Split Hopkinson bar tests on metaconcrete: modeling and numerical simulations

Deborah Briccola^{1,*} and Ezio Cadoni¹

¹DynaMat SUPSI Laboratory, University of Applied Sciences and Arts of Southern Switzerland, Via Francesco Catenazzi 23, 6850 Mendrisio, Switzerland.

Abstract. The work deals with the dynamic characterization of metaconcrete, a mechanical metamaterial with locally resonant inclusions and unconventional dynamic performance. Metaconcrete can be defined as an unusual concrete in which standard aggregates are partially replaced by engineered ones made of a rigid heavy core covered by a compliant layer. From a mechanical point of view, its mitigation properties are associated to the mechanical energy trapped by the inclusions when acted upon by an elastic pulse with a frequency content close to their own resonant frequencies. So far, a discrete number of experimental investigations have been performed but none of these consider the impulsive nature of blast and impact loadings and the direction of the incoming wave with respect to the inclusion orientation in case of a brittle matrix. The results of numerical simulations considering different configurations of engineered inclusions within a single metaconcrete unit are compared in terms of stress level attained as well as internal and kinetic energy involved. Metaconcrete can bring about disruptive applications in several fields of applied sciences, but for the technology to become firmly established a synergism between computational and experimental approaches is paramount.

1 Introduction

Metaconcrete can be defined as a new type of concrete in which traditional aggregates are partially replaced by engineered ones made of heavy spherical cores covered by a compliant outer layer [1]. This promising material has been designed for use in blast shielding, impact protection, and seismic mitigation as it shows unconventional dynamic performance with respect to standard concrete. When acted upon by elastic pulses, if properly designed, metaconcrete exhibits frequency bandgaps close to the inclusion eigenfrequencies. This macroscale behaviour stems from the microscale attitude of the inclusions to trap mechanical energy by starting to displace and deform according to their eigenmodes. Different frequencies can be targeted and thus filtered out from the matrix by properly tuning the geometrical and mechanical parameters of the aggregate: as a result, the vulnerability of standard concrete to damage due to a propagating shock wave is greatly reduced [2, 3]. So far, a discrete number of experimental investigations have been performed to evaluate the attenuation properties of metaconcrete within the sonic and ultrasonic range [4–7], but none of these studies consider the impulsive nature of blast and impact loading. Despite plate impact experiments have been

*e-mail: deborah.briccola@supsi.ch

Figure 1. Traditional (a) and engineered inclusions (b); a finite element model of a single metaconcrete resonant unit (c) is used to study metaconcrete microscale dynamic behaviour.

performed to study the attenuation properties of a phantom made by an epoxy matrix with embedded resonant inclusions [9], experimental campaigns on locally resonant metamaterials with brittle matrix considering soft or hard impact have not been performed yet. The theme of wave propagation in metaconcrete has to be addressed carefully: different design parameters affect the frequency bandgap region [8] and can lead to different mesoscale dynamic behaviour. This work deals with the response of a single metaconcrete unit subjected to soft/hard impact considering different aggregate configurations. The results are compared in terms of stress level attained as well as internal and kinetic energy involved. Testing issues associated to the inherent constituents of metaconcrete are outlined and critically discussed to set the basis for a proper experimental campaign.

2 Modeling single metaconcrete units

To investigate the dynamic behaviour of metaconcrete under different loading rates and to outline some challenges in its testing by means of Split Hopkinson Bar we conduct a numerical study on single metaconcrete units. The design and configuration of metaconcrete aggregates are established first, then their eigenfrequencies are computed by means of analytical formulations and finite element models. Finally, the potential effectiveness of engineered aggregates to trap mechanical energy in case of soft/hard impact is established by means of numerical simulations of Split Hopkinson Bar tests.

2.1 Metaconcrete aggregates and their properties

Metaconcrete inclusions are designed to show inner resonances and replace traditional coarse gravel and stone aggregates with a maximum size of 10-32 mm. A 20 mm spherical aggregate which consists of a steel core coated by a 5 mm thick compliant outer layer has been chosen for current numerical investigations. Table 1 lists the mechanical properties of the matrix, core and coating materials used within the simulations. Different coatings have been chosen to study their influence on the dynamic behaviour of metaconcrete at soft and hard impact strain rate.

Table 1. Material parameters.

Material	ρ [kg/m ³]	E [GPa]	ν [-]
Mortar	2,370	31.00	0.20
Steel	7,800	210.00	0.30
Silicone rubber	550	6.1e-4	0.48
Natural rubber	900	0.0100	0.48
Low density polyethylene (LDPE)	1,100	0.100	0.45
Urea Formaldehyde (UF)	1,500	10.00	0.40

2.2 Metaconcrete aggregate eigenfrequencies and eigenmodes

It has been demonstrated that the selection of proper materials, i.e. mass densities and elastic coefficients, leads to different macroscopic behaviour under dynamic excitations [10]. This means that by tuning the geometrical and mechanical properties of engineered aggregates, these composite inclusions can act as spring-mass systems able to trap the mechanical energy associated to wavelengths (L) greater than the length of the reference volume under consideration (l). If we assume an elastic isotropic behaviour for the aggregate materials, some scaling parameters can be introduced to verify whether inner resonances must be expected:

$$\frac{(\lambda_{coating} + 2\mu_{coating})}{(\lambda_{matrix} + 2\mu_{matrix})} = O(\epsilon^2)$$
(1)

$$\frac{(\lambda_{coating} + 2\mu_{coating})}{(\lambda_{core} + 2\mu_{core})} = O(\epsilon^p), p \geq 1$$
(2)

$$\frac{\rho_{coating}}{\rho_{matrix}} = O(\epsilon^q), q \geq 1$$
(3)

$$\frac{\rho_{core}}{\rho_{matrix}} = O(1)$$
(4)

with $\epsilon = l/L$, where λ_i and μ_i are the Lamé elastic parameters and ρ_i the mass density of the i – th constituent [11]. Under longitudinal tension or compression waves which run over the matrix, only translational eigenmodes are of interest to evaluate the attenuation properties of metaconcrete: thus, in the following, attention is given to this eigenmode solely. Simplified models and closed form solutions can be derived to estimate the aggregate eigenfrequencies before resorting to finite element models.

2.2.1 One-dimensional model for resonant frequency

A simplified model to tune and design engineered aggregates to provide an estimate of the translational eigenfrequency based on an equivalent spring-mass system has been introduced in a previous research on metaconcrete [2]. This model provides adequate estimations when dealing with compressible and soft coating materials.

2.2.2 Closed form estimate for resonant frequency

As an alternative, for instance in case of nearly incompressible coating materials, the following analytical continuum approach can be considered and aggregate resonant frequencies can be obtained in a closed form, after solving the related boundary value elasticity problem [12]. The first rotational and translational eigenmodes can be estimated according to:

Table 2. Translational natural frequency [Hz] for each aggregate configuration computed using (a) one-dimensional spring-mass model, (b) closed form solution derived from a value elasticity problem, and (c) finite element models.

Coating Material	(a)	(b)	(c)
Silicone rubber	344.47	755.60	844.82
Natural rubber	1,295.88	3,061.84	3,218.45
Low density polyethylene (LDPE)	4,414,16	8,657.16	8,602.03
Urea Formaldehyde (UF)	44,141.64	76,940.55	58,451,31

$$f_0^{(r)} = f_0 \sqrt{\frac{15\gamma^5}{\gamma^3 - 1}} \tag{5}$$

$$f_0^{(p)} = f_0 \sqrt{18 \frac{(1 - \nu)(2 - 3\nu)\gamma^2}{(5 - 6\nu)(2 - 3\nu)\left(\frac{\gamma - 1}{\gamma}\right) - \frac{5}{4} \frac{(\gamma^2 - 1)^2}{\gamma^5 - 1}}} \tag{6}$$

with

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{\mu_{coating}}{\rho_{core} \cdot b^2}} \tag{7}$$

where $\gamma = b/a$ with b the outer of the aggregate, a the radius of the core, ν the Poisson’s ratio of the coating, $\mu_{coating}$ and ρ_{core} the Lamé elastic parameter of the coating and the density of the core, respectively. Successive eigenfrequencies can be roughly estimated as integer multiples of these fundamental frequencies, but for this purpose finite element analyses must be preferred.

2.2.3 Three-dimensional model for resonant frequency

A cubic metaconcrete unit containing a single aggregate has been considered and meshed with linear tetrahedral elements with a maximum size of 1 mm. Boundary conditions on displacements are assigned to the outer edges of the metaconcrete unit and eigenmodes are individuated.

2.2.4 Comparison among the eigenfrequency estimation methods

Results show that for nearly incompressible materials the aggregate translational eigenfrequency cannot be recovered by means of the simplified one-dimensional equivalent mass-spring system. Instead, the closed-form solution shown in section 2.2.2 has proved to be a reliable estimate to preliminary design and tuning metaconcrete aggregates whose material components satisfy the scaling parameters assumptions Eqn. (1–4). For material combinations which do not satisfy the above assumptions finite element models are necessary.

3 Finite element Split Hopkinson Bar tests

Metaconcrete has been conceived for use in blast and impact protection thus an experimental programme able to characterize its mechanical behaviour under severe loading conditions is envisaged. Strictly speaking, metaconcrete can be viewed as a composite material made of brittle (mortar), soft (coating) and ductile (core) constituents. As a result, the problems

Figure 2. Finite element model used for numerical investigations on metaconcrete (a), Original and scaled loading profile (see scaling factor s.f.) (b).

encountered during the mechanical characterization of these single materials are emphasized and overlapped when testing metaconcrete. As for traditional materials, the analysis of the transmitted pulse from a conventional experiment, i.e. by considering a rectangular incident pulse, provides useful information to achieve desired testing conditions (constant strain rate) by means of pulse shaping techniques. Moreover, since metaconcrete is a fully tailored material, the study of the influence of design parameters, i.e. geometrical and mechanical properties, on its mechanical response is paramount to understand its attenuation effectiveness upon severe loadings. Numerical simulations have been carried out considering a tension rectangular pulse generated by a Modified Split Hopkinson Bar [13–16]. The analysis of the results provides useful information on the energy absorption capability of metaconcrete and based on this response a more adequate incident pulse can be identified for future experiments.

3.1 Specimen configuration, Split Hopkinson Bar apparatus and dynamic loading

A cylindrical pre-notched specimen with a length-to-diameter ratio of 1:1 has been chosen in view of experimental testing instead of a dumbbell shaped specimen. The specific features of metaconcrete, i.e a 20 mm layered spherical inclusion embedded in a mortar matrix, do not allow for a small representative material volume element. The specimen diameter is the same as that of the incident and output bar to minimize stress concentrations at its edges. The reduced length of the specimen favours the onset of stress equilibrium: the stress state is built up by the wave reflections which occurs at the specimen-bar interface, at least in the first stage of the response. Aluminium bars are considered to minimize the wave impedance mismatch at the input bar-specimen interface to avoid complete reflection upon travelling of the elastic pulse. As it has already been mentioned, a conventional tensile rectangular pulse is applied to metaconcrete specimen. A loading profile similar to that used for tensile experiments on UHPFRCs [17, 18] has been adopted; scaled pulses have been applied to different metaconcrete configurations to preserve stress equilibrium over the test duration, see Figure 2.

3.2 Finite element models

To derive the transmitted pulse due to a conventional rectangular loading on metaconcrete, a finite element model has been set up and used to verify whether the configurations introduced in Table 1 lead to different mesoscale behaviour. To speed up numerical simulations, symmetry conditions are exploited, while to avoid multiple reflections at the bar-specimen interface, non-reflecting boundaries conditions have been applied at the bars edges. As it concerns the material models, a linear elastic behaviour complemented with an erosion condition associated to a maximum negative pressure has been adopted for the mortar matrix. An elastoplastic behaviour with kinematic hardening has been used instead for steel and coating components. For nearly incompressible continuum rubber, i.e. for natural and silicone rubber, a Blatz-Ko material model has been considered as well, for the sake of brevity these results are not included in the present paper.

4 Results

Input (red) and transmitted (green) pulses recorded on the input and output bar surfaces at 8 cm from the specimen edges are depicted in Figure 3 for standard concrete (a) and metaconcrete (b,c,d), respectively. The overlapping of sample stresses in standard concrete as well as in metaconcrete specimens for almost the entire duration of the test demonstrates that stress-equilibrium is achieved. The requirement of a constant strain rate over the duration of the test is not fulfilled as the reflected pulse is not constant, however soft to hard impact conditions are ensured throughout the experiments as indicated in [19, 20] upon evaluation of the strain rate. It appears immediately that the response of metaconcrete to dynamic loading is remarkably different from that of standard concrete and it depends strongly on the aggregate configurations considered.

5 Discussion

The mechanical response of metaconcrete upon soft and hard impact loadings depends on the coating material, as it is shown in Figure 3.

More in detail, natural rubber and low-density polyethylene aggregates trap mechanical energy as it is evident from the stress level oscillations at the end of the test. These oscillations damp out in case of low-density polyethylene coating. With reference to Figure 4 (natural rubber coating) some interesting considerations on the microscale behaviour of metaconcrete resonant unit can be figure out. In the first stage (blue region), the stress level grows with an almost linear trend until the onset of a crack within the mortar matrix which develops from the notch to the outer compliant layer. In this phase the material response is driven by the mortar matrix which is a brittle material that deforms in a nearly linear elastic manner until failure. In the second phase of the response (red region), the stress level grows again until the development of further failure within the mortar matrix. The stress level is built up by the reflections which occur at the outer compliant layer which acts as a reflecting boundary, however the growing rate is limited due to the wave impedance mismatch between matrix and coating. The growth in the stress level is driven by the progressive deformation experienced by the coating layer as the increase of internal energy associated to this material demonstrates. The coating behaves as a ductile material. At that point, the stress level recorded at the output bar begins to oscillate with a frequency which is very close to the eigenfrequencies declared in Table 2. This attitude demonstrates that specific engineered inclusions can trap mechanical energy when acted upon by an elastic loading pulse with a frequency content close to the eigenfrequencies. Moreover, depending on the severity of the damage within the matrix

Figure 3. Input (red) and output (green) pulses for: a) standard concrete; b) LDPE; c) silicone rubber; d) UF coatings.

the loading capability of the metaconcrete unit can be different from zero as the presence of a pulse in the input bar demonstrates. Stress equilibrium is always guaranteed over the duration of the test except when the dynamic response changes from one mechanism to the other. A small-time interval is required for the stress level to be considered homogenous. With respect to standard concrete, metaconcrete can achieve higher strains (area beneath the strain rate curve which is proportional to the reflected pulse) with no significant strength reduction and for this reason it seems particularly suitable for those civil engineering applications in which a post cracking residual strength and energy absorption capability are of interest. Other engineered inclusions do not show the three-phase response described above. More in detail, silicone rubber and urea formaldehyde are not activated by the elastic incoming wave frequency content. For this reason, they represent only a reflection interface with respect to wave propagation.

6 Conclusions

The concept of wave propagation within metaconcrete has been addressed for the first time in a comprehensive manner. Results of numerical simulations of a conventional Split Hopkinson Bar test provides useful information on the microscale behaviour of metaconcrete considering different configurations under soft and hard impact. These outcomes can help the planning and development of a sound experimental campaign. Due to the interplay between different materials, the strain-rate is not constant over the duration of a conventional test. To obtain families of stress-strain curves as a function of strain rate, a proper incoming wave must be defined. For instance, in the first phase of the test a linear rate of stress should be implemented, when the response starts to be driven by the coating layer a trapezoidal pulse would

Figure 4. Natural rubber aggregate (a) AS: input (red) and output (green) axial stress pulses (b) IE: internal energy (c) KE: kinetic energy. For internal and kinetic energy the colormap is the following: green and red are used for output and input bars respectively, yellow for the core, magenta for the coating, and blue and light blue for the concrete matrix.

be more adequate. A trade-off between these two requirements is auspicate. Additional care must be taken with respect to the manufacturing process: flat, plane, and parallel surfaces are paramount and proper grease should be applied to favour the onset of a uniaxial strain test considering also the bar-specimen Poisson moduli mismatch. Despite the challenges posed at an experimental level, metaconcrete is a promising material as it can be easily designed to filter out specific harmful frequencies, while ensuring greater ductility.

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