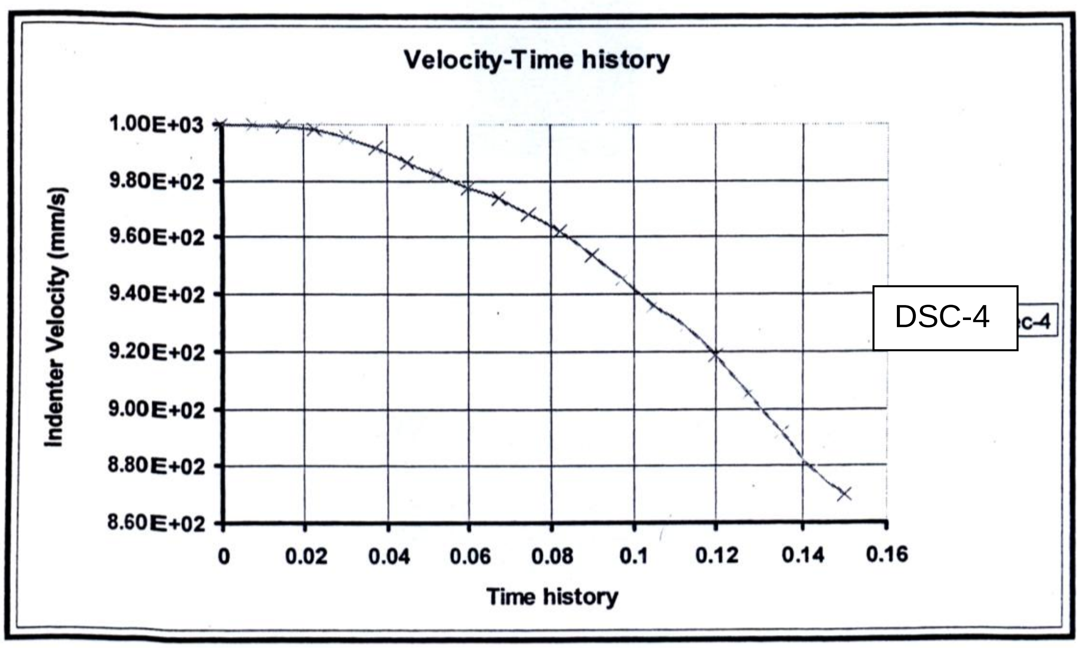

Fig.15 Velocity Time history of DSC- 4

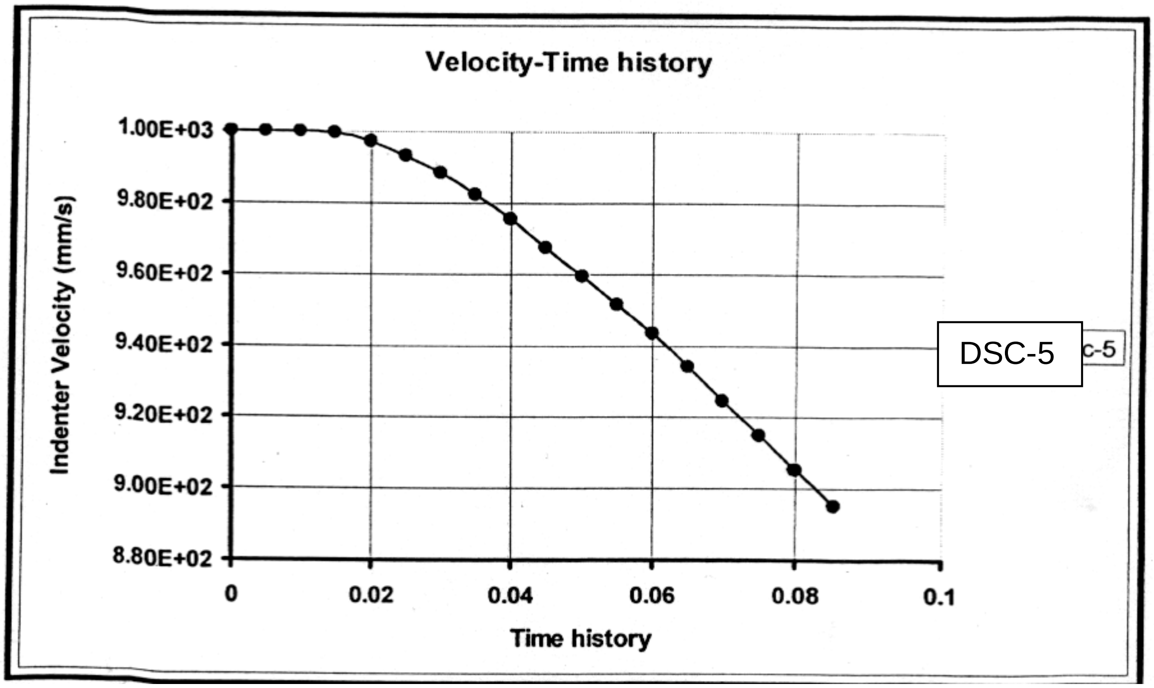

Fig.16 Velocity Time history of DSC- 5

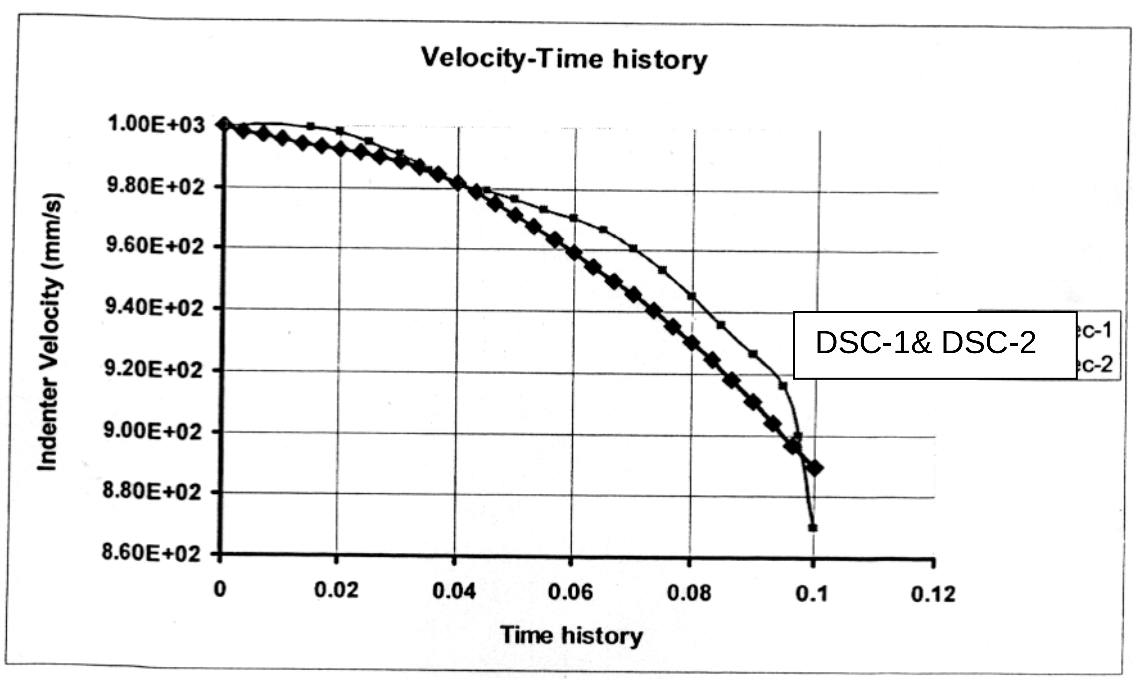

Fig.17 Effect of increasing upper plate thickness (Group A)

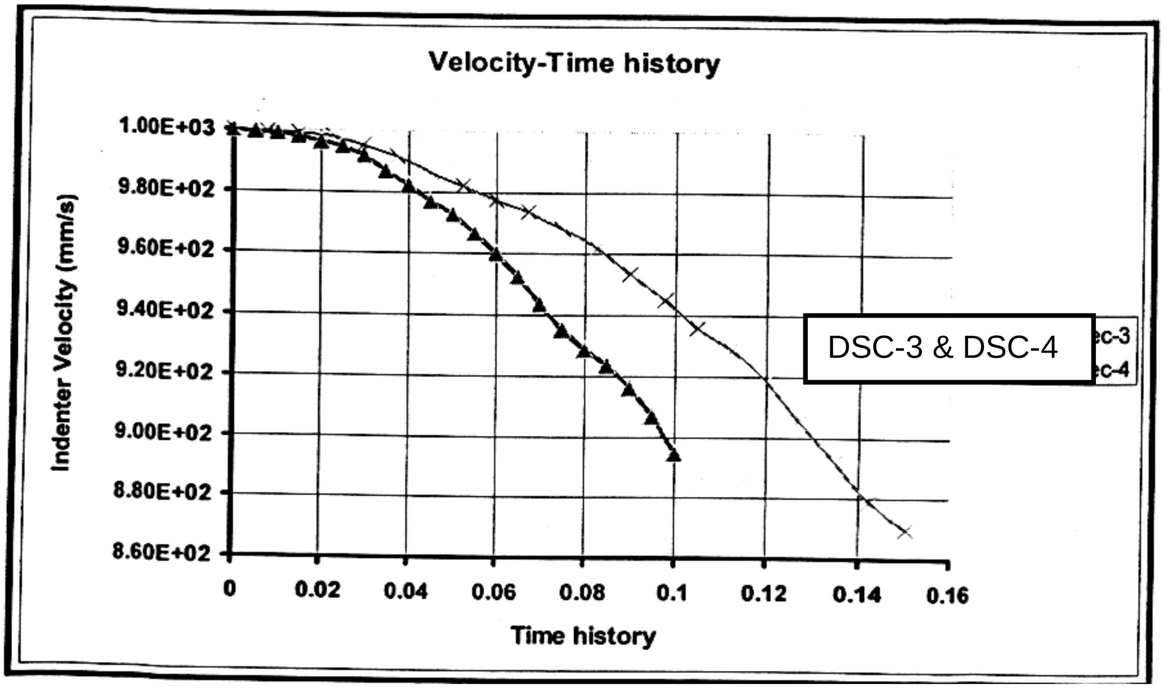

Fig.18 Effect of increasing number of studs in DSC-3 and DSC-4 (Group B)

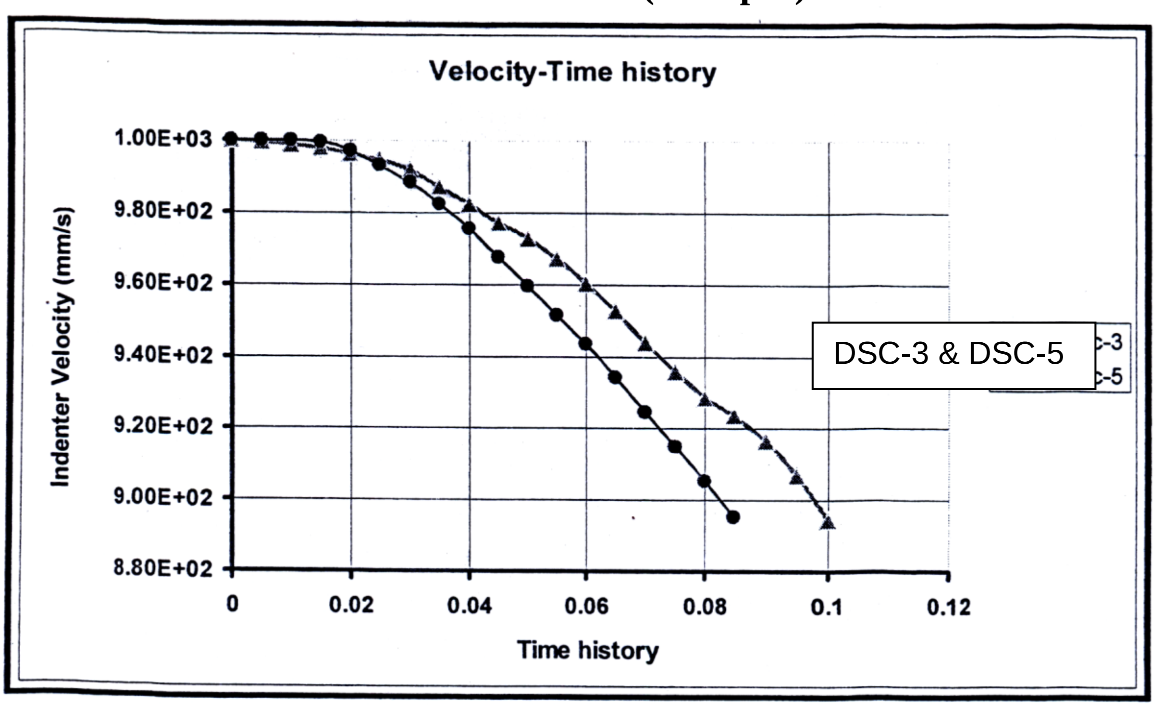

Fig.19 Effect of increasing number of studs in DSC-3 and DSC-5

with different stud distribution density (Group C)

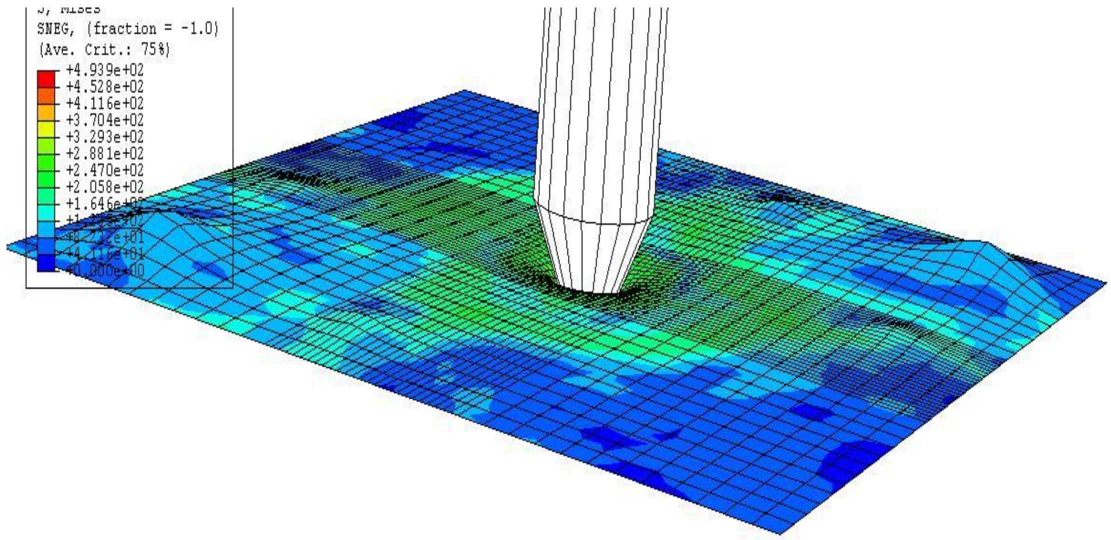

Fig.20 Buckling deformation of upper plate of DSC-5
Due to small number of studs

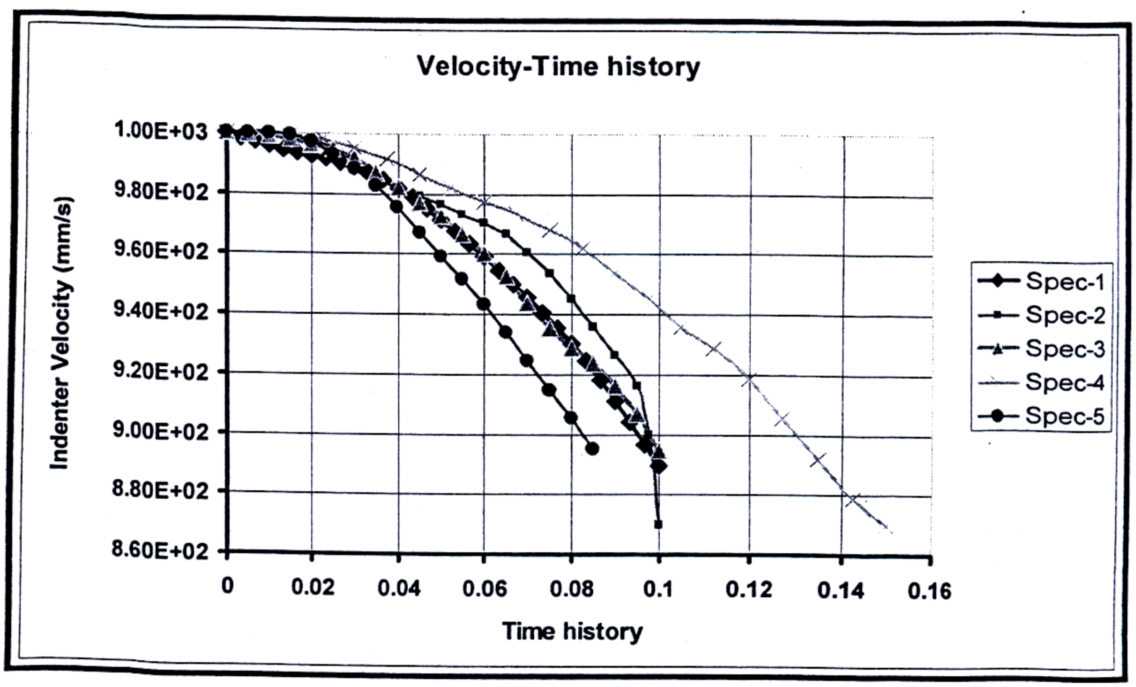

Fig.21 Comparison of results for all models (from DSC-1 to DSC- 5)

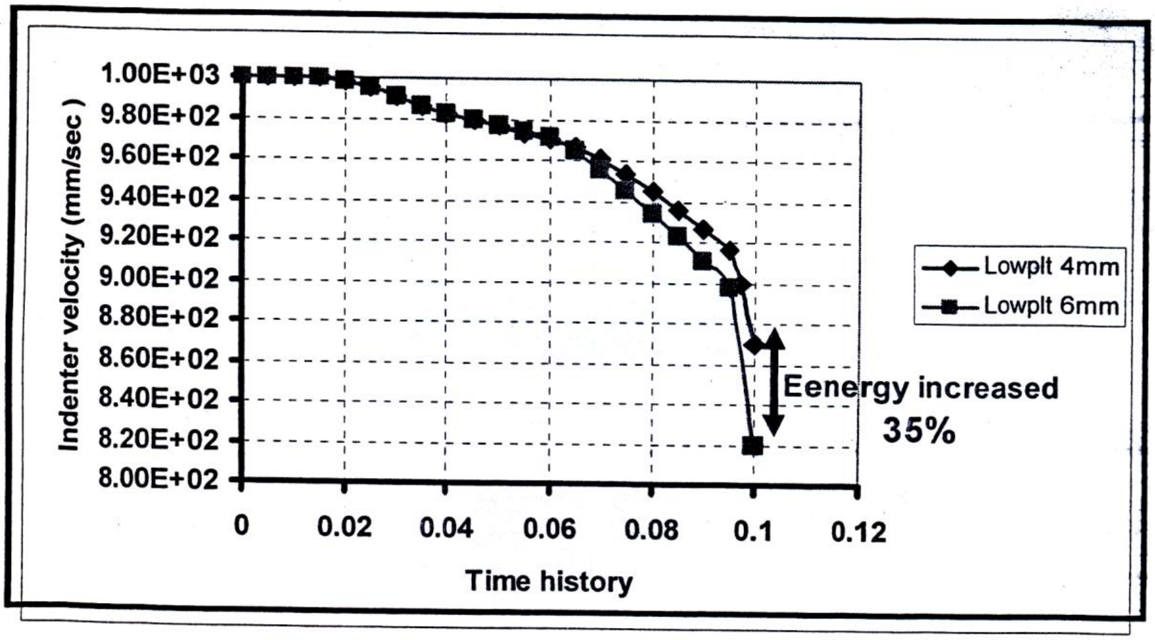

Fig.22 Effect of increasing upper plat thickness of DSC-1 from 4 to 6 mm

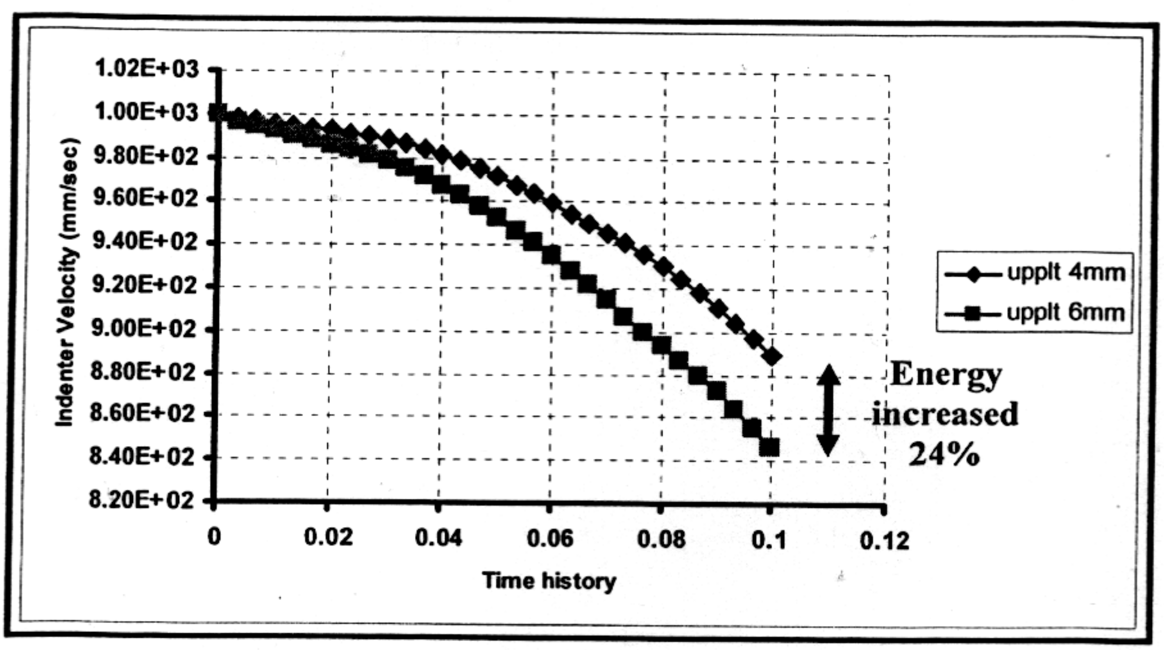

Fig.23 Effect of increasing lower plate thickness from 4 to 6 mm