Impact damage protection mechanisms for elastomer-coated concrete

Chanel Fallon and Graham J McShane

Abstract
Cost-efficient strategies for protecting structural elements against the effects of explosive detonations are of interest for vulnerable infrastructure. Dynamic loading due to both blast pressures and impact from fragments are of concern. This investigation focuses on the protection of concrete structural elements against impact damage. A recent experimental study by the authors demonstrated that an elastomer coating can provide a significant impact mitigating effect when applied to the impacted face of a concrete substrate. Preliminary numerical results have indicated that the elastomer serves to alter the details of damage initiation in the concrete, though there remains a limited understanding of the protective effects at play. In this work, a numerical investigation is performed to determine the mechanisms of impact damage initiation exhibited by a concrete circular cylinder of diameter, 100 mm and height, 100 mm when impacted by a 0.1 kg circular cylindrical (i.e. blunt) projectile, travelling at velocities in the range 5–150 m s\(^{-1}\). The influence of applying a 5 mm elastomer coating on these damage mechanisms is assessed. At the lowest impact velocities, the concrete remains undamaged, though the sub-surface stress state is influenced by the polymer coating. At higher impact velocities, two distinct damage initiation mechanisms are observed. Damage Mechanism 1 is characterised by immediate, severe concrete damage initiating under the indenter corner. Damage Mechanism 2 is characterised by more diffuse, sub-surface damage. Adding a polymer coating serves to shift damage initiation from Damage Mechanism 1–2, delaying the onset of severe concrete damage. Simplified 1D and 2D numerical models are employed to interrogate how the elastomer achieves this effect. Two protective effects are identified: (i) a temporal effect causing a reduction in the magnitude of peak acceleration and an increase in contact duration between projectile and target and (ii) a spatial effect where the stress concentration under the indenter corner is removed.

Keywords
Impact, concrete, elastomer, coating, damage, mechanisms

Introduction
Recent research has highlighted the protective benefits offered by an elastomer coating as a retrofit solution, applied to structural elements. Its low cost and possibility of convenient spray application has gained the attention of industry and researchers seeking a solution for blast and impact mitigation in the built environment.

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Early experimental work studied polymer coatings applied to masonry block wall structures to establish their blast mitigating capabilities. Encouraging results were reported based on the polymer’s ability to hold together the failed masonry block components, causing a significant reduction in fragmentation debris (Davidson et al., 2004; Knox et al., 2000). Despite the potential demonstrated, only a very limited number of studies have extended consideration to the retrofit of concrete and reinforced concrete (RC) structures. Concrete represents a significant proportion of the ageing infrastructure in today’s built environment and thus appears an ideal candidate to benefit from this type of retrofit solution. Recent work focusing on the blast response of elastomer-coated concrete (Fallon and McShane, 2019a, 2021; Raman et al., 2012) has suggested that the coating is most effective in high intensity blast regimes, when the concrete has already been severely damaged.

Studies specifically investigating the impact mitigating capabilities of an elastomer coating are mostly limited to elastomer-metallic bilayer and laminate plates subjected to projectile impacts (Amini et al., 2010a, 2010b; Mohotti et al., 2013, 2015; Roland et al., 2010, 2013; Xue et al., 2010). While encouraging results are reported, the key protective mechanisms at play appear to be a complex picture, dependent on the details of the projectile, substrate and polymer coating. In some cases, it has been suggested that an elastomer layer positioned on the impacted face gives rise to significant energy dissipation via an impact-induced glass transition (Roland et al., 2010, 2013) while in other cases it is argued that it predominantly serves to stabilise the onset of necking in the metal (Xue and Hutchinson, 2007, 2008). In other cases, it has been postulated that the elastomer layer effectively changes the nose shape of the indenter, thereby changing the deformation mode in the metal (Mohagheghian et al., 2016, 2017). In most cases, the focus has been on a ductile (metallic) substrate.

A recent experimental investigation (Fallon and McShane, 2019b) has focused attention on the impact mitigating capabilities of an elastomer coating applied to a quasi-brittle concrete substrate. This substrate will have a very different stress state sensitivity of deformation and damage compared to a metallic target. A 5 mm elastomer layer, placed on a 100 mm side length concrete cube was subjected to impacts from a 0.1 kg, blunt, steel projectile and it was concluded that the elastomer provides a significant protective benefit over the range of impact velocities tested: c.45–150 m s⁻¹. Finite element (FE) analysis was used to interrogate the mechanisms behind the protective benefit offered by the coating. The model was validated at early time steps, before severe concrete damage and during the loading phase of elastomer penetration. Results indicated that the elastomer served to reduce projectile decelerations (and thus contact pressures), thereby influencing the stress state and time evolution of damage initiation in the concrete substrate. However, only a limited number of impact cases were analysed in that investigation, which focused on comparison with the experimental measurements. Further analysis is required to better understand the details of the protective effects at play, and their dependence on key coating and impact parameters.

The present study employs finite element analysis using the commercial code ABAQUS/Explicit (ABAQUS, 2011) to axisymmetrically model the impact indentation of concrete cylinders of diameter, 100 mm and height, 100 mm in two configurations – uncoated and coated with a 5 mm elastomer layer on the impacted face. Normal impact only is considered, that is, with the projectile impacting the target at 90°. A range of impact velocities are considered (c.5–150 m s⁻¹) and the damage patterns exhibited by the concrete targets in each configuration are assessed. The objective is to identify the damage initiation mechanisms and to understand the elastomer influence on these mechanisms. The sensitivity to the concrete and polymer boundary conditions and coating thickness is then examined. Finally, the protective effects contributed by the elastomer are interrogated using simplified 1D and 2D models.
Impact indentation damage mechanisms

Numerical model development

Impact indentation of a concrete circular cylinder of diameter, 100 mm and height, 100 mm is simulated using an axisymmetric model in ABAQUS/Explicit (ABAQUS, 2011), illustrated in Figure 1. The concrete constitutive model is chosen as the same Concrete Damaged Plasticity (CDP) model as described in Fallon and McShane (2019b) which was chosen to match the uniaxial compressive response of cast concrete targets. These are designed to have a target mean compressive strength at 28 days of, $\sigma_{cu} = 47$ MPa. The CDP model considers the concrete as a solid continuum which exhibits damaged elasticity and pressure-dependent plasticity. Damage is prescribed in terms of compressive and tensile damage parameters, $d_c$ and $d_t$ which quantify the degradation in the elastic stiffness. These parameters can take values between 0 (undamaged material) and 1 (fully damaged material). While we opt to omit concrete strain rate dependence given the lack of published data, as discussed subsequently, the model is validated at higher strain rates by comparison with experimental results (Fallon and McShane, 2019b). It is thus deemed an adequate tool for
studying the fundamentals of concrete damage mechanisms and the influence of an elastomer coating. The concrete is modelled as a deformable part and meshed with 0.5 mm, 4-node, axisymmetric (CAX4R) elements across the central 40 mm portion of the target. For computational efficiency, this transitions to a much coarser, 5 mm mesh at the edges, well away from the impact site. An ALE adaptive mesh domain is assigned to the concrete in the region below the indenter to help ensure a good quality mesh throughout the indentation simulation.

A 0.1 kg, circular cylindrical (i.e. blunt) projectile of radius, 14.25 mm is modelled as a rigid part and is assigned an initial velocity, $V_0$. Note that the experiments reported in Fallon and McShane (2019b) indicate that for steel projectiles, no significant deformation of the projectile occurs during impact at the range of velocities and projectile masses considered here. Therefore, a rigid projectile is assumed throughout. In order to prevent severe stress concentrations associated with the sharp corner of a true cylinder, the indenter is modelled with a small corner radius of 1.5 mm, ensuring that three elements span the corner. The mesh size and corner radius were chosen after a detailed mesh sensitivity study, the details of which are described in Fallon and McShane (2019b). Frictionless contact is assumed between concrete/steel material interfaces, which provides the best match to experimental results (Fallon and McShane, 2019b).

For the coated cases, a 5 mm thick elastomer layer is modelled as an axisymmetric, deformable part and assigned a constitutive model based on a series of material characterisation tests performed on a sample of a commercially available spray-on, polyurea/polyurethane coating, described in detail in Fallon and McShane (2019a). A hyperelastic relationship is selected, based on best fit to the uniaxial tensile response up to a nominal strain, $\epsilon = 1$, using data measured at a nominal strain rate, $\dot{\epsilon} = 10^{-3}$ s$^{-1}$. The Yeoh strain energy potential is selected as it is deemed to provide the best fit to experimental measurements. Strain rate dependence is accounted for through a viscoelastic model based on a Prony series for similar materials, obtained from the literature (Table 3.4 in Mauchien (2013)). The elastomer is assumed to be almost incompressible, with a Poisson’s ratio, $\nu = 0.475$ (note that a finite bulk modulus is required, for numerical purposes). The polymer has a density of 1.1 Mg m$^{-3}$. The finite element mesh size, element type and remeshing strategy is chosen to match the concrete. Frictional contact (with a coefficient of friction, $\mu = 0.8$ (Serway and Jewett, 2004)) is specified between concrete/elastomer interfaces, based on best fit to quasi-static experimental data (Fallon and McShane, 2019b). The concrete target is supported on its non-impacted face (displacement is constrained in the direction of impact) and the outer edges of the concrete and polymer are free.

To assess the model’s validity at higher strain rates, the numerical predictions were compared in Fallon and McShane (2019b) with impact indentation experiments performed using 0.1 kg, blunt steel projectiles of radius, 14.25 mm, launched by means of a gas gun at concrete targets (cubes of side length 100 mm). Tests were performed on both uncoated concrete and concrete with a 5 mm elastomer layer placed on the impacted face. The numerical model validation was performed by comparison with projectile velocity-time profiles measured from high-speed video and post-impact visualisation of damage for projectile impact velocities up to $\sim$100 m s$^{-1}$. Good agreement was observed for the loading response of the curve, up to maximum projectile penetration for both uncoated and coated concrete targets. For uncoated concrete, projectile rebound velocities were also well predicted. It was deemed that the model was valid at early time steps, before severe concrete damage and during the loading phase of elastomer penetration. Further details can be found in Fallon and McShane (2019b).

**Damage mechanisms: Reference geometry**

Considering the range of impact velocities, $V_0 = 5 - 150$ m s$^{-1}$, the damage development is assessed by examining the contours of the compressive damage parameter, $d_c$. Figures 2 and 3 present the results for the uncoated and coated cases, respectively.
On each of the images presented in Figures 2 and 3, the value of normalised displacement, $u$, is labelled. This corresponds to the time at which the image is taken. Normalised displacement, $u$, is defined according to Eq. 1, where $u$ is the displacement of the indenter, $H$ is the height of the concrete block ($H = 100$ mm) and $\epsilon_{cu}$ is the strain at the maximum compressive strength of the concrete ($\epsilon_{cu} = 0.005$ according to the uniaxial, quasi-static compression test performed in Fallon and McShane (2019b)).

$$\bar{u} = \frac{u}{\epsilon_{cu} H}$$  \hspace{1cm} (1)

Damage patterns are compared at two phases of the impact response, denoted early damage and developed damage, each defined, on the basis of visual inspection, by a specific $\bar{u}$. The early damage images are taken at a time corresponding to $\bar{u} = 1$ for the uncoated cases and $\bar{u} = 6$ for the coated cases. The time for developed damage is defined to correspond to $\bar{u} = 4$ and $\bar{u} = 9$ for uncoated and coated cases, respectively. For all cases in which the projectile fails to reach this prescribed $\bar{u}$, the image presented corresponds instead to $\bar{u}_{max} = u_{max} / \epsilon_{cu} H$ where $u_{max}$ is the maximum penetration depth of the projectile.

Comparison between Figures 2 and 3 reveals a difference in the early damage behaviour between uncoated and coated targets. This prompts the definition of two distinct damage mechanisms:

- **Mechanism 1**: Severe damage initiates early in the impact, under the corner of the indenter.
- **Mechanism 2**: Diffuse sub-surface damage develops in the region below the indenter, which eventually concentrates under the corner of the indenter.

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| $V_0$      | 5 m s$^{-1}$ | 20 m s$^{-1}$ | 50 m s$^{-1}$ | 100 m s$^{-1}$ | 150 m s$^{-1}$ |
|------------|--------------|---------------|---------------|----------------|----------------|
| Early damage | ![Image](image1) | ![Image](image2) | ![Image](image3) | ![Image](image4) | ![Image](image5) |
| Developed damage | ![Image](image6) | ![Image](image7) | ![Image](image8) | ![Image](image9) | ![Image](image10) |

$\bar{d}_c : \square = 1 \quad \square = 0.8 \quad \square = 0.5 \quad \square = 0.1 \quad \square = 0$

**Figure 2.** Comparing contours of the compressive damage parameter, $d_c$, for uncoated concrete, subjected to projectile impacts at various velocities, $V_0$. 

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For the uncoated targets, Mechanism 1 is observed for all but the very lowest impact velocities ($V_o = 5\text{ m s}^{-1}$), where no damage is observed. The application of a 5 mm elastomer layer serves two effects: (i) the impact speed at which damage first occurs is increased, and (ii) the damage patterns shift to Mechanism 2. At high impact velocities ($V_o \geq 100\text{ m s}^{-1}$), for the uncoated cases, the damage pattern develops to a cone of damaged material directly below the indenter. For the coated cases, there is a more diffuse distribution of concrete damage, although the location of greatest damage is again under the corner of the indenter. The damage again develops to form a cone under the indenter as the impact speed is increased. However, the coating serves to increase both the time and the impact velocity required for this to develop. These findings are consistent with the experimental observations in Fallon and McShane (2019b). The underlying causes of this protective effect provided by the polymer coating are interrogated in more detail subsequently.

**Sensitivity to boundary conditions**

In this section, the influence of the concrete and polymer boundary conditions, and the polymer thickness, on the damage mechanisms are examined.

**Edge constraint.** First the effect of constraining the outer edges of the concrete cylinder is considered. The axisymmetric model illustrated in Figure 1 (the reference case) is subjected to an additional boundary condition on the outer edges to constrain the lateral displacement of the elastomer and concrete. The early and developed damage patterns are compared with the reference case in Figure 14, for one projectile velocity, $V_o = 100\text{ m s}^{-1}$. This comparison illustrates that the additional edge constraint has no effect on the damage mechanisms or the mitigating effect of the elastomer suggesting these effects are dominated by phenomena local to the impact site.
Next, the effect of a change in target geometry is assessed. A more practical structural concrete slab configuration is considered: 50 mm deep, with a span of 1 m. Once more, an axisymmetric model is employed for computational efficiency, illustrated in Figure 4. The edge of the slab (at its outer perimeter) is fully constrained, with all degrees of freedom set to zero. To avoid unrealistic stress concentrations at the perimeter, a degree of boundary compliance is introduced: a 50 mm wide region at the edge of the slab is placed between rigid, frictionless surfaces, which terminate with a radius of curvature of 90 mm. For the coated cases, a 5 mm elastomer layer is modelled on the impacted face and Coulomb friction, with a friction coefficient of $\mu = 0.8$ is assumed at the concrete/elastomer interface. Frictionless conditions are assumed at elastomer/steel and concrete/steel interfaces based on the findings in Fallon and McShane (2019b). The indenter geometry and mesh details remain unchanged, with a fine 0.5 mm mesh in the central 40 mm portion of the slab, transitioning to a much coarser mesh away from the impact site.

Figure 5 compares the early and developed damage patterns for the reference geometry (Figure 1) and the slab (Figure 4) for a projectile impact at $V_0 = 100 \text{ m s}^{-1}$. There is no significant difference between the damage patterns for the cylinder and the slab, for these timescales. This indicates that damage initiation in a cylindrical target is fully representative of that in a slab of practical dimensions, that is free to bend. Once more, this suggests that the damage mechanisms are dictated by phenomena local to the indentation site.

**Elastomer-concrete bond strength.** To explore the influence of contact conditions at the elastomer/concrete interface, two limiting cases are compared – frictionless and perfectly bonded (tying all degrees of freedom at the interface). This is compared with the reference case, assuming Coulomb friction with a friction coefficient of $\mu = 0.8$ (determined in Fallon and McShane (2019b)) to give the best fit to quasi-static experimental data). The effect on the early and developed damage patterns is presented in Figure 6 for the reference geometry (Figure 1) subjected to a projectile impact at $V_0 = 100 \text{ m s}^{-1}$.

First, it is noted that the elastomer/concrete interface strength does not affect the damage initiation mechanism in the concrete: this remains Mechanism 2 for all coated cases. However, the interface does appear to have an influence on the level of developed damage in the concrete. While the perfectly bonded interface and $\mu = 0.8$ cases result in similar developed damage patterns, the frictionless case shows less damage. This would imply that reducing shear tractions at the interface is beneficial to reducing impact damage. A reduction in shear tractions at the interface may affect the distribution of stress triaxiality, to which concrete is particularly sensitive. This is investigated in more detail subsequently (Figure 10). However, it is noted that a frictionless interface would be challenging to realise in practice.

**Coating thickness.** Finally, the effect of varying the coating thickness on the damage mechanisms is considered. Figure 7 compares a 5 mm coating with a 10 mm coating, assuming a coefficient of
friction, $\mu = 0.8$ at the elastomer/concrete interface. It is clear that the thicker coating serves to delay the onset of damage in the concrete substrate. Minimal damage is observed for an impact velocity of 100 m s$^{-1}$ for a 10 mm thick coating. Therefore, as expected, a thicker coating appears to increase the protective benefit. However, from a design perspective, this added benefit must be weighed against the increase in weight and cost.

Investigating the protective effect of the coating

The previous section has highlighted that the application of a relatively thin elastomer layer to a concrete substrate affects the damage mechanisms in the underlying concrete, providing a significant protective benefit across a range of impact indentation velocities. In this section, the objective is to understand precisely how the elastomer achieves this effect.

Projectile acceleration and contact pressure

Considering first the reference geometry and boundary conditions, illustrated in Figure 1. The numerical model, defined previously, is used to interrogate the projectile acceleration-time histories for two different impact velocities and the results are presented in Figure 8.

For the low velocity impact case (Figure 8(a)), the concrete exhibits an elastic response and the shape of the acceleration-time profiles of both uncoated and coated cases are approximately sinusoidal. The peak acceleration recorded for the 5 mm coated case is significantly lower in magnitude than that for the uncoated case. Increasing the coating thickness to 10 mm reduces the peak
acceleration further. Additionally, the duration of contact is much longer with the coating present, with the duration increasing with coating thickness. There is therefore a fall in the average projectile accelerations with the addition of a coating. For the lower velocity case, average accelerations are measured up to the time when acceleration falls to zero ($t = 35 \mu s$ and $t = 195 \mu s$ for the uncoated and 5 mm coated cases, respectively). Table 1 compares peak and average accelerations for the uncoated and 5 mm coated cases.

Next, the higher velocity impact case in Figure 8(b) is examined. For the uncoated case, there is an initial transient on impact, giving a high peak acceleration. Comparing to Figure 8(a) (and subsequently Figure 12(a)) it is interesting to note how the shape differs, and appears to be related to both projectile impact speed and projectile corner radius, with a low impact velocity and small projectile corner radius, smoothing the sharp peak of the initial transient in acceleration upon impact. In Figure 8(b), the sharp peak is followed by a slower rise in acceleration as the projectile indents the concrete. The acceleration then tails off, as plastic deformation and damage develops in the concrete. For the 5 mm coated case, damage initiation in the concrete is also predicted, and is evident in a drop in acceleration at around $50 \mu s$. The coating serves to reduce the magnitude of the initial transient peak in acceleration, delaying the time at which damage develops (indicated by the drop in acceleration), and to increase the duration of interaction between projectile and target. These effects are denoted collectively as the temporal effect contributed by the elastomer.

|       | Frictionless | $\mu = 0.8$ | Perfectly bonded |
|-------|--------------|--------------|-----------------|
| Early damage | ![Diagram](image1) | ![Diagram](image2) | ![Diagram](image3) |
| Developed damage | ![Diagram](image4) | ![Diagram](image5) | ![Diagram](image6) |

$\bar{a} = 6$

$\bar{a} = 6$

$\bar{a} = 6$

$\bar{a} = 9$

$\bar{a} = 9$

$\bar{a} = 9$

$\bar{a} = 9$

$\bar{a} = 9$

$\bar{a} = 9$

$d_c$ values: $\blacksquare = 0.3$, $\blacksquare = 0.25$, $\blacksquare = 0.15$, $\blacksquare = 0.05$, $\blacksquare = 0$

$d_c$ values: $\blacksquare = 1$, $\blacksquare = 0.8$, $\blacksquare = 0.5$, $\blacksquare = 0.1$, $\blacksquare = 0$

**Figure 6.** Comparing contours of the compressive damage parameter, $d_c$ for the reference geometry (Figure 1) when subjected to a projectile impact at $V_0 = 100 \text{ m s}^{-1}$. Three cases are considered for the contact condition at the elastomer/concrete interface: frictionless, friction coefficient of $\mu = 0.8$ and perfectly bonded.
Table 1 shows that while peak accelerations for the higher impact velocity case are significantly reduced with the addition of the coating, average accelerations are not. This is in contrast to what was observed for the lower impact velocity case and is likely due to the severe concrete damage experienced after the initial transient peak in acceleration. Average accelerations are measured up to the time when acceleration falls to zero ($t = 400 \mu s$ and $t = 300 \mu s$ for the uncoated and 5 mm coated cases, respectively). However, as discussed in Fallon and McShane (2019b), the FE model is only deemed valid at time steps before the concrete becomes severely damaged. An extra column is added to Table 1, tabulating average accelerations, measured up to the time step when severe concrete damage initiates (examining the FE simulations, this time corresponds to the first sharp drop in acceleration-time, at $t = 1 \mu s$ for the uncoated case and $t = 50 \mu s$ for the 5 mm coated case). These average accelerations are significantly reduced with the addition of the coating in the higher impact velocity case. Since no damage is observed for the lower velocity impact case, the average accelerations are unchanged.

Next, the spatial contact pressure variation is interrogated in Figure 9. For both low and high impact velocity cases, the magnitude of the contact stresses experienced by the concrete are significantly reduced with the coating present. This is due to the significant reduction in peak accelerations discussed previously. However, another coating benefit is also identified. Examining the lower velocity impact case in Figure 9(a), the addition of the coating results in a much more uniform distribution of contact pressure under the indenter. When uncoated, there is a concentration in contact pressure

| Uncoated | 5 mm coated | 10 mm coated |
|----------|-------------|--------------|
| Early damage | | |
| Developed damage | | |
| $d_{c,\text{uncoated}}$ | | |
| $d_{c,\text{coated early}}$ | | |
| $d_{c,\text{coated developed}}$ | | |

Figure 7. Comparing contours of the compressive damage parameter, $d_c$ for the reference geometry (Figure 1) when subjected to a projectile impact at $V_0 = 100 \text{ m s}^{-1}$. Three cases are considered: Uncoated, coated with a 5 mm elastomer layer and coated with a 10 mm elastomer layer. A coefficient of friction, $\mu = 0.8$ is assumed between the elastomer/concrete interface.

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Figure 8. Projectile acceleration - time histories for the reference geometry (Figure 1) subjected to projectile impacts at: (a) $V_0 = 5 \text{ms}^{-1}$, and (b) $V_0 = 100 \text{ms}^{-1}$.

Three configurations are considered at each velocity: Uncoated, coated with a 5 mm elastomer layer and coated with a 10 mm elastomer layer.

Table 1. Peak and average accelerations measured from the plots in Figure 8.

| $V_0$ (m s$^{-1}$) | Peak acceleration ($\times 10^6 \text{m s}^{-2}$) | Average acceleration ($\times 10^6 \text{m s}^{-2}$) | Average acceleration$^{\dagger}$ ($\times 10^6 \text{m s}^{-2}$) |
|------------------|---------------------------------|---------------------------------|---------------------------------|
|                  | Uncoated | 5 mm coated | Uncoated | 5 mm coated | Uncoated | 5 mm coated |
| 5                | 0.3      | 0.07        | 0.2      | 0.04        | 0.2      | 0.04        |
| 100              | 4.8      | 1.7         | 0.3      | 0.4         | 4        | 0.97        |

$^{\dagger}$Denotes average accelerations measured up to the point of severe concrete damage only (defined in the main text).
under the indenter corner. With the coating in place however, the magnitude of the contact pressure remains spatially more uniform. Similar effects are observed for the higher impact velocity case in Figure 9(b).

Furthermore, Figure 10 provides evidence that the coating also serves to change the sub-surface stress state. The stress triaxiality is more uniformly distributed in the coated case. However, the magnitude of the compressive stress triaxialities (plotted negative in Figure 10) also tends to reduce for the coated case. This may be of concern, as the strength of the concrete is sensitive to the stress state, and increases with the magnitude of the compressive stress triaxiality. However, the triaxiality is similar in the coated and uncoated cases at the critical locations of maximum contact pressure. And so, reducing the magnitude of the contact pressures with the coating offers a net benefit for delaying damage...
initiation. Also, the more uniform distribution of stress triaxiality observed for coated concrete (Figure 10(b)) may account for the more uniform distribution of sub-surface damage that characterises the early damage response of coated concrete (illustrated in Figure 3 and defined as Mechanism 2.) These effects are denoted collectively as the \textit{spatial effect} contributed by the elastomer.

\textbf{Interrogation of the protective effects}

In this section, simplified 1D and 2D models are used to understand to what extent the protective effects described above rely on indentation, that is, to what extent they are 2D, rather than 1D, phenomena. This provides insights that may help the future development of simplified models to capture these effects and support coating design.

\textit{1D model}. Figure 11(a) and (b) illustrate simplified models giving a 1D representation of the projectile impact on uncoated and coated targets. Thus, any 2D indentation phenomena are eliminated from the analysis.

A linear elastic model is chosen for the concrete target in this simplified analysis, with a Young’s Modulus, $E_0 = 28.3$ GPa and a Poisson’s ratio, $\nu = 0.2$. The concrete column is also made long enough to avoid internal reflections, so that the target can be assumed effectively semi-infinite. The elastomer model remains unchanged from that described previously. The boundary conditions on the column are as illustrated in Figure 11(a) and (b). The flat-faced projectile is again modelled as a rigid body. The projectile acceleration-time histories obtained using these 1D models are presented in Figure 12.

It is observed that the addition of the elastomer coating in a purely 1D analysis replicates the \textit{temporal effect} observed for the impact on the concrete targets in Figure 8. The presence of the coating reduces the magnitude of the peak accelerations (and hence contact pressures). Furthermore, the coating serves to increase the duration of the response. Thus, it is established that 2D indentation effects are not required to reproduce the \textit{temporal effect} of the coating – a 1D analysis is sufficient.
Figure 11. Axisymmetric models used to interrogate the protective effects: (a) 1D model, uncoated, (b) 1D model, coated, and (c) 2D model, coated, indenter radius, $R_c$. In all cases, the concrete column is made long enough to prevent interference from wave reflections. Not to scale.
In a 1D analysis, no spatial effect can be predicted – the contact pressure must be spatially uniform. However, the contact pressures (and thus sub-surface stresses) for the coated case are significantly reduced in the 1D calculations, confirming the protective benefit of the temporal effect. For projectile impact at 5 m s\(^{-1}\), the peak contact pressure recorded is 44 MPa for the uncoated case compared with 10 MPa for the 5 mm coated case, each recorded at the time corresponding to peak projectile acceleration, \(t = 0.9 \mu s\) for uncoated and \(t = 76 \mu s\) for coated.

2D model. The spatial effect observed for the concrete targets, involving radial variations in contact pressure, is necessarily a 2D phenomenon, and hence likely to be linked to target indentation effects. A simplified 2D model is now used to interrogate the transition from the 1D case to the indentation of an effectively semi-infinite half space, to see at what point the spatial effect becomes apparent. The same target properties described in the previous section are used, but now a 2D
axisymmetric calculation is performed with a variable target radius, $w$ (Figure 11(c)). Simulations for increasing values of $w$ show that the spatial effect may be reproduced once the concrete domain width, $w$ becomes even slightly larger than the indenter radius, $R_i$ (i.e. for $w/R_i \approx 1.1$).

Indentation of the polymer is therefore key to delivering the spatial effect. Next, we consider whether this effect is equivalent to changing the projectile tip geometry. It was shown by Mohagheghian et al. (2016) that for thin metallic targets, the spatial effect induced by a polymer coating was key to the protective benefit, and could therefore be reproduced to a large extent by altering the projectile tip geometry. To investigate this for the current problem, a number of variations on the model presented in Figure 11(c) are considered. A large concrete domain width is selected ($w/R_i = 3$), a 5 mm coating is included and the indenter corner radius is reset to its initial value, $R_c = 1.5$ mm (all as defined previously). The acceleration-time history and contact pressure spatial variation are compared with uncoated cases, impacted by projectiles of increasing corner radius: $R_c = 1.5$ mm, $R_c = 3$ mm and $R_c = 14.25$ mm (i.e. hemispherical). The results are presented in Figure 13.

First, the spatial variation in contact pressure is examined in Figure 13(b). Doubling the corner radius to $R_c = 3$ mm has a negligible influence on the magnitude of the contact pressures recorded. The spatial variation in contact pressure is also unchanged and it is clear that considering impact from an indenter with a larger corner radius does not produce a similar spatial effect to that observed for the coated case. Impact from a hemispherical projectile produces a very different response compared with the other cases. There is a sharp stress concentration at the punch tip, reaching much higher pressures than those recorded for the other cases. This rapidly reduces to zero a short distance away from the impact site. Once more, this response is very different to the spatial effect identified for the coated case. These results suggest that the redistribution of contact stresses provided by the coating are not equivalent to a projectile nose-shape change, for this target configuration.

Next, considering the acceleration-time histories in Figure 13(a), doubling the corner radius to $R_c = 3$ mm for an uncoated target has an almost negligible effect on the peak acceleration and pulse duration. Considering impact from a hemispherical projectile ($R_c = 14.25$ mm) on uncoated concrete, the peak accelerations are reduced and the pulse duration is lengthened. Thus, the projectile nose-shape change can provide a temporal effect, but this is much less pronounced than that provided by the polymer coating.

In summary, it has been shown that indentation of an elastomer coating is required to achieve both the protective temporal and spatial effects. The temporal effect is essentially a 1D phenomenon where the key consequence is to reduce peak accelerations and thus contact pressures. The spatial effect is observed when there is indentation of the target (even when the concrete domain size is relatively small with respect to the indenter i.e. $w/R_i > 1.1$). Furthermore, the spatial effect contributed by the elastomer is not equivalent to impact from a projectile with a more rounded tip geometry. Instead, the elastomer coating is required to reduce the stress concentrations under the indenter.

**Conclusion**

A numerical study is performed in ABAQUS/Explicit to interrogate the impact indentation of a concrete cylinder of diameter, 100 mm and height, 100 mm in two configurations: uncoated and coated with a 5 mm elastomer layer on the impacted face. The concrete damage mechanisms are identified and the elastomer’s influence is assessed. The following conclusions are established:

- Two distinct damage initiation mechanisms are observed. Mechanism 1 is characterised by severe concrete damage, initiating over shorter timescales under the indenter corner. Mechanism 2 is characterised by more diffuse, sub-surface concrete damage which develops over longer timescales, before eventually concentrating under the indenter corner.
For all but the very lowest impact velocities, where no damage is observed, uncoated targets exhibit Mechanism 1 and coated targets exhibit Mechanism 2. By shifting the damage mechanism, the coating achieves a significant increase in the projectile velocity required to cause severe damage. Increasing the coating thickness provides an increased protective benefit.

A frictionless interface between the concrete and elastomer appears to provide a protective benefit. However, this would be difficult to achieve in practice.

The elastomer achieves its protective benefit via two mechanisms – a temporal effect (a reduction in the magnitude of the peak acceleration and an increase in the duration of contact between projectile and target) and a spatial effect (a more uniform contact pressure.

**Figure 13.** (a) Projectile acceleration - time history and (b) spatial contact pressure variation for a projectile impact at $V_0 = 5 \text{ m s}^{-1}$.

Four variations on the model illustrated in Figure 11(c) are considered: coated with 5 mm elastomer and $R_c = 1.5 \text{ mm}$, uncoated and $R_c = 1.5 \text{ mm}$, uncoated and $R_c = 3 \text{ mm}$ and uncoated and $R_c = 14.25 \text{ mm}$. Contact pressure outputs are taken at a step time corresponding to the peak projectile acceleration in each case (for coated and $R_c = 1.5 \text{ mm}$: $t = 78 \mu \text{s}$; uncoated and $R_c = 1.5 \text{ mm}$: $t = 12.5 \mu \text{s}$; uncoated and $R_c = 3 \text{ mm}$: $t = 14 \mu \text{s}$, uncoated and $R_c = 14.25 \text{ mm}$: $t = 63 \mu \text{s}$).
distribution is achieved, removing the stress concentration under the indenter corner and providing a more uniform state of stress triaxiality under the indenter).

- To achieve both temporal and spatial effects, the indentation of an elastomer coating is required. The temporal effect is essentially a 1D phenomenon but the spatial effect is only observed when there is indentation, that is, once the concrete domain width is larger than the projectile radius ($w/R_i > 1.1$). Furthermore, the spatial effect cannot be reproduced by a projectile with a more rounded tip geometry.

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**Appendix**

**Sensitivity to boundary conditions**

**Edge constraint.** Figure 14 compares the early and developed damage contours for the reference geometry case (Figure 1) with the addition of an edge constraint, constraining the lateral displacement of the outer edges of the elastomer and concrete.

| Damage | Reference Case | Edge constraint |
|--------|----------------|-----------------|
|        | Early          | Developed       | Early          | Developed       |
| Uncoated | ![Early](image1) ![Developed](image2) | ![Early](image3) ![Developed](image4) | ![Early](image5) ![Developed](image6) |
| Coated   | ![Early](image7) ![Developed](image8) | ![Early](image9) ![Developed](image10) | ![Early](image11) ![Developed](image12) |

\[ d_c : \text{■} = 1 \quad \text{■} = 0.8 \quad \text{■} = 0.5 \quad \text{■} = 0.1 \quad \text{■} = 0 \]

\[ d_{c,\text{coated early}} : \text{■} = 0.3 \quad \text{■} = 0.25 \quad \text{■} = 0.15 \quad \text{■} = 0.05 \quad \text{■} = 0 \]

\[ d_{c,\text{coated developed}} : \text{■} = 1 \quad \text{■} = 0.8 \quad \text{■} = 0.5 \quad \text{■} = 0.1 \quad \text{■} = 0 \]

**Figure 14.** Comparing contours of the compressive damage parameter, \( d_c \), for the reference geometry case (Figure 1) and that with an additional edge constraint. A projectile impact at \( V_0 = 100 \text{ m s}^{-1} \) is considered.

There is no significant effect of the additional edge constraint in terms of concrete damage initiation. Furthermore, the influence of the coating is unchanged – it serves to shift the concrete damage initiation mechanism from Mechanism 1 to Mechanism 2.