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Alternatives to prevent the failure of RC members under close-in blast loadings

Ramón Codina, Daniel Ambrosini *, Fernanda de Borbón

[a] Struct. Eng. Master Program. Eng. Faculty, University of Cuyo, Mendoza, Argentina
[b] CONICET, National Research Council from Argentina, Argentina

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ABSTRACT

In this paper, an experimental study of the dynamic response of reinforced concrete (RC) members protected in different ways is presented. Two alternatives for the protection of RC members are designed and studied; classical steel jacketing and a new reinforced polyurethane sacrificial layer. The mitigation of shock and absorption of energy from the blast is studied with experimental methods. For comparison purposes, a RC member without protection is also tested and studied. As expected, the steel jacketing provided excellent protection reducing the maximum final deflection as well as reducing damage to the member. On the other hand, the proposed reinforced polyurethane protection performed reasonably well. The obtained results are useful for exploring new alternatives for the protection of RC columns as well as for the calibration of numerical codes.

1. Introduction

Blast incidents in recent years show that most of the terrorist attacks on public structures were explosions within short standoff distances. In this context, columns are the most vulnerable structural components and their failure is the primary cause for progressive collapse in framed structures. On the other hand, many of the research efforts in this field have been devoted to the effects of far-field explosions on structural elements. The effects of near-field explosions on structural elements, especially columns, have not been widely investigated [1].

The three basic strategies for protecting columns and preventing a possible collapse are: 1) Establishing a secure perimeter by placing physical barriers that prevent a near field explosion [2,3]. However, this alternative is not always possible due to limited space or functionality, 2) Reinforcing the columns by increasing their strength and ductility and 3) Absorbing blast energy received by the column with sacrificial cladding layers.

The steel jacketing is the most common retrofit technique, within the second strategy mentioned above [4,5]. It usually involves wrapping steel plates, steel strips or steel bars in the transverse direction. The advantages of steel jacketing are: a small increase of the cross-sectional dimensions; ease and speed of construction; lower cost of structural intervention and interruption of use. Moreover, the general consensus in the current literature is that rectilinear jacketing is usually effective for increasing the strain capacity and the ductility of the columns, although it may or may not increase the strength of the column [6]. On the other hand, steel jacketing is not the only method that improves the response of the columns. Increasing the residual strength of the column itself is another option. Alternative materials and constructions from the field of protective structures, like polymer

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* Corresponding author.
E-mail address: dambrosini@uncu.edu.ar (D. Ambrosini).

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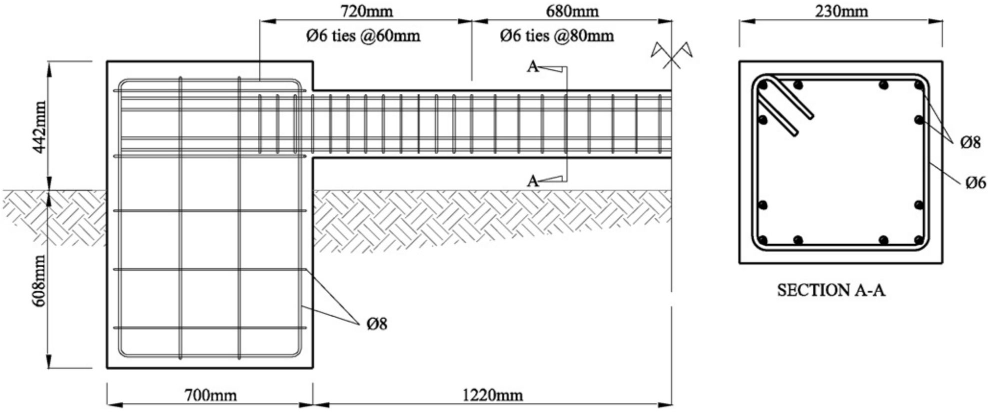


Fig. 1. Member geometry and reinforcement characteristics.

concrete or high-performance fiber concrete can be used [7–8]. Other alternative consisting of columns made with ultra-high performance fiber reinforced concrete is presented in [9].

The third strategy mentioned above is a vast field of research where several types of sacrificial layers have been studied and proposed. The sacrificial layers absorb energy and in doing so undergo a significant amount of deformation. First developed for the automobile industry [10], the use of sacrificial cladding was rapidly extended to different types of structures and buildings. These protections are usually sandwich panels with crushable cores like metallic foams that provide high energy dissipation [11]. Similarly, crushable materials can be reinforced with different types of metallic structures [12]. Low-density polymeric foams, textile materials and low-density metallic foams are excellent in reducing the risk of damages from ballistic impact. However, under blast loading, a “shock enhancement” phenomenon has been observed, that is, transmitted pressure is amplified, rather than attenuated as one might expect [13]. Another possibility of deformable energy absorbers are circular or square tubes, honeycombs cells and corrugated tubes where the plastic energy can be dissipated by axial crushing, splitting, lateral indentation and lateral flattening [14].

Finally, some hybrid methodologies exist combining the advantages of second and third strategies by increasing the strength and/or ductility of the columns and also by dissipating some amount of energy. These methods include plates and shells that can be added to columns as armors or coatings. Composite plates and materials with carbon nanotubes [15] and carbon fiber sandwich panels [16] can be used for this purpose.

The current methods for the analysis of RC beams and columns under blast loading consist of two major approaches, experimental and numerical studies. Many experimental studies are not feasible because the preparation and measurements in full-scale field experiments are complex and expensive. Bao and Li [17] studied the residual strength of RC columns after blasts. They proposed a method for the determination of the residual strength of RC columns based on the ratio of center deflection to the height of the column. Their research indicates that an anti-seismic design of RC columns can effectively reduce the destruction of buildings under blast loading, thereby reducing the probability of progressive collapse. Dakhakhni et al. [18] drew Pressure–Impulse curves of RC columns and proposed a pressure – impulse bands (PIBs) technique as a tool for vulnerability

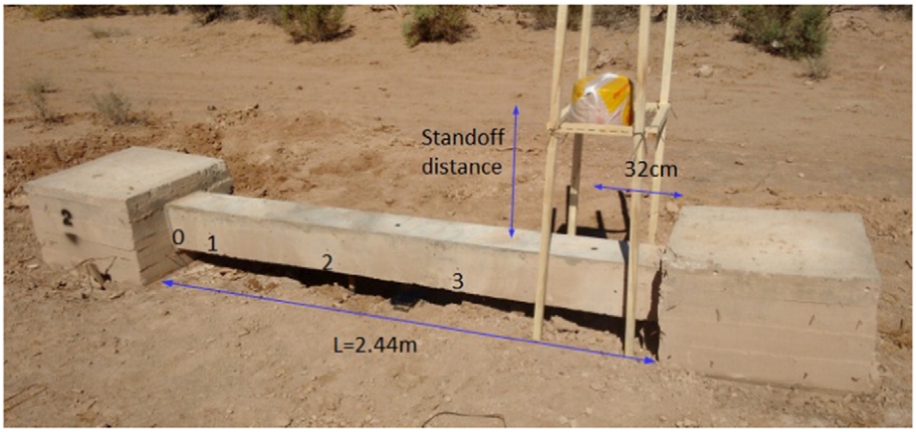


Fig. 2. Experimental setup.

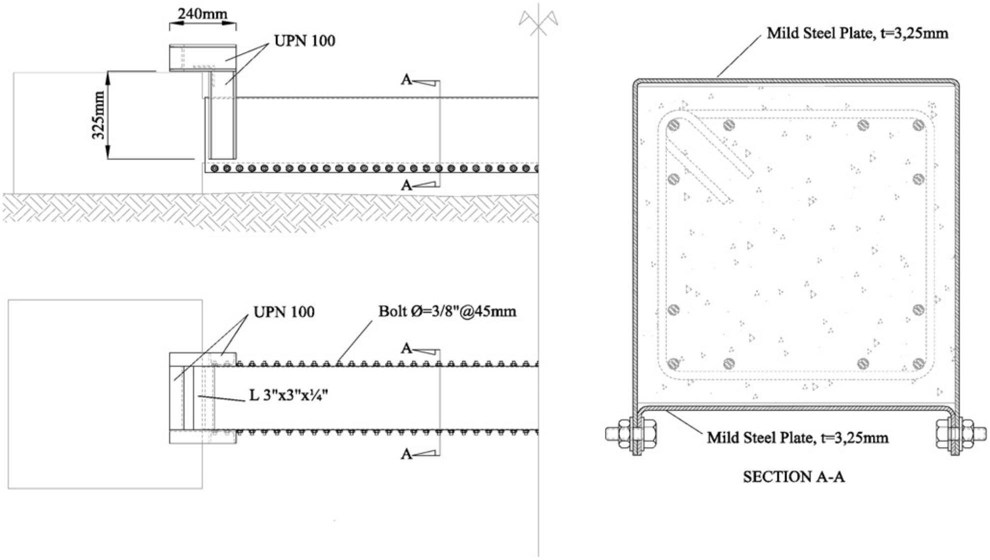


Fig. 3. Steel jacketing protection.

screening and capacity assessment of RC column under blast loading. Zhang et al. [19] carried out many experiments in order to obtain images of different degrees of damage corresponding to different scaled distances Z and for testing if scaling law (or geometrical similitude law) of blast experiments was still available. Regarding numerical studies, many methods can be found in the literature, such as advanced single-degree-of-freedom (SDOF) model [20]; the two-step method, the model condensation method, and the new combined two-step and dynamic condensation method [21] and complex 3D numerical models with intensive simulations, using specialized hydrocodes [22–23].

In the present paper, an experimental study of the dynamic response of reinforced concrete (RC) members with two different types of protections is presented. The mitigation of shock and energy absorption under blast loading of members with steel jacketing and a new crushable composite material formed by reinforced polyurethane cladding are studied using experimental methods. For comparison purposes, a RC member without protection is also tested.

Although the RC members don't have axial force, they were designed as columns and the reinforcement is representative of a typical column. On the other hand, the paper presents a comparative study between different types of protection. The relative responses are analyzed and discussed.

The obtained results are useful for exploring new alternatives of protection for RC columns as well as to calibrate numerical codes. It is clear that in such cases a full fluid–structure interaction model should be made as the net blast loading acting on the specimen in such a complex environment cannot be possibly estimated by any simplified approach.

Fig. 4. Detail of a shear key of the steel jacketing protection.

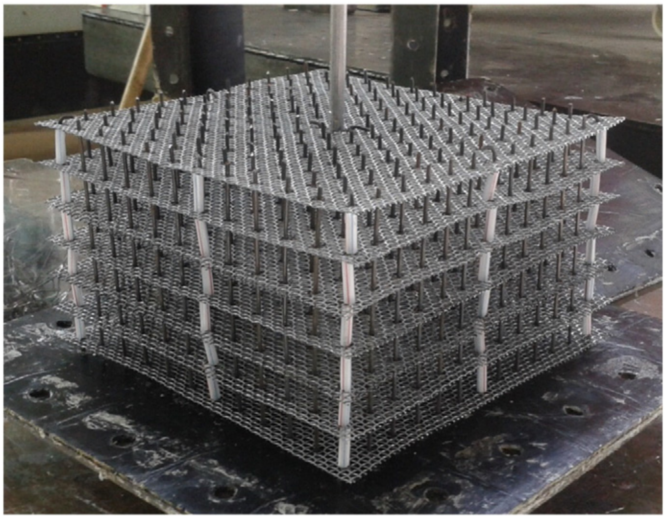


Fig. 5. Reinforcement of polyurethane bricks.

2. RC member and experimental setup

2.1. RC specimen characteristics

Five reinforced concrete specimens were built to be subjected to blast loads. The specimens had a square section of 230 mm × 230 mm and a free span of 2.44 m. Semi – buried concrete blocks at the end of the specimens were used as fixed support for the members in order to avoid rotation. Hence, the members were assumed to be fully clamped. The concrete strength was fc = 30 MPa and the yield stress of the bars was fy = 420 MPa. Transverse reinforcement was densified at the ends of the specimen within the plastic hinge region to avoid shear failure. Geometry and characteristics of the reinforcement can be seen in Fig. 1.

2.2. Experimental setup

The specimens were tested in a horizontal position, similar to other studies in the literature [24]. The type of explosive used in the tests was Gelamón VF65, a NG based gelatinous explosive theoretically equivalent in mass to 65% TNT. It should be pointed out that the equivalency of TNT was verified with tests in open air for which the overpressures a various distances were measured.

Prior to testing, numerical simulations were carried out with an explicit software code for studying the concrete member response under different explosive charges and standoff distances. The objective of the numerical study was to define the quantity of explosive (or the scaled distance) that could cause considerable damage in the member without protection, but not its collapse [25].

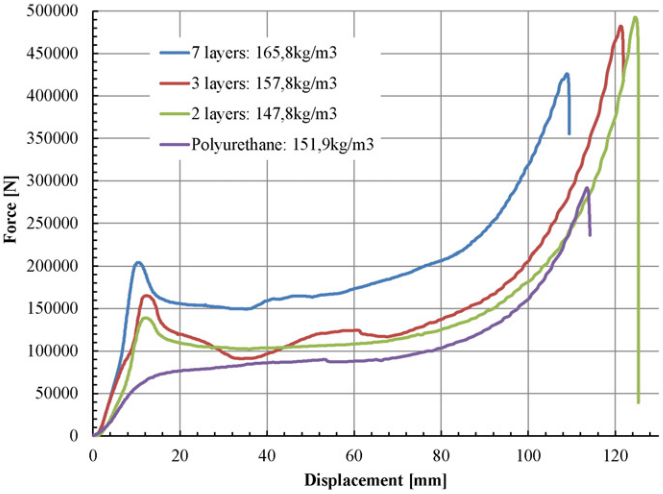


Fig. 6. Static response of polyurethane bricks.

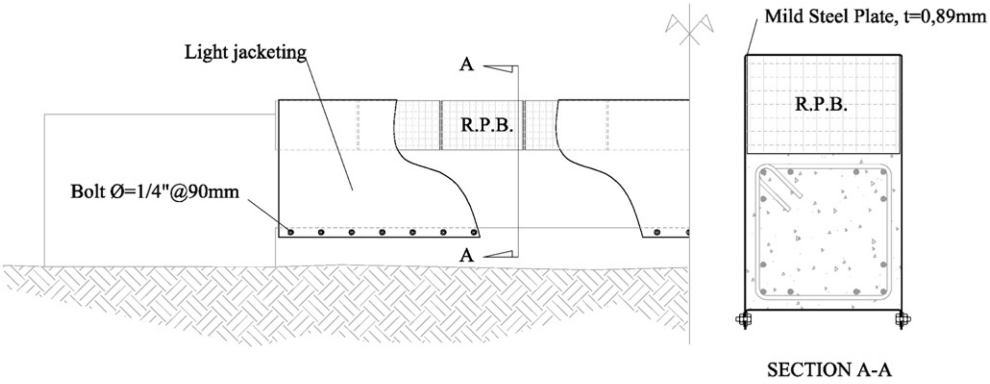


Fig. 7. Reinforced polyurethane bricks protection.

Fig. 8. Reinforced polyurethane bricks over the member.

For all the tests, 8 kg of equivalent TNT was used as explosive charge. The load was cylindrically molded and a wood framed structure was built as support. The vertical standoff distance was 60 cm, measured from the center of the TNT charge to the top surface of the nude specimen. Hence, the scaled distance Z was 0.3 m/kg$^{1/3}$, for which the tests were performed in the near field range. In a terrorist attack against a building, the explosive load is commonly located inside a vehicle or alternatively in a suitcase. In both cases the blast load is located near the ground, generating a blast wave with higher intensity near the bottom of the column. Before the tests many numerical simulations were carried out, comparing actual cases, like bombs located inside vehicles, with the cases studied. The conclusion was that an explosive load located 32 cm from one of the concrete blocks can simulate an actual case.

On the other hand, it was decided in all cases to maintain the same scaled distance with respect to the nude face of the RC member because it is supposed that the standoff distance between the explosive from a terrorist attack (ex. a malevolent vehicle) and the target building remain invariable. In the member with a proposed sacrificing layer, the standoff distance between the charge and concrete surface is the same as the unprotected beam. The scaled distance with respect to the face of the sacrificing layer will be smaller, but the scaled distance with respect to the nude face of the RC member will be the same.

Table 1
Properties of Gelamón VF65 (www.fab-militares.gov.ar).

Density g/cm^3	**Velocity of detonation** m/s	**Pressure of detonation** Kbar	**Released heat** Tm/kg	**Volume of gases** l/kg
1.5	6000	139.5	919	682

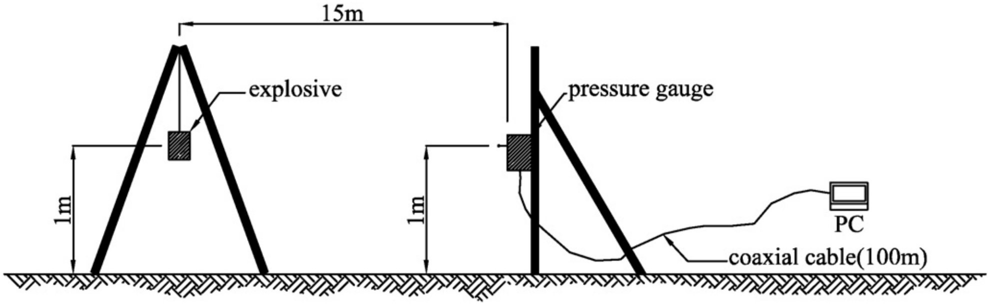


Fig. 9. Experimental setup for TNT equivalency verification tests.

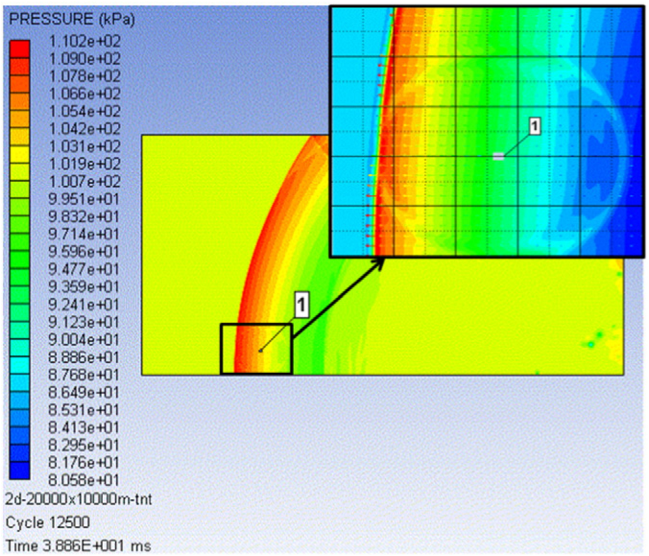


Fig. 10. Numerical model. Propagation of blast wave.

The experimental set up can be seen in Fig. 2. All explosive charges were detonated using an electric initiation system with a detonator that was inserted at the top of the charge.

The final deflection suffered by the member was measured in the gauge points labeled in Fig. 2. Before the explosion, the gauge points were marked with an alcohol level, using an external point off the specimen that cannot be affected by the blast as a point of reference.

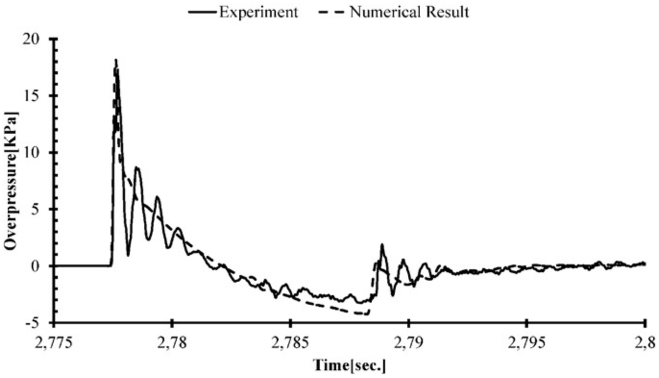


Fig. 11. Numerical-experimental comparison.

Table 2
Final deflections measured in concrete members [mm].

Gauge point	Distance [mm]	RC specimen	RC + Polyurethane	RC + Jacketing
0	0	0.00	0.00	0.00
1	200	5.30	4.10	1.20
2	870	20.80	15.10	10.40
3	1540	67.20	52.50	28.60

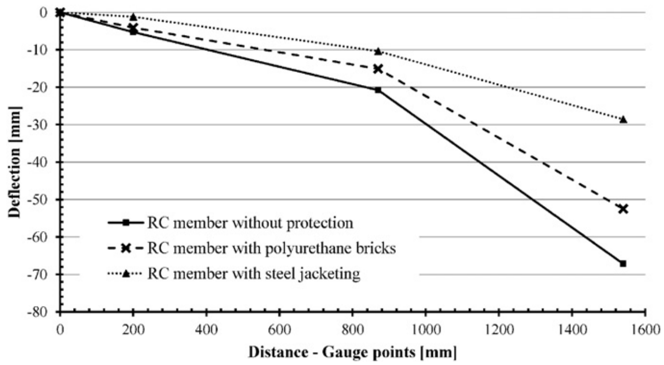


Fig. 12. Final deflection measured in gauge points.

3. Member protections

3.1. Steel jacketing

Steel # 1/8″ (3.25 mm of thickness) was used to build the jacketing of the concrete member. A system of bolts 3/8″ in the back of the specimen allowed the jacketing to be removed and to study the damage on the concrete after the blast (Fig. 3).

As the strength and ductility of the member is increased by the steel jacketing, shear keys of UPN100 were welded at the ends of the specimen to prevent a local shear failure (Fig. 4).

3.2. Reinforced polyurethane bricks

A new cladding of reinforced polyurethane bricks was built as an alternative protection. This protection can be classified as the third strategy described in section 1, i.e., absorbing blast energy with sacrificial cladding layers.

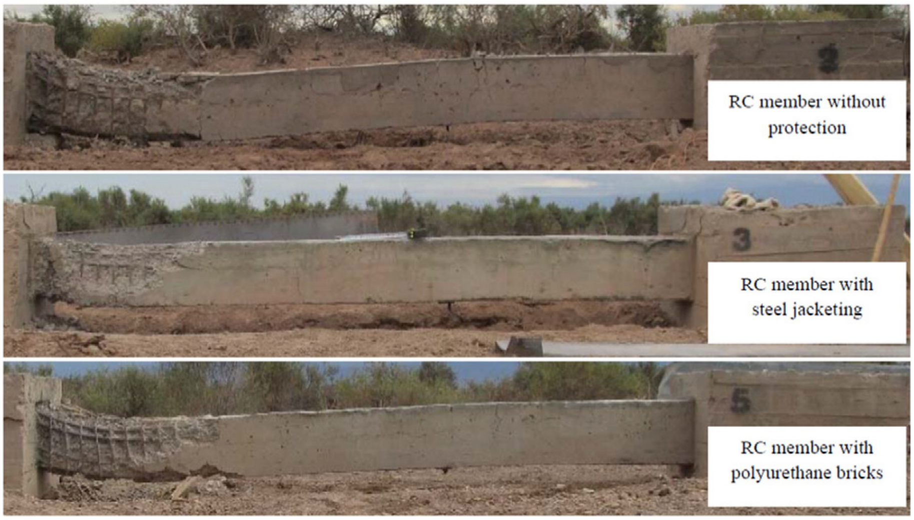


Fig. 13. Global view of the tested members.

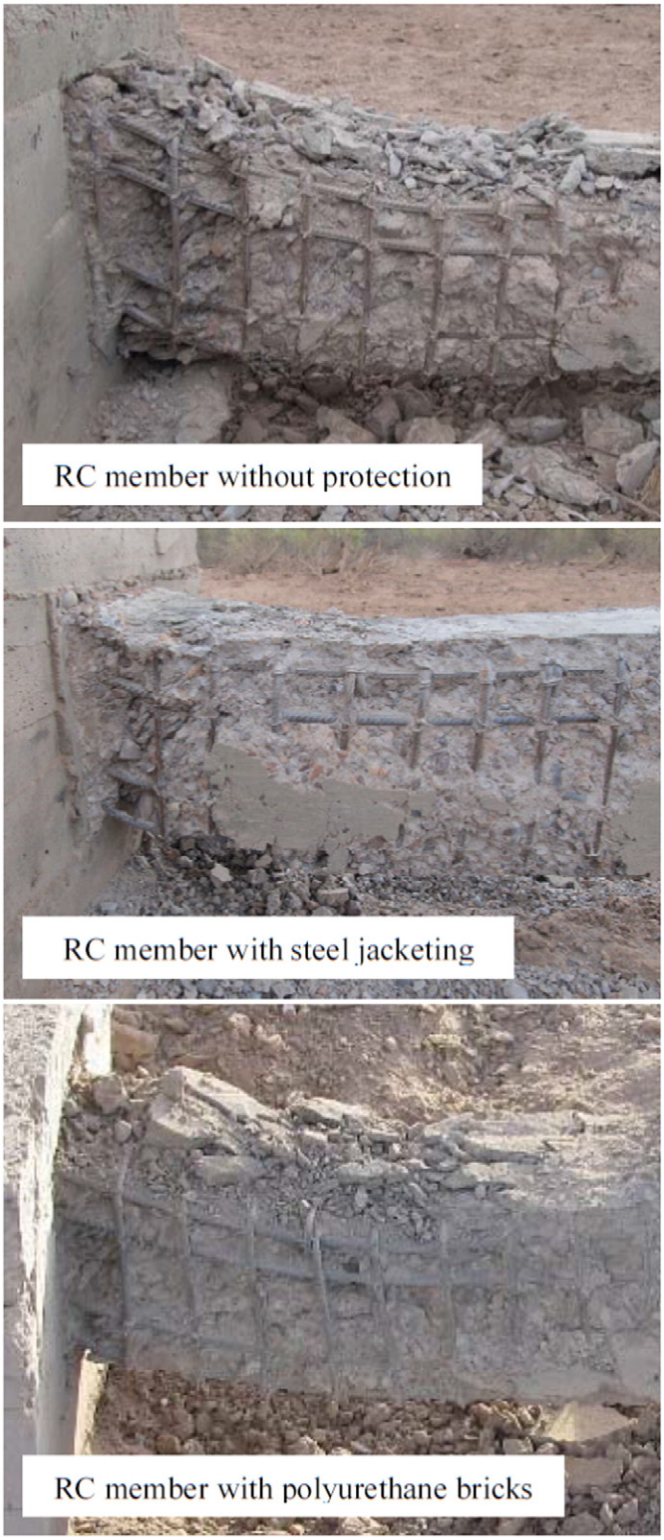


Fig. 14. Detail of the damage suffered by the members for the blast load.

The dimensions of the bricks were 23 cm × 24 cm × 14.5 cm. The reinforcement was a fabric of seven layers of galvanized steel and mild steel #14 (Fig. 5). This configuration was chosen after compression static tests that revealed better energy dissipation (Fig. 6).

The idea of the proposal of this new protection was that the buckling of the vertical steel bars can dissipate energy; while, at the same time, the crushing of the polyurethane foam produces additional dissipation of energy. Different quantities of layers of galvanized steel produce different lengths of buckling. This can be seen in Fig. 6 where lower lengths of buckling increase energy dissipation. Moreover, the layers of steel simplify the construction of the reinforced of the foam, allowing an easy collocation of vertical bars.

The reinforcement was put in a special mold that prevented polyurethane leaks. The two components of the industrial polyurethane were injected using the proportions indicated by the manufacturer. The bricks of polyurethane without the reinforcement had a density of 165 kg/m3. This density is similar to the density of aluminum foam present in the literature [26]. If the polyurethane has a low density, it could be crushed quickly and transmit high overpressure to the member. A light jacketing of steel #20 (0.89 mm of thickness) was put over the bricks with the only purpose of maintaining the bricks in position. In Fig. 7, it can be seen that because of the characteristics of the system, the light jacketing does not provide further strength to the member. If the bricks are compacted, the jacketing can freely slip. Finally, the cladding bricks are shown in Fig. 8.

4. Experimental results

1.1 *Previous tests. Verification of TNT equivalency.*

Prior to the specimen tests, a series of tests in free air were carried out with the objective of verifying the TNT equivalency of the commercial explosive, Gelamón VF65.

The properties of the explosive given by the manufacturer are presented in Table 1.

For all the tests, 1.54 kg of Gelamón VF65, theoretically equivalent to 1 kg of TNT, was used as the explosive charge. The load was cylindrically molded and a wood framed structure was built as its support. The distance to the soil surface was 1 m. An 180PC Honeywell pressure sensor was located 15 m away from the charge (Fig. 9).

In order to verify the equivalency of theTNT, a numerical model was built using the hydrocode AUTODYN [27]. At first, the use of symmetry conditions allows the initial blast wave expansion to be represented with a 2D model with axial symmetry. The number of cells required to produce accurate solutions is greatly reduced when compared with a full 2D model. When the blast wave begins to interact with the soil, the flow becomes multi-dimensional. However, before this time the 2D symmetric solution can be imposed, or remapped, onto a specific region of the full 2D model. The calculation can then proceed from that point. The initial symmetric model has dimensions of 2 m × 1 m with cells of 2.5 mm and the full 2D model has dimensions of 10 m × 20 m with 10 mm cells. The explosive load used was a cylinder of 1 kg of TNT. Fig 10 shows the numerical propagation of the blast wave and, in Fig 11, the numerical-experimental comparison for one of the tests is presented. The numerical and experimental results show a difference of less than 5% for the peak overpressures when compared. For this reason, the equivalency of TNT was considered as verified.

4.1. Specimen tests

All the specimens were tested with the configuration described in Section 2.2 and Fig 2. The loading conditions on the specimens are very complex due to the interaction between shock wave, specimen and ground. The shock wave reflection from the ground generates an upward load, which acted on the bottom of the specimen. When taking into account the final deformation

Fig. 15. Plastic strain in steel jacketing.

of the members, it can be observed that this effect is smaller than the direct blast load on the front face of the specimen because a counter-intuitive behavior is not observed. It should be emphasized that the paper presents a comparative study between protections strategies and all specimens were exposed to similar complex load conditions.

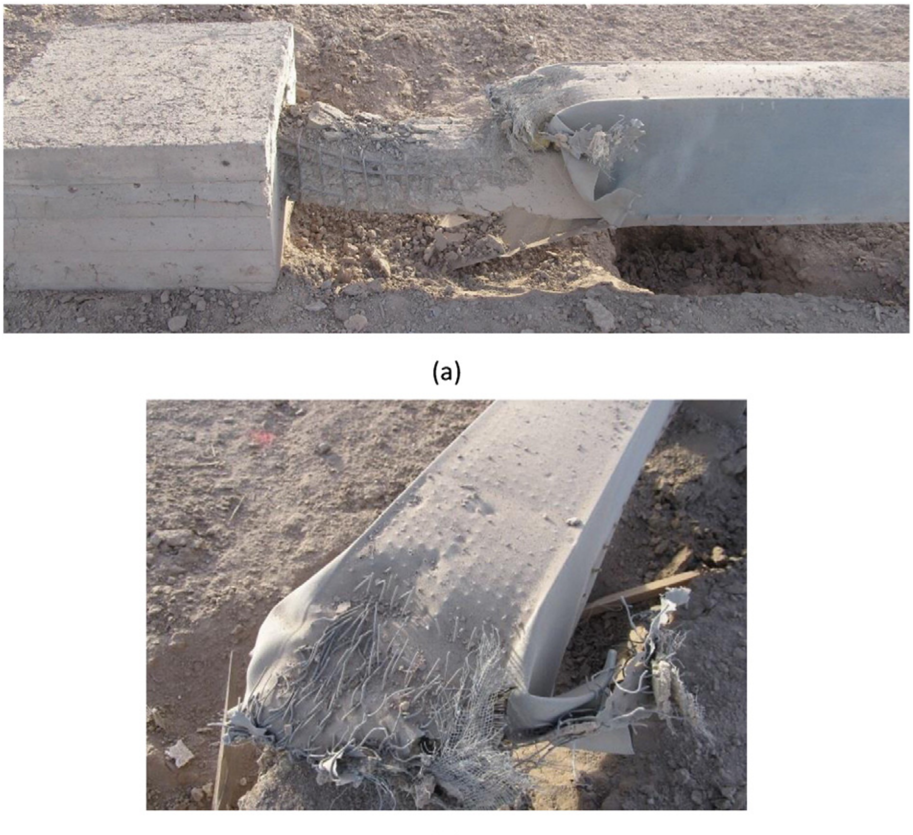
After the blast, the final gauge point positions were compared with the reference level. The measured deflections of the members are presented in Table 2 and Fig. 12.

The final deflection, in point 3, with respect to the specimen without protection, is 57.4% lower for the steel jacketing and 21.8% lower for the reinforced polyurethane.

After the steel jacketing and the polyurethane bricks were removed for this study, the damage on the specimens with the protections was compared with the RC member without protection. All the concrete members were damaged in flexure mode (Fig. 13) with concrete crushed on the front face, concrete spallation on the bottom surface and concrete flake off on the side surfaces (Fig. 14). Also, the concrete is confined by the transverse reinforcement. In the specimen without protection, a second point of inflexion can be seen with deep cracks. The shear keys do not influence the global damage and response of the member significantly (Fig. 13). Locally, less damage can be observed at the end of the member near the explosion (Fig. 14).

Nevertheless, it is evident that the member with steel jacketing is less deflected than the others because of its greater strength. Also, the concrete on the front face is less crushed. In Fig. 15, the plastic strain of the steel produced by the blast wave can be seen, but without perforations.

The response of the polyurethane cladding is inferior to the steel jacketing. This indicates that, in this case, the absorption and dissipation of energy is less effective than increasing the strength of the member. However, the shock enhancement reported in the literature is not observed in the studied case. The specimen is less deflected than the member without protection which shows an intermediate successful strategy. In Fig. 16 the final state of the sacrificial cladding can be seen. It can be observed that bricks 1 and 2 (Fig. 8) were almost completely destroyed. Brick 3 was partially destroyed and the remaining bricks have minor deformations. Then, 3 bricks (shown in Fig. 8) had high energy dissipation partially fulfilling the original idea and the remaining bricks had low energy dissipation. In order to distribute energy dissipation more, a possible improvement would be to have higher density bricks near the blast load and the bricks further away to be of lower density.



(a)

(b)

Fig. 16. Final state of the reinforced polyurethane bricks protection. (a) General view, (b) Detail showing the buckling of vertical bars.

5. Conclusions

Two strategies of protection against blast loading for RC columns are designed and studied: classical steel jacketing and a new composite material of crushable reinforced polyurethane. The mitigation of shock and energy absorption under blast loading conditions is studied using experimental methods. For comparison purposes, a RC member without protection is also tested and studied.

As expected, the steel jacketing protection presents excellent behavior and shows the best results. The maximum final deflection was lowered by almost 60%. Consequently, there was less damage to the member and obviously, it can be inferred that this member has a higher residual capacity, preventing progressive collapse.

On the other hand, the proposed reinforced polyurethane protection presented reasonably good behavior. It reduced the maximum final deflection by more than 20%. The damage in the member was also significantly reduced. In order to have better distributed energy dissipation, a possible improvement could be to have higher density bricks near the blast load while the bricks further away have lower density. It should be noted that this protection is cheaper and lighter than steel jacketing.

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