Perforation of Composite Floors

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ABSTRACT

Rapid construction methods for multi storey buildings involve maximising the tasks that can be carried out simultaneously on site. The risks of construction workers, fitting out lower floors, being hit by large objects dropped during installation can be managed by understanding the protection provided by the intermediate floors. This paper describes a Finite Element based methodology for assessing the impact event using LS-Dyna. The aim of the method is to evaluate low velocity impacts of heavy objects dropped onto concrete floors in order to establish the potential for perforation. The methodology is validated by comparing the simulation results with empirical penetration formulae available for concrete structures and with some experimental results. It is concluded that the perforation limits can be predicted with good confidence, but that further experimental research in the low velocity range is desirable.

Keywords:
Impact, dropped objects, Winfrith concrete, perforation limits, NDRC formula

INTRODUCTION

This paper describes the use of LS-Dyna for assessing perforation limits of steel sections impacting reinforced concrete slabs. The aim was to develop a Finite Element (FE) based method for assessing the risk of perforation of floor slabs in multi-storey buildings by dropped objects during construction. The principal application was to assess the risk of injury to construction workers fitting out lower floors in the event of steel sections being dropped during crane operations while constructing the floors above. This paper describes the analysis approach used in simulating the impact event and the experimental data and empirical formulae used for validation.

BACKGROUND

During construction of large, multi-storey developments the risks of objects dropped during crane operations needs to be considered. Efficient construction programmes often depend on work being carried out at lower levels while objects (such as heavy building components) are craned to the upper floor. The risks to workers fitting out the lower levels being struck can be managed by ensuring that any falling objects from cranes will be arrested by the floors slab(s) in between. In traditional multi-storey steel frame construction, “rules of thumb” are often employed when determining programmes for work at lower levels. Typically, contractors allow for one clear storey between crane operations and workers completing the lower floors. However, accurate guidance as to the consequences of an accidental drop is not available.

Significant experimental work on projectiles penetrating reinforced concrete has been carried out by the nuclear and defence industries, but for a limited range of objects, and typically for velocities higher than those expected in a construction context. A reliable numerical approach would enable a wider range of objects and drop heights/impact velocities to be assessed and the risks associated with drops could be managed accordingly.

OBJECTIVES OF THE STUDY

The aim has been to develop a FE based analysis method for simulating objects dropped onto reinforced concrete slabs. This would enable the damage associated with various impact velocities to be assessed. In particular, the velocity resulting in perforation (i.e. complete penetration of the slab) is of interest as the damage associated with lower velocities is unlikely to be critical. Scabbing (i.e. incomplete penetration resulting in ejection of material from the underside of the slab) is not considered critical in slabs formed on permanent formwork as the steel decking will prevent scabs from falling.

In order to validate the FE based method, experimental results and empirical formulae have been utilised. These originate from the nuclear and defence industries as little or no research has been carried out within the construction industry on impacts between typical floor slabs and steel sections. Empirical formulae[1][2][4] have been developed from experimental testing programmes. The formulae predict the penetration depth and define limiting velocities for perforation. Some experimental scale testing has recently been carried out by Heriot-Watt University. This data has also been employed in validating the method.

Following validation for well understood impact scenarios, the study was expanded to consider situations applicable to construction sites. This included impacts on reinforced composite floor with profiled steel decking (as used in

EXPERIMENTAL DATA FOR VALIDATION

Two approaches have been used to validate the results. Firstly, empirical formulae based on testing and secondly tests carried out by Heriot-Watt University.

Empirical formulae:

The main part of experimental research has been carried out on solid steel projectiles impacting flat reinforced concrete and steel slabs. This impact scenario was therefore selected for validation of the FE models. The most commonly applied formula for assessing perforation limits of reinforced concrete slabs is the modified NDRC formula[1]. The formula, originally proposed in 1946, is based on a significant amount of experimental data for smaller objects impacting at velocities above 150m/s – the term "modified" indicates its development from the NDRC formula that is applicable to steel plate. The formula has since been extended for larger objects and slower impacts[4] to give the following expression for perforation thickness, t_p:

$$x = \sqrt{4KNWd\left(\frac{V}{100d}\right)^{1.8}} \quad for\ \frac{x}{d} \leq 2.0$$

$$x = \left[KNW\left(\frac{V}{100d}\right)^{1.8}\right] + d \quad for\ \frac{x}{d} > 2.0$$

$$\frac{t_p}{d} = 3.19\left(\frac{x}{d}\right) - 0.718\left(\frac{x}{d}\right)^2 \quad for\ \frac{x}{d} \leq 1.35$$

where x is the is the penetration depth [in], d the missile diameter [in], V the impact velocity [ft/s], K a measure related to the concrete strength, N a coefficient for the missile shape (flat, blunt, sharp etc.) and W the missile mass [lb]. The calculation derives the perforation thickness from the penetration depth equations. While the concrete strength is considered, there is no variable related to the reinforcement content. The test data is based on lightly reinforced sections (0.3-1.5% each way) so the formulae are most applicable to concrete sections with reinforcement content in that range.

More recently, the CEA-EDF data has been used to define a formula for perforation, presented by Berriaud et al.[2] This is based on impact velocities between 27 and 300m/s and has been found to give better correlation with experimental data in the slower impact range[3]. The formula for perforation is given as:

$$t_p = 0.765(f'_c)^{-3/8}\left(\frac{W}{d}\right)^{1/2} V^{3/4}$$

where f'_c is the concrete cylinder ultimate compressive strength. Again, all units are imperial and the formula assumes lightly reinforce concrete.

For validation purposes, limits of perforation of a 200mm thick reinforced concrete slab by a flat-faced 150mm diameter solid cylindrical steel projectile have been predicted with these two formulae and used here for comparison with the FE data.

Sliter[3] summarises experimental work carried out on steel pipe projectiles impacting reinforced concrete slabs. The perforation formulae based on this research can be used as a more direct comparison with the perforation limits of steel sections predicted by the FE analyses. For pipe sections, an alternative application of the modified NDRC formulae has been found to give the best correlation with experimental results[3]. This considers both the cross sectional area and outer diameter of the missile. Perforation limits based on this formula, referred to as the NDRC pipe formula, have been used for validation of the FE analyses of the steel section impacts.

Impact testing programme at Heriot-Watt University

Experimental impacts tests for concrete slabs have recently been carried out by May and Chen at Heriot-Watt University[6]. The tests included impacts between steel sections and lightly reinforced concrete slabs at low impact velocities, providing data applicable to the construction context. For validation purposes, three impact scenarios were studied. In all cases the impactor and target remained the same: a 200kg 102x64mm steel I beam impacting a 78mm thick flat slab. Impact velocities varied between 3.8 and 7m/s.

FINITE ELEMENT ANALYSES

The FE modelling was carried out using dynamic, non-linear, explicit analysis in LS-Dyna[5]. The approach employed non-linear material properties for both the steel and concrete and allowed large deformations and failure. The reinforced concrete was modelled using the MAT_WINFRITH_CONCRETE model with MAT_ADD_EROSION and MAT_WINFRITH_CONCRETE_REINFORCEMENT, allowing failure and representing the reinforcement implicitly. The steel components (impactors and decking) were modelled using MAT_PLASTIC_KINEMATIC with a plastic limit defined. The concrete and solid impactors were modelled using 8 noded solid elements and the steel sections and decking using 4 noded shells. A typical mesh used in the analyses can be seen Figure 1.

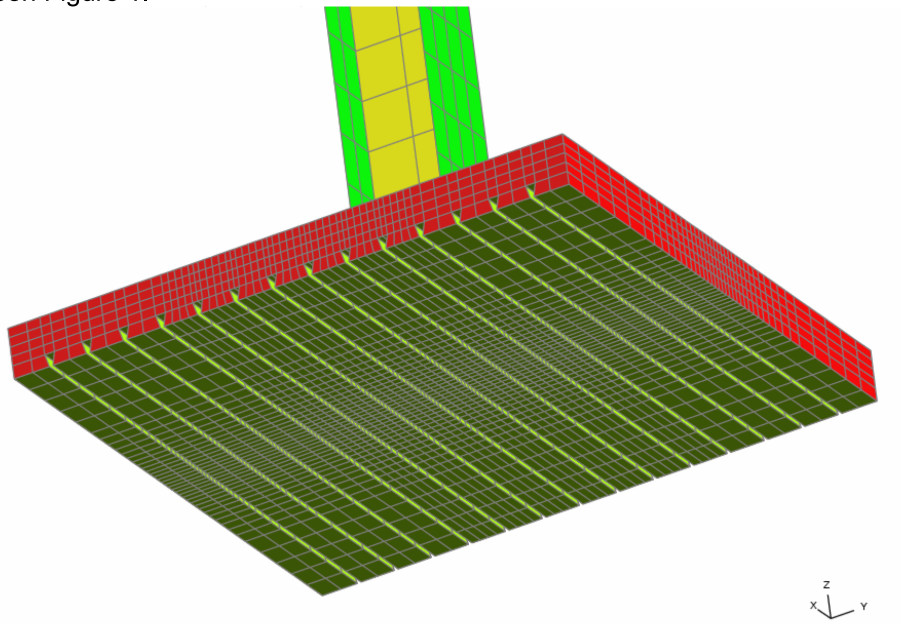

Figure 1 *Finite Element mesh of steel section impacts on concrete with profiled steel decking*

For validation purposes, FE simulations of impacts between the solid cylindrical steel impactors and a 200mm thick reinforced concrete slab (as studied with the empirical formulae) were carried out. A range of impact velocities were considered to determine limiting velocities for perforation of the slab by each object. Objects arrested by the slab would typically cause some damage and partial penetration as shown in Figure 2 while at higher velocities complete penetration would occur as shown in Figure 3.

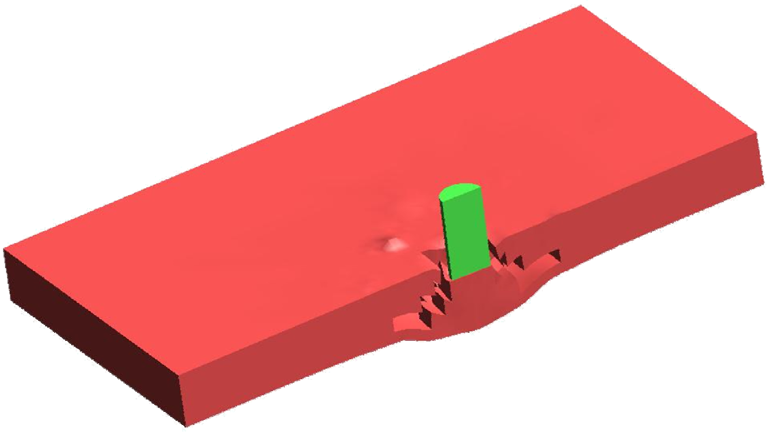

Figure 2 *Solid projectile arrested by slab (500kg object at 12.5m/s into 200mm RC slab without steel decking)*

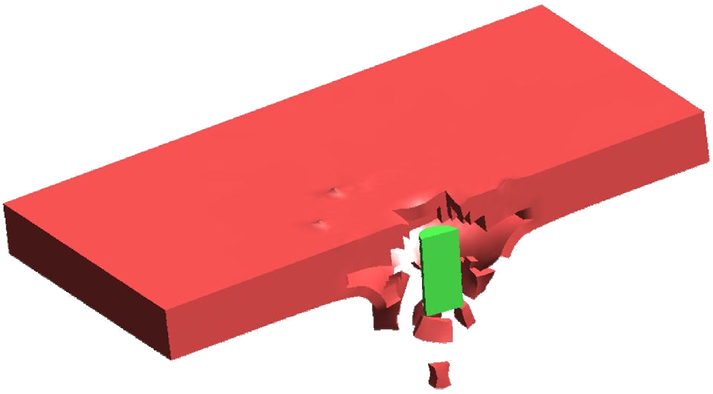

Figure 3 *Solid projectile perforating slab (500kg object at 14.0m/s into 200mm RC slab without steel decking)*

The FE models were then altered to consider typical steel sections rather than solid cylindrical objects. Perforation limits for UC 356x406x340 sections of varying mass impacting the same 200mm flat slab were determined.

As profiled steel decking is commonly used in composite floor construction, the benefit of the decking acting as a "net" for the falling objects has been studied. Perforation limits for the same steel sections impacting a 200mm slab formed on 1.2mm gauge re-entrant steel decking have also been determined. Examples of arrested and perforating impacts between the UC section and the composite slab with decking are shown in Figures 4 and 5 (showing impacts at 22 and 25m/s, respectively).

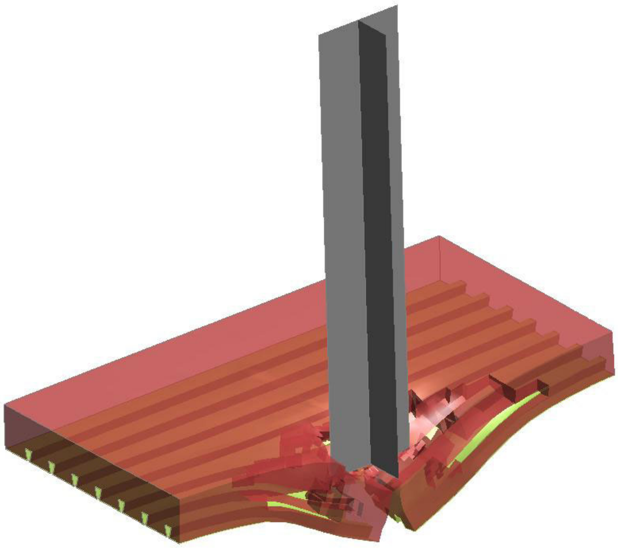

Figure 4 *Steel section arrested by slab and decking*

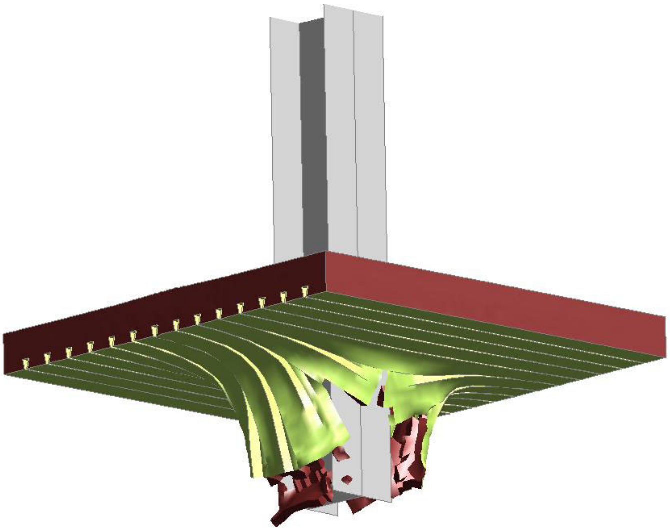

Figure 5 *Steel section perforating slab and decking*

RESULTS

Curves of the perforation limits predicted by the NDRC and the CEA-EDF empirical formulae are shown for light, fast moving object in Figure 6 and for heavier, slower moving objects in Figure 7. Included in the same figures are the plot points of perforation and non-perforation predicted by FE analyses. For slower impacts, the two empirical curves and the FE results all agree well. For higher velocities, the CEA-EDF and the NDRC results deviate somewhat, while the FE results fall in between the curves, nearer the CEA-EDF results (which are considered more accurate by Sliter[3]).

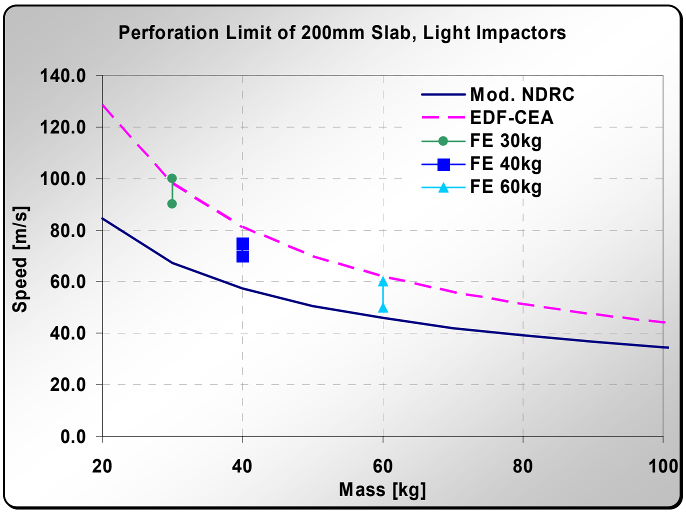

Figure 6 *FE-Empirical correlation: Perforation limits of light cylindrical impactor*

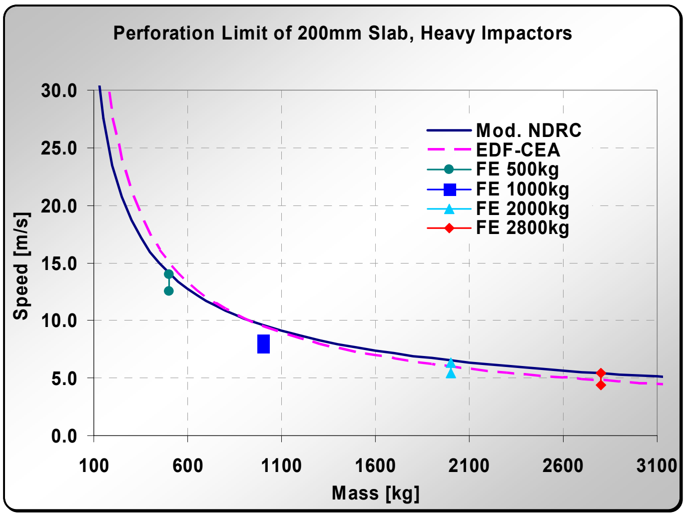

Figure 7 *FE-Empirical correlation: Perforation limits of heavier cylindrical impactor*

The open cross sections on the UC section studied mobilised a larger area of the slab during impacts. For the same mass, it is clear that a geometrically larger object requires a larger velocity to perforate the slab. Figure 8 shows the perforation limits for the section impacting a flat slab based on both FE analyses and the modified NDRC formula adapted for pipe missiles. This is considered the most accurate formula for pipe missiles[3]. Good correlation is found between the empirical curve and the FE results. When comparing these results with those in Figure 7 the increase in velocity required for perforation is clear.

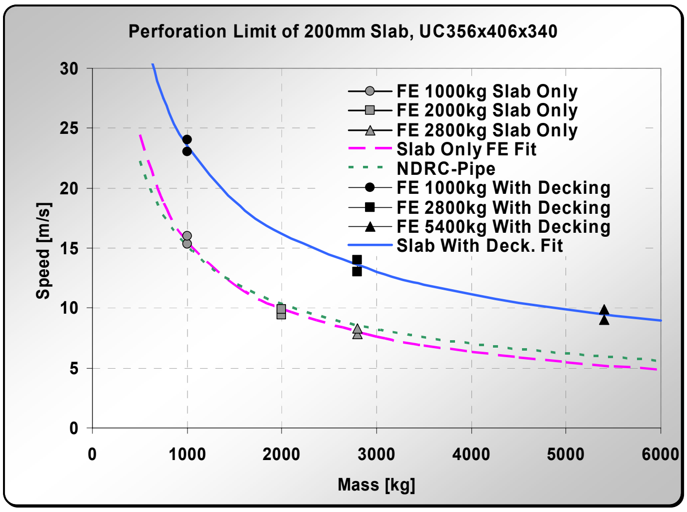

Figure 8 *FE and empirical prediction of perforation limits for UC section*

The results for the concrete and steel decking composite slab showed enhanced ability to absorb impacts. The perforation limits for the UC sections impacting the flat and composite slabs are shown in Figure 8. For this scenario, only FE results are available, as no experimental impact tests have been carried out on the effect of the decking.

The empirical formulae do not consider gravity, so the results presented in terms of velocity are analogous to a horizontal impact. For the relatively slow impacts by heavy objects of relevance to construction sites, the gravitational forces may be significant. The FE analyses have therefore also been carried out with gravity included. The perforation limits for the UC section with gravity are presented in terms of drop height in Figure 9. This gives a theoretical estimate of the drop height from which the objects would be on the threshold of perforating the slab and continue to lower levels.

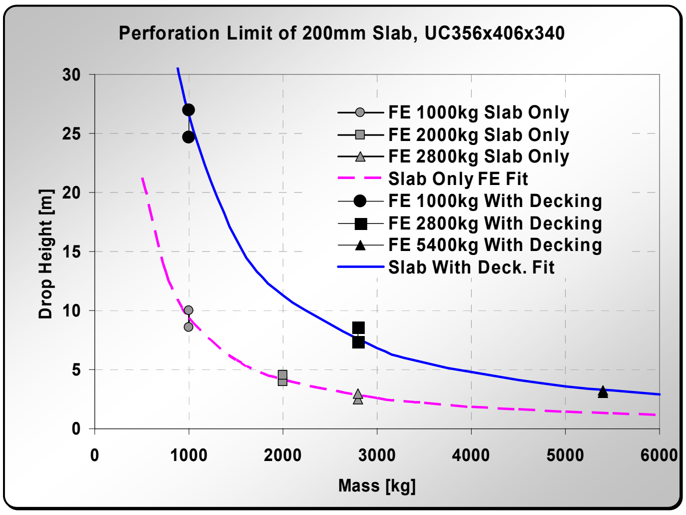

Figure 9 *Limiting drop heights for UC section perforating slab*

The experimental tests at Heriot-Watt resulted in perforation for impact velocities of 7.0 and 5.4m/s but not for 3.8m/s. Examples of the failure modes when perforating can be seen in Figure 10 while the arrested impact is shown in Figure 11. The perforation/non-perforation results for the three impacts were reflected by the FE analyses as shown in Table 1.

Impact velocity	3.8m/s	5.4m/s	7.0m/s
Experimental	Arrested	Perforated	Perforated
Finite Element	Arrested	Perforated	Perforated

Table 1 *Validation of perforation against Heriot-Watt test results*

Figure 10 *7.0m/s drop resulting in perforation*

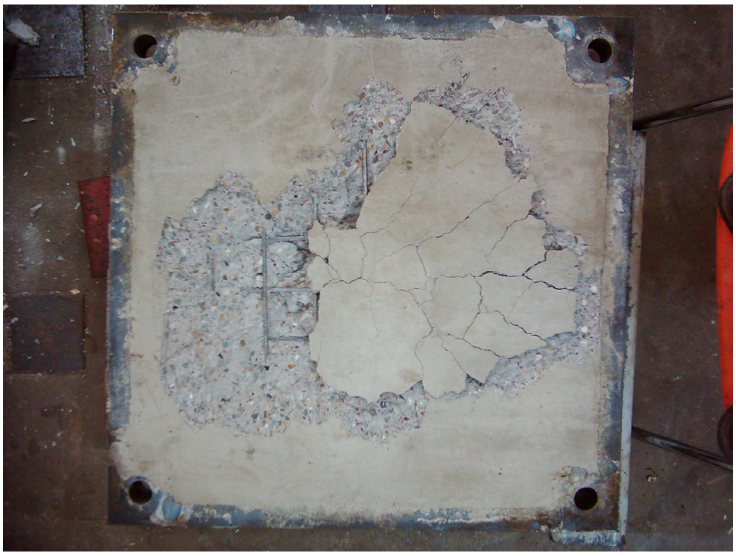

Figure 11 *3.8m/s drop penetrating but not perforating*

CONCLUSIONS AND RECOMMENDATIONS

Excellent perforation limit agreement was found between the empirical and FE results for the full range of masses and velocities studied in the validation process. This applied to both the solid and UC section impactors. Similarly good correlation was obtained for the specific impact scenario recently studied at Heriot-Watt University. The direct comparisons between experimental and simulation data has gone a considerable distance towards validating the analysis method.

The FE analysis tool has also been extended to consider the resistance offered by the profiled steel decking typically used in composite floor construction. This enables analytical assessment of potential construction site impact scenarios and can be used to determine limiting lift heights for perforation. However, little experimental data exists for the most applicable range of objects and velocities and further experimental research is recommended to fully validate the approach.

At this stage it looks likely that an approach using FE analyses with LS-Dyna can be used to predict perforation limits for specific lifts or slab types. This will have benefits over the “rules of thumb” or empirical methods currently available.

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