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Effects of impulsive loading and deformation damage on reinforced concrete slabs during building construction

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ABSTRACT

The effects of impulsive loading and deformation damage in reinforced concrete slabs were observed for analyzing the under-construction buildings for specific period of time. To fully harvest the structural capacity of building under constrcution with reinforced slabs sections exposed to combined actions, it is necessary to leave behind the simplicity of treating the verification of structural adequacy for normal stresses separately from that of shear stresses and instead fully exploit the advantages of choosing more efficient stress distributions. By exploring the vast possibilities of other statically admissible systems using optimization routines for deformation damage reduced to 20% from 80% in the work, the longitudinal reinforcement near the neutral axis in reinforced concrete can be utilized much more efficiently. In addition, by adhering to the interdependency constraints between normal and shear stresses in reinforced concrete a much more precise picture of the actual service stress state can be determined for impulsive loading and deformation damage where the maximum deformation and impulsive loading on RC-slab were observed at strain $91s \leq t \leq 97s$ on RC-slab in the total simulation steps from 0s to 398s. There is therefore a need for a one- step, automated design tool capable of addressing such verifications holistically which was performed in the simulation of this study using Matlab R2019b. In this paper the theoretical basis and a free to use open-source design tool is presented, allowing for easy access to highly optimized designs capable of observing the impulsive loading and deformation damage on reinforced concrete materials to their limits

Keywords: *Reinforced concrete; deformation; construction; damage; load; strain: stress.*

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1. Introduction

Normally conventional buildings are incapable to resist out-of-plane loads and such events have brought the topic of strengthening important buildings against the impulsive load to the forefront. Whilst many techniques have been introduced to achieve the above demand, the cost and the feasibility of any implementation method should also be considered [1]. Increasing the stand-off distance by using fences or barrels, enlarging the mass of the strengthened elements, using a capture system to hold the fragments of the failed elements from targeting the occupants and other elements following the impulsive wave by using cables, fabrics or thin gauge steel sheets, installing sacrificial panels on the impulsive load of the building to mitigate the magnitude of the impulsive pressure and externally strengthening the element by utilizing stiff or ductile materials are some of the conventional methods used [2].

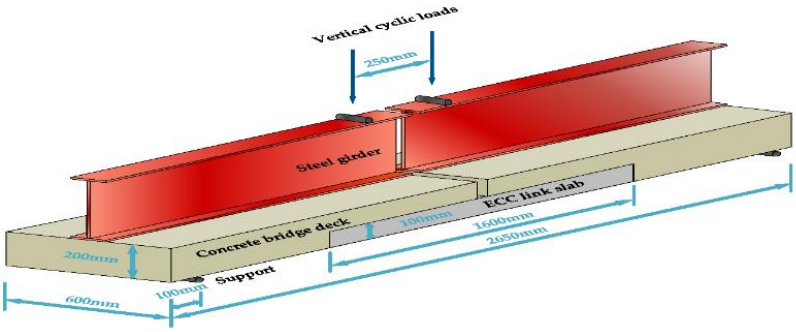

Figure 1. Vertical cycle load and its impact on concrete bridge deck considering ECC-link slab [3]

Reinforced concrete with different loads (impact and impulsive) used to be the conventional material to improve the impulsive resistance of structures. Recently, with the invention of materials, steel is being replaced with new stiff and lightweight RC-slab materials as an external retrofitting material as shown in Figure 1 [3]. When the impulsive wave impinges structure, if the external elements (walls, columns, etc.) are strong enough to resist the impulsive effect, the shock penetrate inside through the weak elements such as windows or doors, leading to subjecting the interior elements such as slabs and floors and the occupants to high pressure and shreds of broken glass. While if the external elements were incapable to resist the impulsive load, collapse or localized failure is the potential scenario with lots of fragments of the crushed concrete or stones which will enter inside the building following the impulsive wave making further loses in the building and the occupants. With the increase of the stand-off distance, the duration of the positive phase (duration time) increases while the amplitude of the incident pressure decreases. Explosive charge situated very close to a target (close-in distance) impose high incident pressure over a localized region of the target as explained in [4]. While further away explosive charge imposes lower incident pressure which distributed uniformly over the entire structure of the concrete design in the constructed building.

As the chemical explosion happens, mass of hot gases (3000-4000ºC) is produced under a high pressure of about 300 kilo bar. These gases expand outward of their occupied space. As a result, the surrounding air particles are compressed then pushed out of the explosion point with pressure above the ambient atmosphere called overpressure [5]. After that, the pressure decays in a regular manner within a very short time (duration time) to reach the ambient pressure again in the reinforced concrete slabs. This changing of the transferring pressure with time is called a shock wave (impulsive wave). The maximum overpressure occurs at the front of the impulsive wave which is called the peak overpressure (incident pressure or side-on pressure). With a distance from the explosion point, the decay of the pressure continues and becomes less than the ambient pressure (negative phase) which then rises to reach to the ambient pressure. During the negative phase, a partial vacuum is initiated with an air sucked in (high suction wind) carrying the debris from the explosion venue to long distances as shown in Figure 2[6].

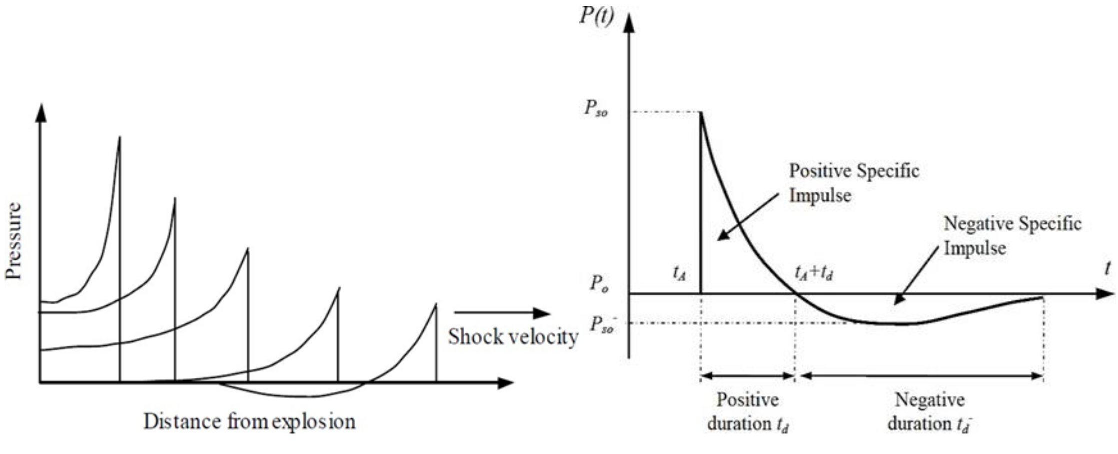

Figure 2. The simulated impulsive wave and deformation, propagation with distance and typical impulsive pressure profile in the RC slabs [6]

1.1. Problem Statement

The main problem addressed in this paper is to conduct a theoretical and practical research on observing the effects of impulsive loading and deformation damage in reinforced concrete (RC) slabs during building construction. The structural response of the buildings to the impulsive load and the contributing factors are presented. To review the existing knowledge in this area, a review of the studies that have been done so far on enhancing the structural response to the impulsive loading is presented as well and their results are discussed highlighting their strengths and limitations. In this paper, the methods and the materials that have been used in the impulsive strengthening is highlighted with a focus on the pros and cons of each one. Both experimental and numerical studies that were conducted in this area are covered in this paper.

1.2. Aim of study

This study aims to enrich the existing knowledge of the structural impulsive load resistance by conducting experimental and simulation programs related to the impulsive load resistance of Reinforced Concrete (RC) slabs by covering some important aspects that have not been studied in depth before, such as the energy dissipation, failure modes, and the ductility of the construction system. The construction of the buliding as a strengthening method in one-way RC slab against impulsive and impact loads was considered in this research to investigate and interpret its behaviour under short transient loadings such as impulsive and impact loadings. The slabs were selected to be strengthened as they represent the weakest and the most vulnerable part in the structure to the impulsive loading effect due to their wide surface which subjucts to the impulsive pressure for all form of the slabs such as as floors, wall panels, cladding panels.

2. Background

Many retrofitting materials were tried and their feasibility in the impulsive retrofitting field were investigated, but these materials were not designed to resist impulsive loading. Further research is needed to understand their performance under impulsive loading and to develop new innovative material for the impulsive load resistance [7]. The innovative material should comprise all the factors needed for the best retrofitting material against the impulsive loading such as stiffness, ductility, resistance to the environment and vandalism and easy installation processing. Since the impulsive-resistance design is still in its infancy with the absence of any design guidelines, the reviewed literature was aiming to understand the structural performance of the RC slab elements by conducting experimental tests under real explosion event. To understand the impulsive performance of the retrofitted elements by measuring relevant factors such as deflection, ductility, strength, and pattern of failure. But the destructive energy produced from the explosion within very short duration (milliseconds) makes it difficult to achieve the desired accuracy by using laboratory instruments whereas it is difficult to quantify the difference or the enhancing factor of the mechanical properties of the structure after retrofitting against this type of destructive loading [8]. Considering that, in addition to the cost and the secure nature of the explosion tests, there is a need to develop theoretical or numerical models with accepted accuracy level. Further, it is not possible to achieve all behaviours by using laboratory instruments to validate the theoratical work [9].

2.1. Response of structures to different types of loads

Loads on structures are mostly classified into two categories: static load and dynamic load. The static load is insensitive to the time effect, while the dynamic load is sensitive to the time effect. According to that, the static load may be defined as any load which is applied constantly for relatively long time (compared to the natural period of the member), while dynamic load may be defined as the transient and changeable load that occurs within a short duration (milliseconds) such as vibration, seismic, impact and impulsive load [10].

Applying the load within very short time results in a higher loading rate leads to an increase in the deflection rate of the loaded member, and as a result, increasing the strain rate of the structural materials inside the member. Typically, impulsive and impact loads produce high strain rates due to the high loading rates associated. Some materials have different mechanical properties under different strain rate values. These are referred to as strain rate dependent materials and the strain rate effect of the dynamic loads, especially with high strain rates, should be considered well in any design procedure.

2.2. Strain response associated with different type of structure

The structural behaviour including ductility, failure mode, strength and energy absorption is found to be affected by the strain rates. So, investigating each loading regime from low to high strain rate values is needed for a better understanding of the structural behaviour. Much research has been done in the quasi-static regime while less research has focused on the high strain rate regimes as shown in Figure 3 such as impact and impulsive loading due to the destructive nature of such these tests which make it difficult to quantify and measure the obtained results instrumently as given in [11]. The structures behave inconsistently under either impact or impulsive loads. The result is a complete absence of any design guideline for the protection against impulsive events. So, more research into the high strain rate regime should be done to enrich available guidance on the impulsive-resistance topic.

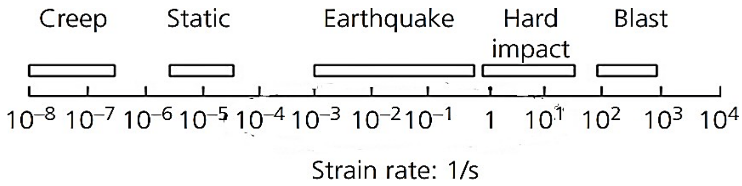

Figure 3. Spectrum of the approximated strain rates corresponding to different loadingEnvironments on the RC slabs [11]

When a structural reinforced concrete member is subjected to a very short transient load, such as impulsive and impact load, the reinforced concrete member oscillates producing a periodic displacement-time function with multiple peaks. The first peak of the displacement which occurs in the first phase of the displacement wave has the highest magnitude and the highest effect on the member as the peak deflection reduces in the consequent phases of the oscillation due to the damping effect. So, only the first peak of the displacement is considered in analyzing the structural response to the impulsive and impact loading.

2.3. Prediction of impulsive pressure and impact on the RC slabs

To overcome the difficulties of conducting a real explosion test, non-explosive tests are used to simulate the impulsive load effect on structures. Dropping weight with low velocity or applying hydraulic pressure with different loading rates are widely used. To design a structure against impulsive loading, prediction of the impulsive pressure is needed [12]. Many studies have been conducted to provide adequate prediction of impulsive load. The impulsive pressure on any target is related to the energy of the impulsive and to the stand-off distance. While the explosive energy is related to the type of explosive charge and its weight.

Dropping a mass with high velocity by either increasing the dropping hight or by imposing an initial velocity in the dropping mass, such as using the impulsive impact tower also can be used in simulating the impulsive loading due to the high impact impule with short duration of loading produced by this type of hard impact action. The main difference between the impulsive and the hard impact loading is in the loading way where the impulsive loading tends to act in a distributed way compared to concentrated way in case of the impact loading [13]. This difference can be mitigated if a proper loading layout rig is used in the contact surface between the impactor and the impacted bodies. Due to security and integrity factors, the real impulsive experimental tests have been conducted in the free space area. This means that the interaction between the impulsive wave and the surrounding buildings was neglected. This interaction was found to have a significant effect (mitigated or intensified) on the impulsive wave that applied on the individual element which depends on the interacting in the pressures that are reflected from the surrounding buildings.

3. Methodology

Protecting the civil structures from the impulsive load effect is crucial task to reduce the financial or human losses caused by building collapse or from the loading effect. Many strategies, discussed below, can be applied to increase the impulsive resistance of structures. Cost and ease of implementation are the main factors to select the suitable method of the protection. Increasing the strength of the structure by extra concrete or reinforcement is an old strategy to reduce the progressive collapse. However, the high cost and duration of installation in addition to the extra weight make it an unfavorable solution [14]. Surrounding the structures with fences, walls or bollards to keep them away from the explosion point may help to mitigate the impulsive effect due to reduced pressure. This strategy is not feasible in the urban area where space is not available or is very expensive after manufacturing the reinforced concrete (RC). Increasing ductility and energy absorption capacity of existing walls could be augmented by using steel studs in the connection between the walls and the floor or ceiling since steel behaves in a ductile manner when it fails. These elements and the stud as well should be designed so as not to fail. The disadvantage of this technique is in loss of space and the long time needed for installation. Below the RC slab has some certain impacts after the certain weight dropped on it i.e. (a) compressive local damage, (b) Flexural cracks, (c) Local load of slab, (d) Global strain cracks and in last (e) inclined flexural-shear cracks on RC-slabs as shown in Figures 4 and 5.

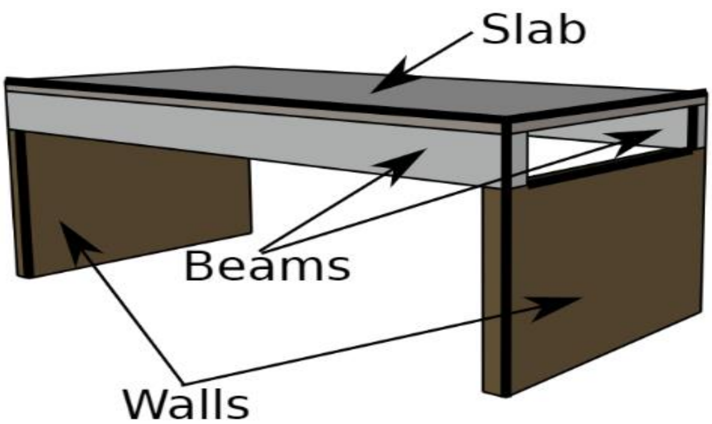

Figure 4. Different types of impacts faced by the RC slabs under normal loading testing stage from the angle of 135^o

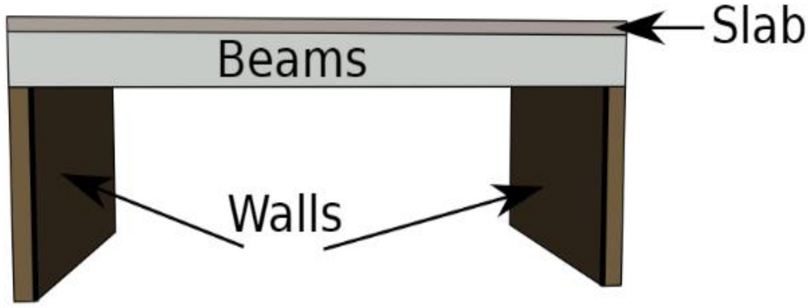

Figure 5. Different types of impacts faced by the RC slabs under normal loading testing stage from the angle of 180^o

External bonding of steel plates (EB) to the RC structural elements can improve their mechanical properties, such as the flexural strength or shear strength, based on the strengthened member and positions of the EB plates. Lateral confinement of RC columns by EB steel plates enhances their compressive strength and improves their ductility as well. Corrosion of the steel plates, extra weight, and costly maintenance are the common problems with this technique. Under low explosive charge (22.4 kg) the RC slabs composite enhanced the impulsive resistance of the panels by providing more residual strength when tested statically. The enhancing factor was about 75%. While under the higher explosive charge (33.4 kg), the results were found to be scattered with no clear trend. Using RC slabs for the close-in explosion (i.e. a small scaled distance of about $1^{m/kg1/3}$) may not be advantageous. The failure of the strengthened panels was dominated by shear cracks rather than delamination of the composite. The non-delaminated composite was the key factor for the improvement in the residual strength of the panels. Based on the effects they stated the need for more experimental work to assess the effectiveness of the Rc slabs in mitigating the impulsive effect

3.1. Computational effect by excerting load on slab

To investigate their model for the dynamic analysis validation under impulsive load effect on the RC slabs, the same slab was subjected to hypothetical impulsive load caused by an explosive charge of 453.44 kg of RC-slabs in construction with an estimated scale distance of (Z=0.348 $m^{kg-1/3}$). The impulse and the time duration resulting from this charge were predicted based on approximation charts. The function of the impulsive load on the element was idealized as a triangular pulse rather than an exponential decay function, also the negative phase of the load was neglected too. These simplifications lead to decrease the accuracy of the results by an unknown level.

Thus, it is suggested that using strain rate independent model for relatively low strain rate cases is acceptable. The numerical results indicated the validity of retrofitting the slab by slab strips. This was indicated by reducing the historical displacement of the retrofitted slab compared to the control slab [15]. The study also tested retrofitting the slab on both sides. Figure 6 showed that using slab strips on both sides reduced the maximum displacement of the slab from 37.5 mm for the as-built slab to 16.55 mm for the retrofitted slab. This is reasonable since strengthening the tension face of the slab leads to enhance its absorping energy in the early stages of the response (elastic energy) due to the enhancing in the stiffness of the element which as a result lead to absorb more energy under lower displacement magnitude compared to the reinforced control slab.

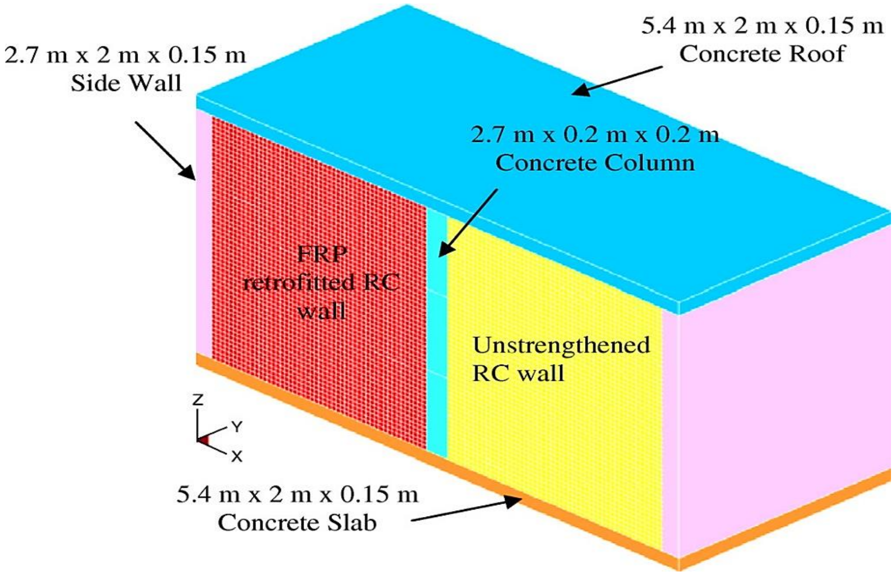

Figure 6. The computational effect on the mid-point of the slab with total applied on RC-walls [15]

Solution algorithm for assessment of loading and damage to the building

This algorithm detailed steps for generating assessment analysis of impulsive loading and deformation damage in reinforced concrete slabs during building construction. Algorithm steps are as follows Figure 7:

Preventive measure and composites have been used by researchers to reinforced structures against high loading rates in many different shapes, such as fabric, rods, strips, and slabs. Retrofitting slabs, beams and columns by designs are studied and qualified by researchers. Wrapping some reinforced concrete (RC) elements like columns or beams with fabric was found to be adequate in term of enhancing ability to resist impulsive loading effects, where both the ultimate strength and the ductility of the strengthened members were enhanced by wrapping them with fabric.

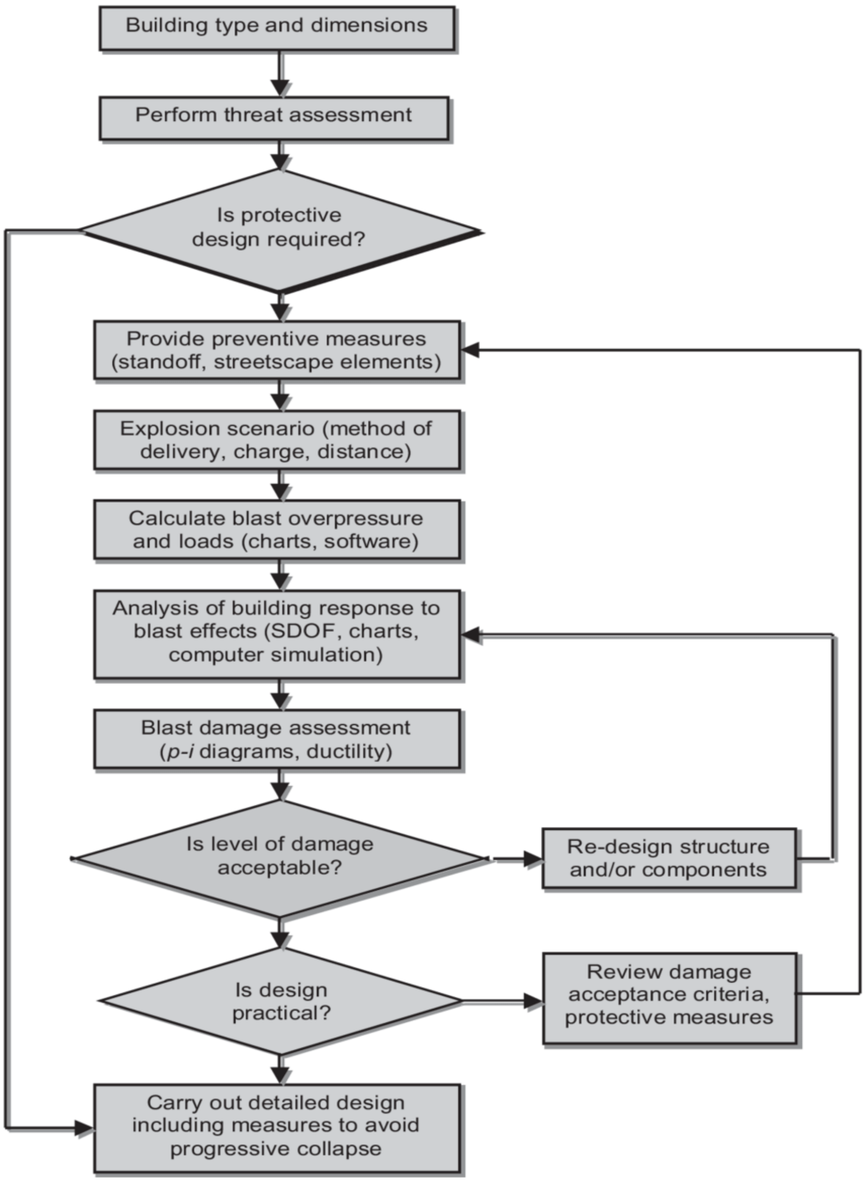

Figure 7. The methodological steps depicted by the flowchart

3.2. Determine Impulsive Load and Deformation Damage

To improve impulsive and impact load resistances of slabs, it seems prudent to try and investigate means of avoiding balling of the slabs which adversely affects slab contributions at higher slab lengths. To that end, tested under impact (drop weight) both plain RC panels and panels reinforced with 100 mm long carbon slabs coated with a thermoplastic material to reduce balling of the long slabs at the wet concrete stage. The reinforced panels were found to outperform the normal reinforced concrete slabs on both first crack and ultimate loads where strain on slab is defined by σ_x, and impulsive loading by 't' on reducing deformation and loading by 80%, on reducing residual deflection and on exhibiting more ductility represented by 'M'. The impulsive effect of reinforced concrete is determined by the following equations as shown in Figure 8:

$$t = \int A \, \sigma_x(y, z) \, dA \qquad (1)$$

$$M_t = \int \varepsilon/\varepsilon_{cu}\, \sigma_x(y, z) \cdot (d_x - ds)\, dA \qquad (2)$$

$$M_t = \int \varepsilon/\varepsilon_{sy}\, \sigma_x(y, z) \cdot (y_s - y_{CG})\, dA \qquad (3)$$

$$M_t = \int \varepsilon/\varepsilon_{su}\, \sigma_x(y, z) \cdot (y_x - \varepsilon/\varepsilon_{sy})\, dA \qquad (4)$$

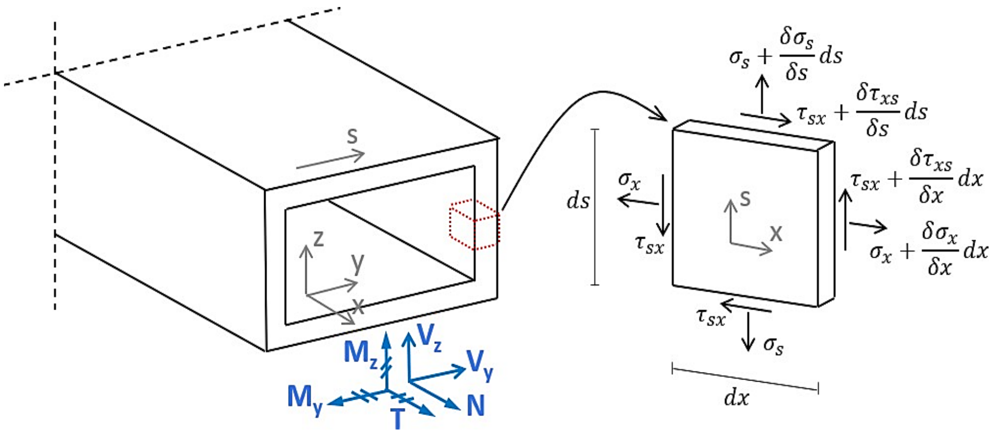

Figure 8. Reinforced concrete section with coordinate and loading sign convention including the local equilibrium for impulsice loading in thin walled element under plane stress

$$\frac{\partial \sigma_x}{\partial_x} + \frac{\partial \tau_{xs}}{\partial_s} = 0 \qquad (5)$$

$$\frac{\partial \sigma_s}{\partial_s} + \frac{\partial \tau_{xs}}{\partial_x} = 0 \qquad (6)$$

$$\sigma x = \sigma c \cos^2(\theta) + \rho sx\ \sigma s,x \qquad (7)$$

$$\sigma s = \sigma c \sin^2(\theta) + \rho sy \sigma s,s \qquad (8)$$

$$\tau xs = \sigma c \cos(\theta)\ sin(\theta) \qquad (9)$$

The RC slabs were subjected to real impulsive loads by detonating 10, 20 and 30 kg of load. They reported that the longer slabs produced better impulsive resistance. The highest impulsive performance was obtained by using 1.0% of reinforced concrete. Loading of the concrete was observed related to the longest slab under loading. So, they recommended that increasing slab lengths up to a limiting value improved the impulsive resistance of RC panels. The impulsive response of the RC structures can be modeled based on the impulsive response of the constituent structural materials (concrete, steel and strains) and the bonding behaviour between them. As there are many different types of strains owning different mechanical properties, as discussed in the previous sections, it is difficult to provide a comprehensive numerical model to simulate the RC materials. Furthermore, the bonding behaviour between the RC panel layers (when multi layers are used) or with the concrete is a typical as it depends on many factors, such as type of the FRPs material, type of the adhesive, and the environmental conditions Figure 9.

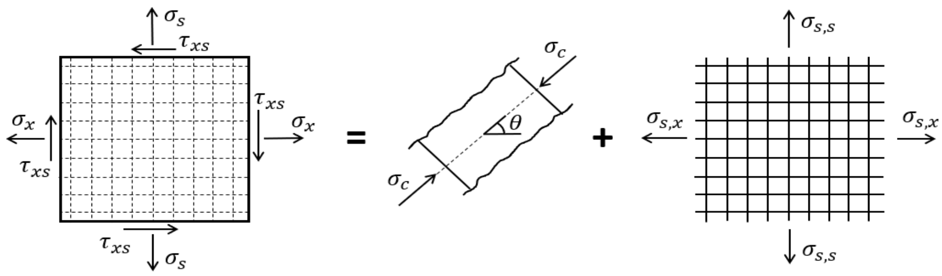

Figure 9. Internal membrane cracked equilibrium of reinforced concrete slab to find out the deformation damage

Impulsive loading in reinforced concrete material models were proposed to describe the mechanical behaviour of the slab composite materials in terms of the failure criteria and evolution of damage. In addition to that, several contact models are proposed to simulate the bonding behaviour between the constituent materials. However, all of the proposed models comprise factors need to be assumed or pre-defined based on the actual behaviour of each composite material.

4. Results

The tool successfully deals with the interdependency between the distribution of normal and strain flow in any single-celled reinforced concrete for deformation damage control. This is practically impossible to carry out in a reasonable way by manual means due to the overwhelming number of possible suboptimal solutions. Only by implementation of advanced open-source nonlinear optimization algorithms is the tool able to deliver optimized solutions in a highly efficient manner. The results of the nonlinear optimization algorithms are shown in Figures 10 to 14.

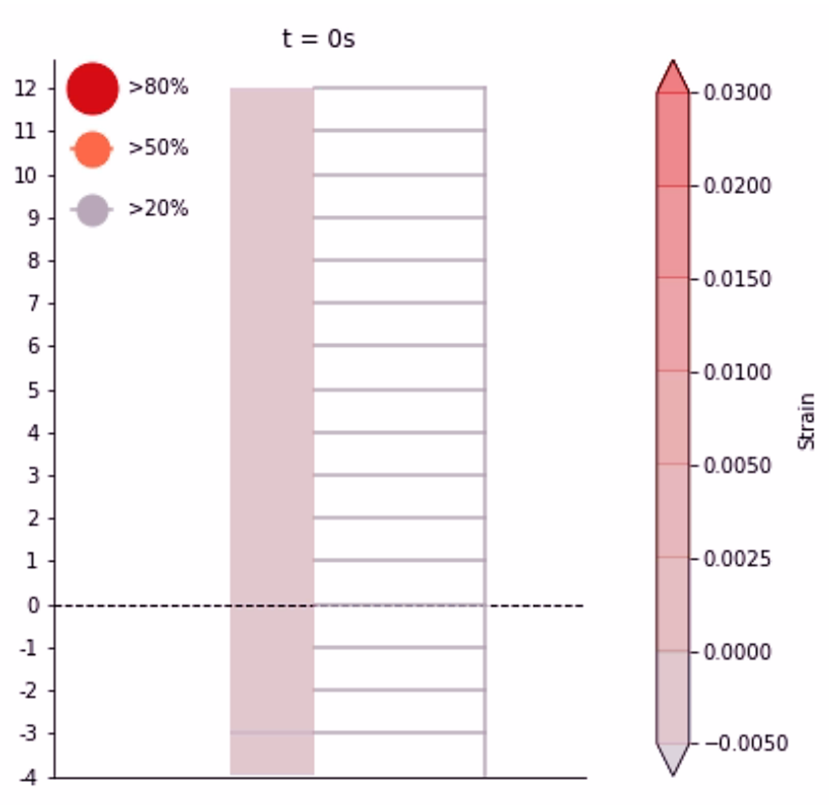

Figure 10. The reinforced concrete slab at the beginning of simulation for observing the deformation damage and impulsive loading is not initialized

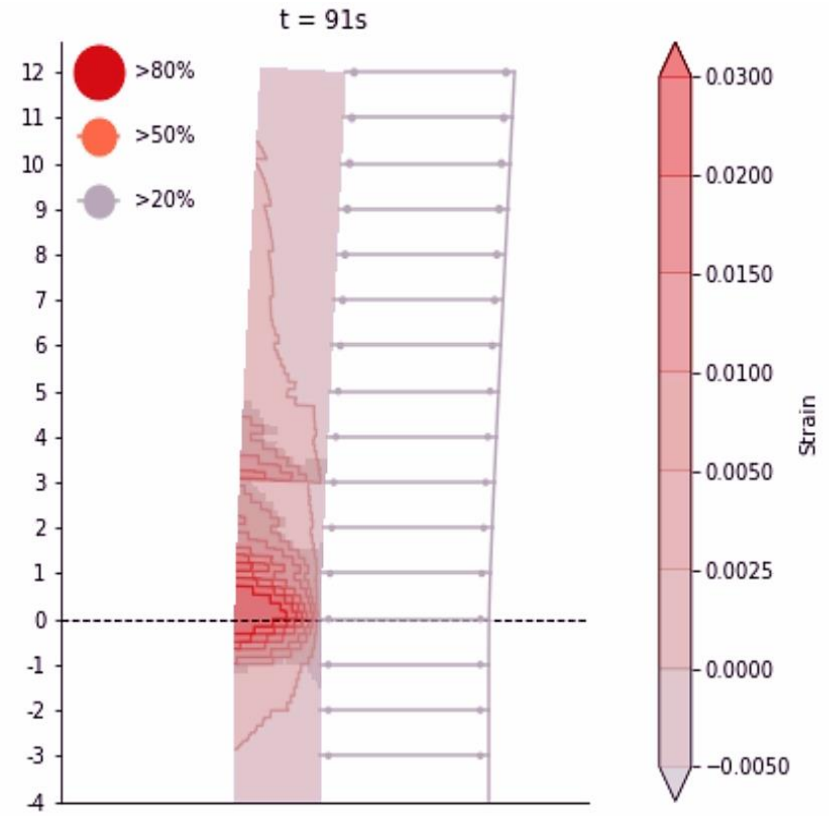

Figure 11. The reinforced concrete slab under the maximum strain at t=91s to observe the maximum deformation damage and impulsive loading on RC-slab

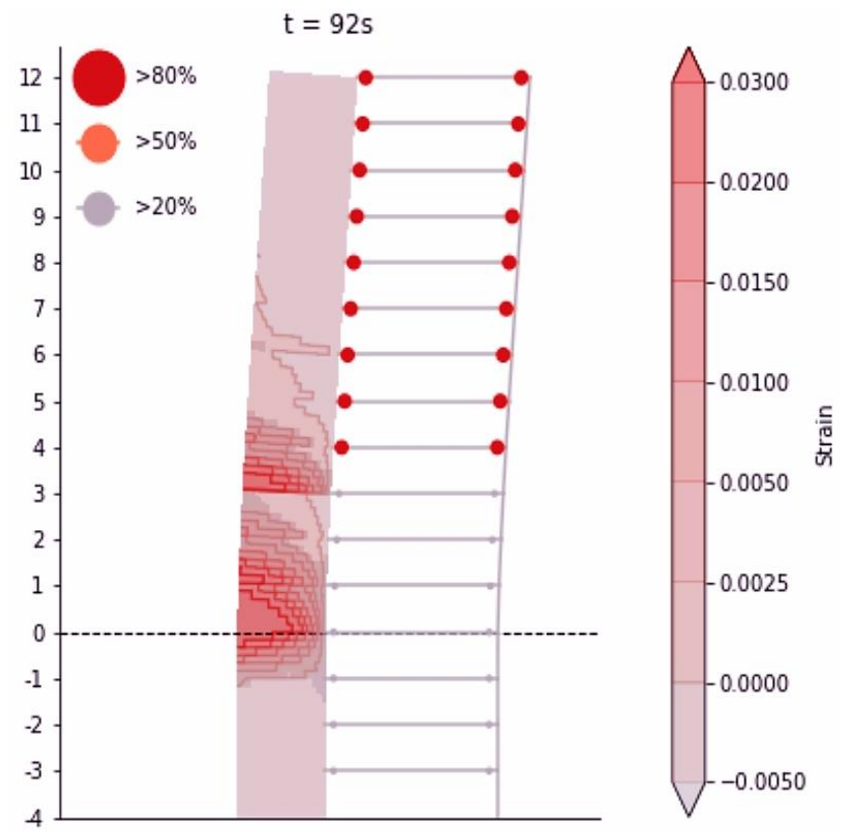

Figure 12. The reinforced concrete slab under the maximum strain at t=92s to observe the maximum deformation damage and impulsive loading on RC-slab

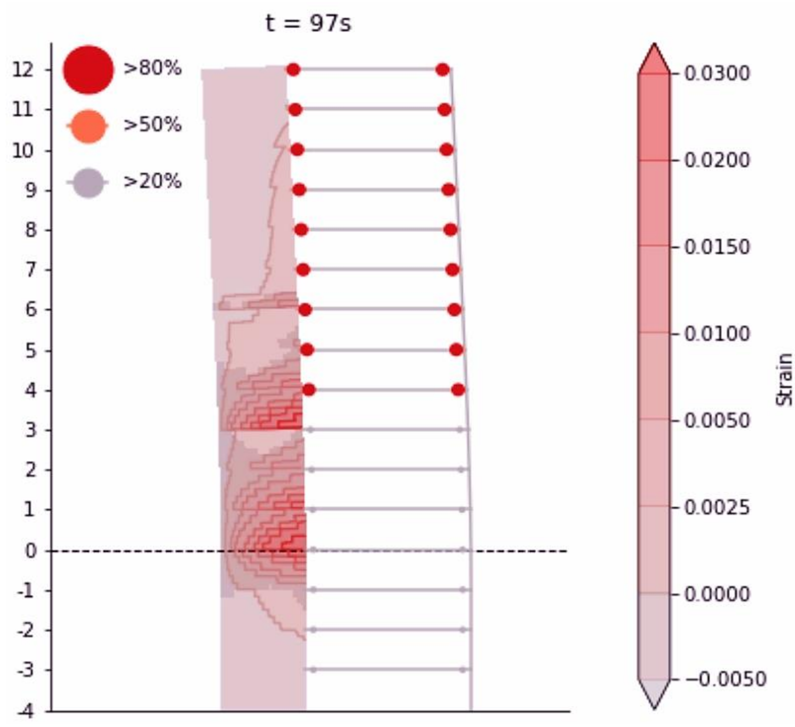

Figure 13. The reinforced concrete slab under the maximum strain at t=97s to observe the maximum deformation damage and impulsive loading on RC-slab

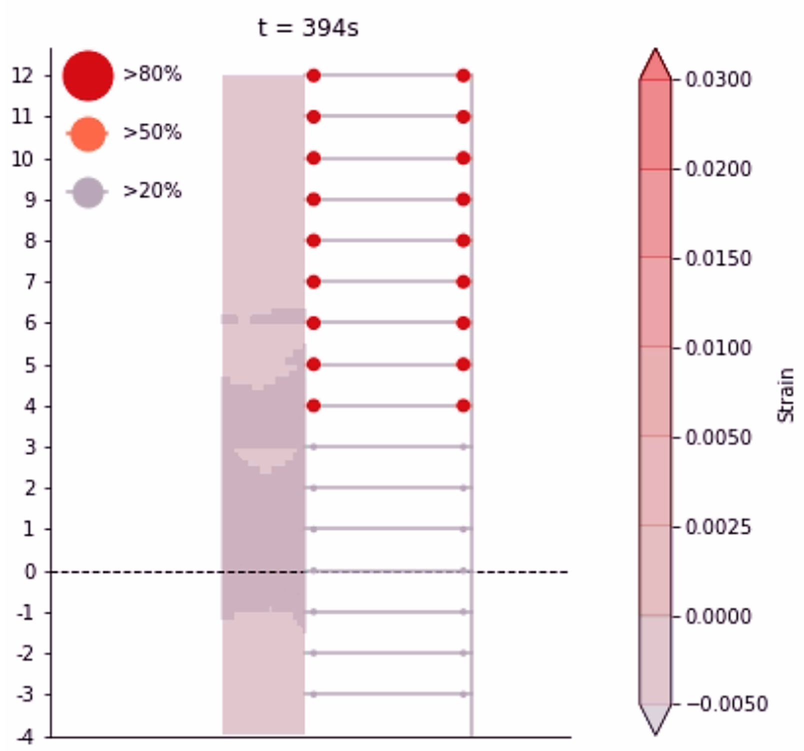

Figure 14. The reinforced concrete slab under the minimum strain at t=394s to observe the minimum deformation damage and impulsive loading on RC-slab

The developed impulsive load and deformation damage analysis-based design tool allows for a fully automatic optimization of the possible plastic strain states and thus load carrying capacity, ensuring an optimal usage of the RC-slabs. Reinforced concrete slabs generally allow for a holistic verification of arbitrary single-cell hollow RC sections under combined loading and is made freely available to immediate usage. Despite the tool requiring minimal input, it provides the user with significant data to evaluate the structural adequacy. Moreover, automated optimization modeling eliminates the need for multiple user choices during the building construction process alongside ensuring less conservative designs towards material savings and consequent generation of value.

5. Discussion

A practical, easy-to-use design tool applicable to arbitrary and impulsive loading on the reinforced concrete sections that addresses the challenges described above has been developed during the construction of buildings. One of the paramount goals was that the design tool automatizes the manual procedure of validating the strength demand on the section under combined actions while making use of conventional design code friendly assumptions as compared to the work performed by authors in [16]. In addition to catering for capacity evaluations it also delivers reliable evaluations pertaining to the performance of the hollow sections under service conditions. The latter addresses a typical limitation of Lower Bound based design approaches where compatibility is disregarded which often leads to additional shell model analysis. Figure 15shows the evaluation of different comparison parameters between reinforced concrete slabs metrics for strain on the RC-slabs under deformation

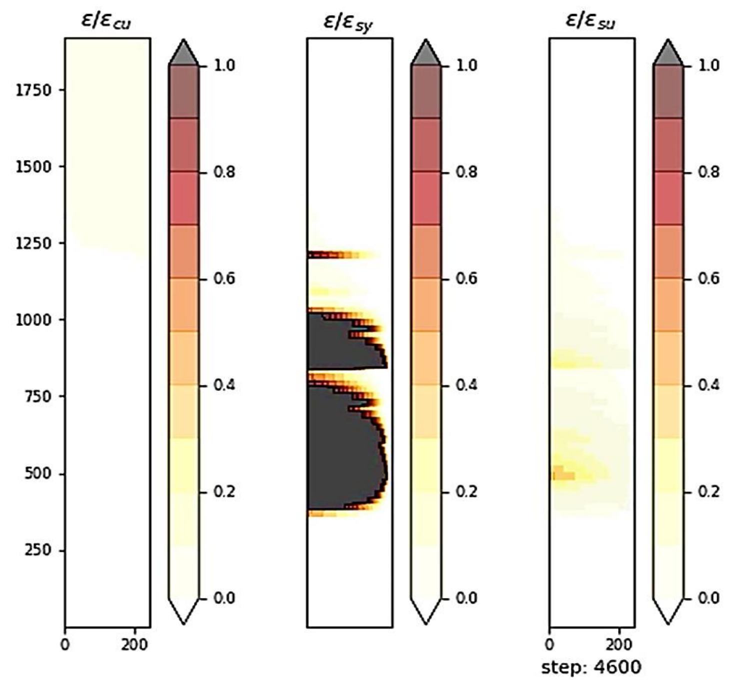

Figure 15. Evaluation of different comparison parameters between reinforced concrete slabs metrics for strain on the RC-slabs under deformation

The reinforced concrete slabs exposed to a strain torsional moment the designer would be forced to introduce an additional stain flow in at least two of the walls. Consistently trying to avoid exposing any walls to a combination of shear and normal stress often results in very conservative designs. Alternatively, one could allow for the combined exposure and now deal with the more complicated flow distributions. Additionally, the designer would have to deal with in-plane membrane verification of all the possible critical combinations using either the reinforcement equations in this work. However, this impulsive loading and deformation damage to RC-slabs in iterative design methodology simply becomes too cumbersome to carry out manually in the design of hollow sections with more complex shape or if there are multiple load cases to be considered.

6. Conclusion

To sum up the paper, the study of the structural behaviour of reinforced concrete slabs under impulsive loading and deformation damage effects. Many difficulties were involved in the experimental investigations make it difficult to gather all the data needed before building any comprehensive guideline design for the impulsive protection. The difficulties involve the highly cost impulsive experiments in terms of the materials and the instruments, the destructive nature of loading within very short time, and the limitations of conducting the impulsive events for security reasons. Thus, the need to develop rational model to simulate the structural response to the impulsive loading is crucial as the rational modeling can provide all the data needed to provide additional insights onto the entire behaviour of the composite material structural response, particularly for the data which is challenging to measure during the experiments. Such this kind of computational model, after validated with sufficient experimental data, can be used to gather as much of data as possible to cover all the aspects that needed to build the design procedure.

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