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Simulation of the Reinforced Concrete Slabs under Impact Loading

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Abstract

Many older structures were designed for static loads but more recently there has been a growing awareness that some must be designed to resist both dynamic impact and static loads. An accidental impact load can be caused by mishaps in industry as well as accidents stemming from transportation or man-made disasters. There are number of ways of predicting how an impact load will affect a concrete slab, some of which may be impractical or expensive but because there have been significant developments in technology, numerical techniques rather than experimental approaches have become popular methods for developing detailed responses. Therefore, to numerically examine reinforced concrete slabs subjected to impact load in order to better understand their behaviour, may be considered a cost effective matter.

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1. Introduction:

Structural components can be subjected to a range of deliberate impact loads such as military activity or terrorist attacks. A large proportion of the surfaces of concrete structures are covered by reinforced concrete slabs. Slabs are often slender elements, which mean they are vulnerable to flexural, shear, or a combination of both modes of failure when subjected to impact loading. Numerical modelling of concrete slabs subjected to impact loads is an essential design concept that has not yet been fully developed. An impact analysis of concrete structures has thus far relied on conservative and traditional methods. Furthermore, current codes are unable to suggest clear and realistic approaches to designing concrete structures subjected to impulsive loading and therefore a proven method for analysing and predicting vibration in slabs is definitely required. To accurate modelling of flexural steel reinforcement as well as vertical and inclined shear reinforcement, is a significant task which will be studied in this paper because the interaction between the flexural and shear reinforcement is a difficult stage in any kind of finite element analysis. Assessment of the reliability of numerical non-linear analysis as a versatile tool for understanding how reinforced concrete slabs subjected to impact loading react will be addressed.

A number of different types of reinforced concrete slabs will be examined numerically, and the results will be validated by comparing them with experimental observations. The number of researches have undertaken numerical modelling of reinforced concrete slab subjected to impact load. Miyamoto *et al.* [1] used Drucker-Prager to model concrete when they researched the analytical and numerical failure modes of reinforced slabs subjected to impulse loads. Shirai *et al.* [2] used DYNA-3D to simulate a double-layered reinforced slab subjected to impact loading, and modelled non-linear behaviour that included initial crack, compressive yielding, and crack closing. Agardh and Laine [3] used the commercial finite-element package LS-DYNA to numerically determine the effectiveness of perforating reinforced concrete slabs with high-velocity fragments. Krauthammer and Oh [4] compared the capability of different finite element codes for simulation purposes. They numerically investigated steel and reinforced concrete beams subjected to impact loads and developed several models. Zineddin [5] studied the reaction of reinforced slabs subjected to impact loading both numerically and experimentally. He developed differently designed slabs under impact loads and validated the results experimentally. Teng *et al.* [6] numerically examined the same tendency to evaluate the usefulness of containment structures withstanding impact loads from normal and oblique projectiles. Leppanen [7] used AUTODYN to numerically and experimentally examine local and global damage which might occur from the impact of fragments on a thick concrete block. Huang *et al.* [8] used the LS-DYNA code to numerically simulate the perforation of concrete targets subjected to dynamic transient loading. Wang *et al.* [9] confirmed the same tendency after numerically analysing the penetration of concrete slabs with the commercial finite element code LS-DYNA, and by using the erosion algorithm to model concrete under a transient dynamic. Luccioni and Luege [10] handled theoretical comprehensive analysis to better understand the reaction of concrete pavements under blast loads. Tai and Tang [11] developed a numerical model of previous experimental results carried out by Hanchak *et al.* [12]. They utilised the Johnson-Holmquist model which is a brittle cracking failure model available in the LS-DYNA material library. Therefore, a controversial area in this discussion is numerically modelling the behaviour of concrete and a composite action in reinforced concrete structures.

While the majority of researchers carried out some numerical simulation, they have not modelled and compared concrete subject to impact loading.

2. Experimental preparation

Table 1 contains the dimensions of all the reinforced concrete slabs which were tested, and the data elements of their particular structure. These slabs were simply supported along both edges. The main variables of this study were the use of different types of shear reinforcement. Samples were manufactured at the laboratory of the school of civil engineering of the University of Wollongong. The dimensions of the two-way slabs are $1355 \times 1090 \times 90 \text{ mm}$. To design reinforced concrete slabs under impact loading, shear reinforcement should generally be taken into account. In this investigation the respective executive problems and opportunities to use the proposed shear reinforcement were considered. Indeed, there is no reliable practical code or guideline for designing reinforced concrete slabs that will be subjected to impact loading. There was vertical shear reinforcement with single stirrups between the top and bottom flexural reinforcement. Inclined or lacing shear reinforcement are one of the types of shear reinforcement tied to the top and bottom reinforcement.

Table 1 Specifications of the slabs

Series No	Shear reinforcement	Notation	Projectile velocities (m/s)
1	-----	SL1	3.2
2	-----	SL2	3.2
3	Vertical shear	SLV1	4.5
4	Vertical shear	SLV2	4.5
5	Lacing shear	SLL	4.5

3. Drop hammer at the University of Wollongong

The drop hammer which was used to apply an impact load to the slabs is illustrated in Figure 1. The hammer, including the impact plate and load cell, weighs about 635 kg and can be dropped from a maximum height of 5.5 metres.



Figure 1 Main structure of the drop hammer

3.1 Load cell

The load cell used to measure the reaction of the slab could also establish adequate sensitivity. It provided a frequency response that was greater than or equal to the frequency of the load applied. The Model 1200 Flange load cell manufactured by the Interface Company was used to determine the significant parameters of the slab and was able to measure the maximum applied load of approximately 1200 kN. Figure 2 illustrates the structure of the load cell used in this research. It was manufactured from heat treated high carbon steel.



Figure 2 Structure of load cell.

3.2 Measuring displacement

Displacement was measured by Micro-Epsilon model LD 1607 contact - less laser sensors situated underneath the centre of slab (Figure 3). The Opto-NCDT 1607/1627 sensors have a semi-conductor laser with a wavelength of 670 nm. This laser can also operate in a pulse mode which does not correspond to the frequency used for taking measurements.



Figure 3 Contact less laser sensor.

4. Numerical modelling process

On the basis of the principal objectives of this research, three dimensional finite element models of reinforced concrete slabs were developed, and the various items concerned with modelling were addressed as follows: Selection of element type, material properties, assemble the sections, to specify proper step analysis to undertake calculations, contact interaction, boundary and initial conditions, meshing process, to define job solution and post-processor investigations.

The numerical simulation of a reinforced concrete structure requires an accurate model of the structural elements and its constituent members acting as a composite made up of concrete and steel. A sketch of each section should be created separately with ABAQUS/Explicit which can then be extruded in any direction; this is why a 3D solid element in “modelling space” using a deformable type for beam and slab section was created. In order to develop concrete slabs, 8-nodes solid element with one-point integration were utilised initially.

When modelling flexural and shear steel reinforcement however, including lacing reinforcement, they were modelled by two-node beam elements connected to the nodes of adjacent solid elements. In this case a two node beam element with a six translational and six rotational degree of freedom was taken into account. Material properties can play an essential role when undertaking any kind of non-linear finite element analysis. A controversial discussion in this part of the study is related to modelling the post cracking behaviour of concrete. Therefore, different types of material behaviour have been addressed to enhance our understanding of visco-elastic, visco-plastic and post-cracking in reinforced concrete structures subjected to impact loading. Accordingly, when it comes to the meshing of the elements, in ABAQUS the capabilities of meshing in any model is classified into three main categories, the function for assigning mesh attribution, the function for mesh generation,

and the function for mesh verification. Furthermore, with connected surfaces such as impact hammer, an important aspect is generating mesh in the Master and Slave surfaces. Indeed, because there should never be more seeds in the Master surface than the slave surface (refer to Figure 4).

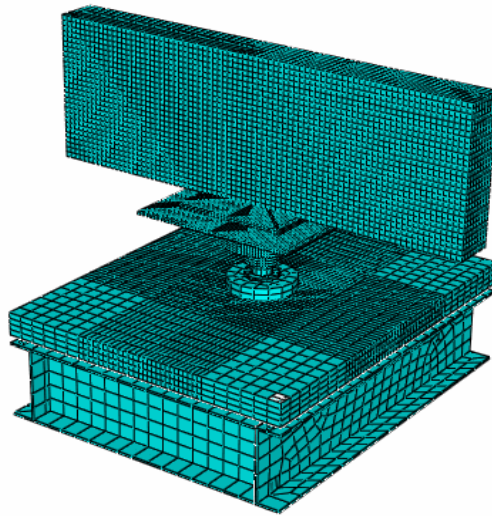


Figure 4 Meshing of master and slave surfaces.

4.1 Defining the material properties

Material properties can play an essential role when undertaking any kind of non-linear finite element analysis. A controversial discussion in this part of the study is related to modelling the post cracking behaviour of concrete. Therefore, different types of material behaviour have been addressed to enhance our understanding of visco-elastic, visco-plastic and post-cracking in reinforced concrete structures subjected to impact loading. Because access some individual data such as the triaxial test results for concrete, tensile test and uni-axial damage factors was lacking, the relevant data regarding the behaviour of normal concrete was extracted from ABAQUS/Explicit [13] users manual. However, in order to obtain realistic simulations, some individual experimental tests of concrete should be taken into account. Table 2 indicates details of the factors used in this analysis.

Table 2 Cap Plasticity model parameters

Material cohesion (Pa)	Material angle of friction (β)	Cap eccentricity parameter (R)	Initial cap yield surface position	Ratio of flow stress (k)
4705672	51^0	0.65	1.1×10^{-3}	1

The significant parameters in this kind of material property are β , R and k , where β is the angle of friction R is a parameter which controls the shape of the cap; and k is a parameter which is dependent on temperature. And in this kind of modelling the effectiveness of the strain rate from impact loads was considered. Furthermore, an elastic-plastic hardening behaviour by respecting to the strain rate was considered to model steel reinforcement.

5. Discussion about obtained results

Figures 5 and 6 show comparison between numerical and experimental results from impact load versus deflection in the centre of simple slab 1 (SL1) and simple slab 2 (SL2). Here the critical time or duration of impact to critical analysis was taken into account, and the results from dynamic loading, after subtracting and modifying extra values such as inertia forces and arbitrary pulses after impact, were illustrated. The maximum load from experimental observation is around 100 kN and the apex point in the graph of load versus time does not descend sharply, on the other hand, obtained results from simulation are higher than experimental calculation. It means that the supposed data for modelling of concrete have been considered conservatively. However, there is an acceptable agreement between numerical and experimental results. And it can be obtained that the slab may still be in the flexural mode after testing due to limited crushing of concrete on the top.

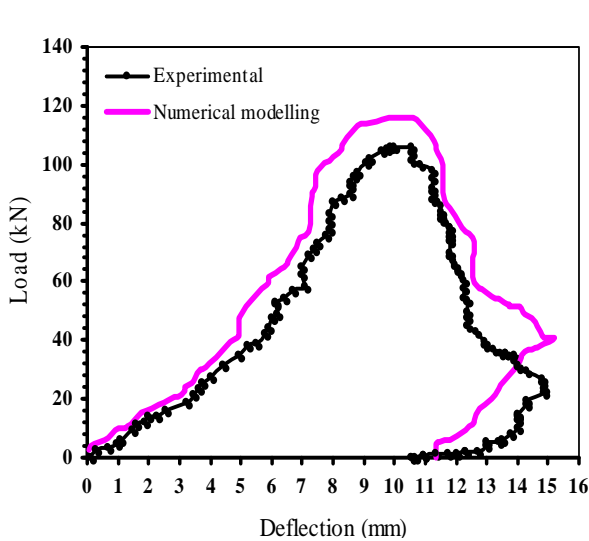


Figure 5 Load-deflection in SL1.

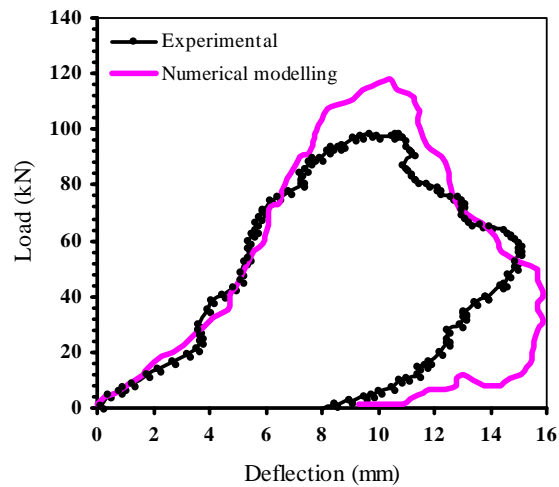


Figure 6 Load-deflection in SL2.

As an example, Figure 7 illustrates comparison about crushing on the top surface. There is a good estimation to predict numerically failure mode in reinforced concrete slab. As illustrated, there is a limited crushing on top slab, and there is a negligible cracking in tensile region.

Common point

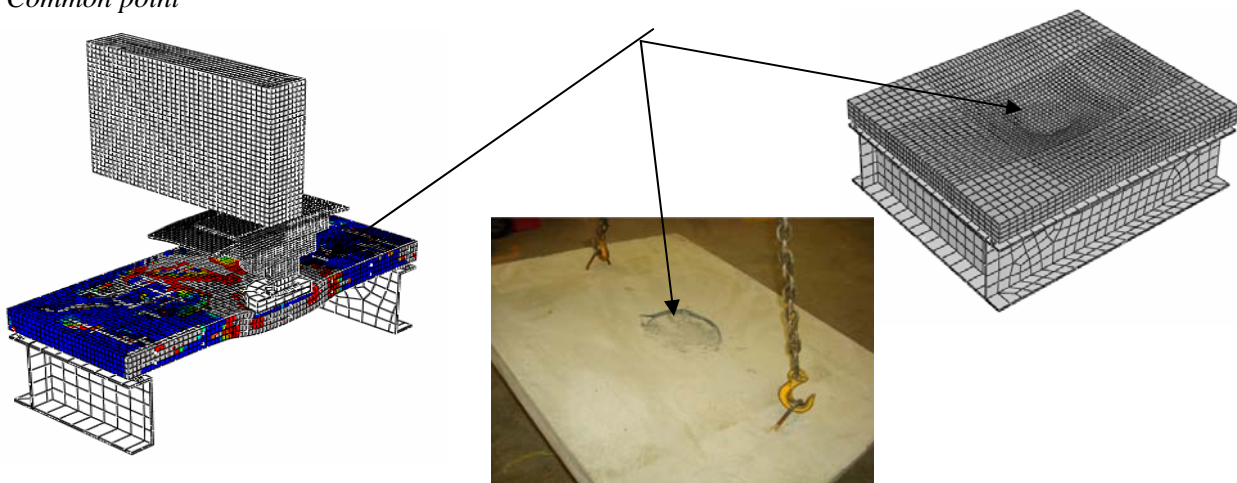


Figure 7 Simulation of crushing on top of SLL.

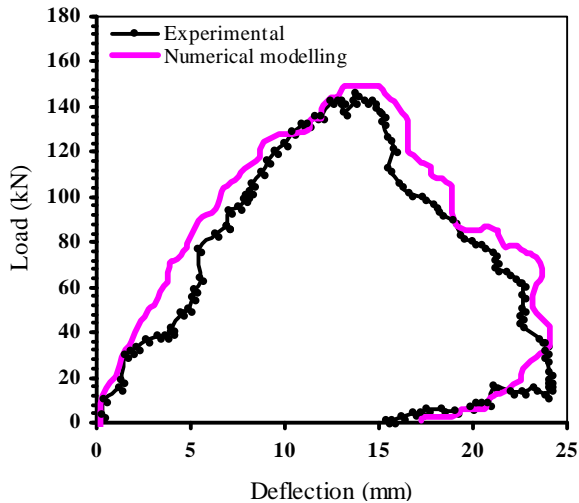


Figure 8 Load-deflection in Sv1

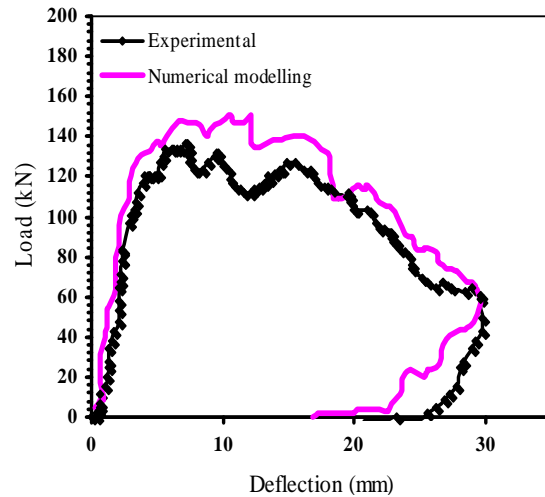


Figure 9 Load-deflection in SLL

Figures 8 and 9 illustrate load versus deflection in the centre of slab with inclined (SLL) and vertical (SV1) shear reinforcement. As presented, the maximum load is around 140 kN. By considering cracking concrete in the tensile region, full crushing in the compressive region as well as yielding of steel reinforcement, the bending to punching shear failure mode can be nominated as a failure mode in tested slabs. Figure 10 shows the feasibility of establishing a realistic inter-action between inclined reinforcement, flexural reinforcement, and concrete. Provided there is an appropriate contact between the shear and main reinforcement, obtaining a reasonable simulation is achievable when modelling all types of material. Besides, it can demonstrate failure process such as crushing, cracking in the tested slab and deformation of steel reinforcement.

Common point

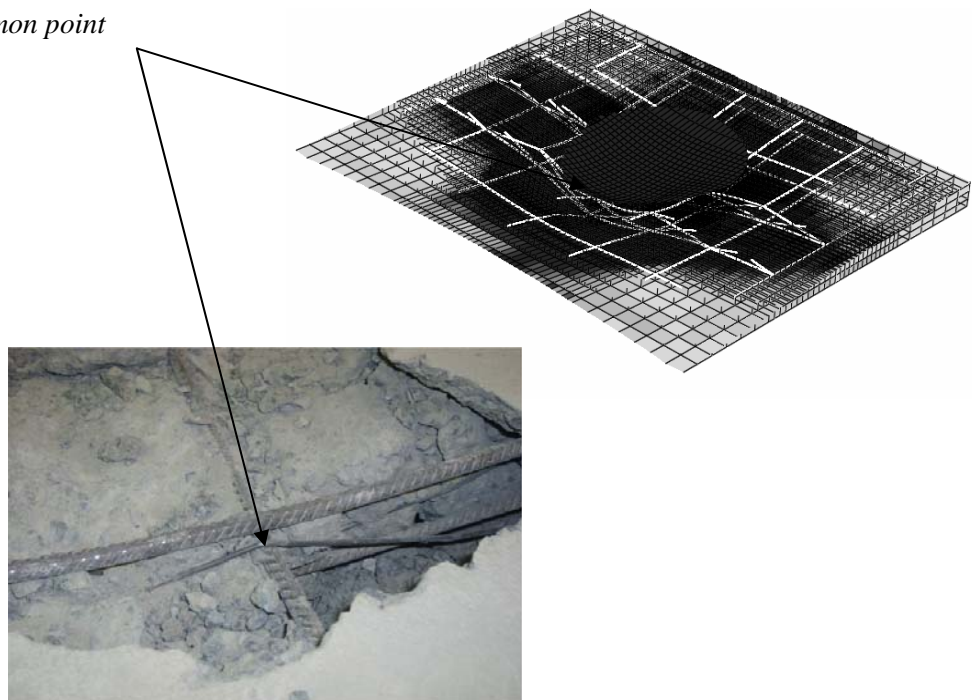


Figure 10 A comparison between the tested and modelled lacing shear reinforcement.

As illustrated by Figure 11, there is a good agreement between the simulation and experimental analysis to deformedly model of steel reinforcement and therefore this kind of calculation can be used to verify the numerical calculation.

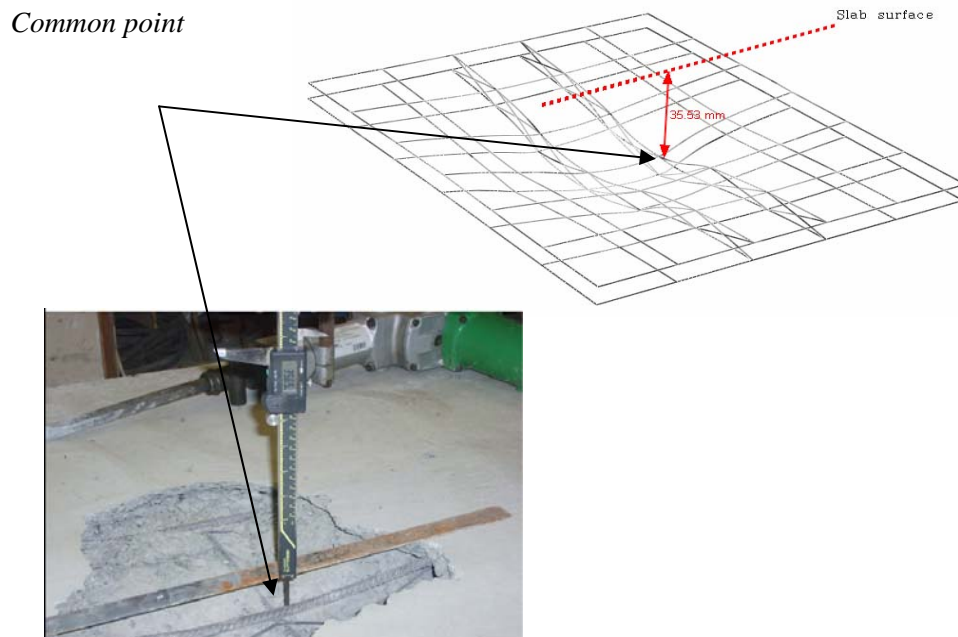


Figure 11 Verification of measured deflection in shear lacing slab.

6. Numerically evaluating the distribution of cracking

Besides, to simulate crack distribution in concrete structures is a big achievement because one of the major limitations is determining the correct trajectory propagation on the surface. In this part of the study, Brittle Cracking in the material is modelled individually to predict the propagation of cracking in the tensile region of reinforced concrete structures. Cracks generally occur first, followed by initial yielding (plasticity) of concrete under compression, and finally the reinforcement yields. In order to find an acceptable estimation of direction and shape of distribution, different kinds of mesh densities were examined. Clearly, selecting a sufficiently fine mesh is very important to adequately define the deformation and stresses in impact loading.

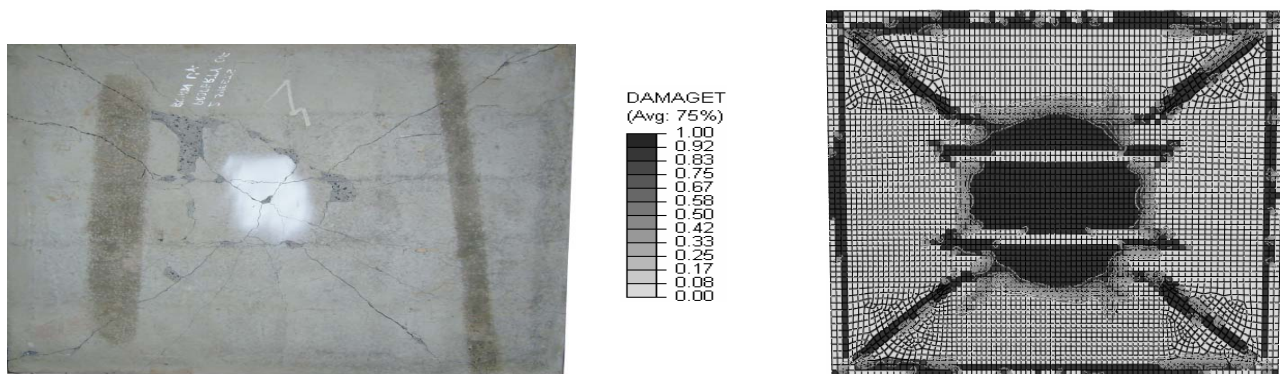


Figure 12 Cracking pattern in numerical and experimental observation.

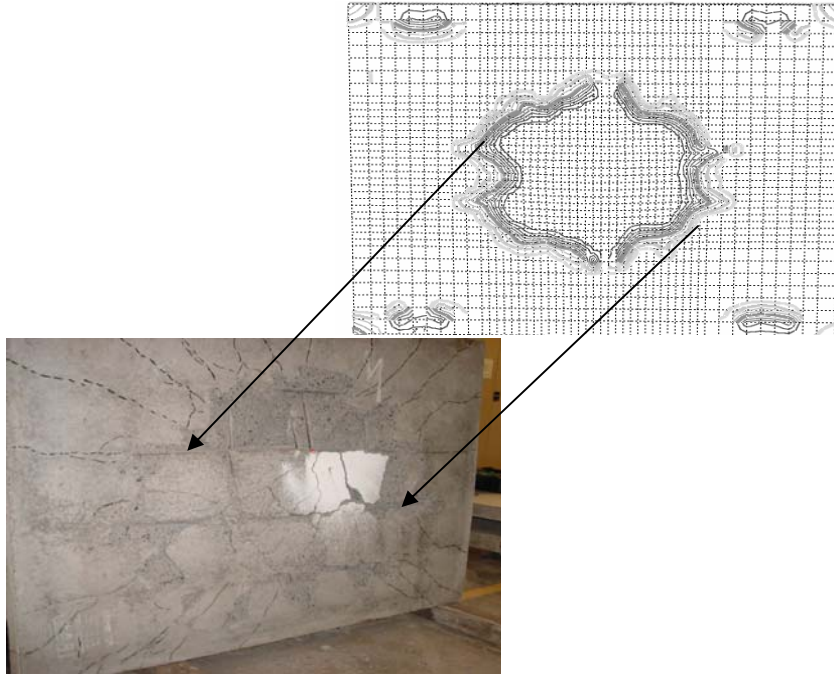


Figure 13 Cracking pattern in numerical and experimental observation.

As stated earlier, by increasing the number of elements and considering the possible direction of cracking, it is then possible to predict and determine the critical region in the tensile zone and the density of cracking. Basically, most cracks radiate out from the middle of the slab towards the outer edges and local failure also occurs near the mid-span (refer to Figure 12). This can be described by respecting to the decreasing local stiffness on surface of concrete in the tensile region. Figure 13 also shows the same comparison between a simulated slab with shear reinforcement and the experimental observation. As a result, by using the appropriate mesh generation and possible trajectory of cracking, an ideal estimation of the distribution of cracking is obtainable.

7. Classification of the obtained results

Finite element analysis is capable of making reasonable estimations available in order to determine the possible failure modes of reinforced concrete slabs subjected to impact loads. Numerical simulation can be used to construct the physical interaction between steel and concrete (bond action) as well as create an interaction between flexural and shear reinforcement. Modelling composite material such as a reinforced concrete slab is possible provided that the appropriate conditions for creating the interaction between steel and concrete is fulfilled. The quantity of mesh density and direction of the sub-division on the surface of a concrete slab, where it may follow the trajectory of cracking, can play an important role in simulating finite element analysis.

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