Effect of Hourglass Control on LS-DYNA® Concrete Constitutive Models in Low Velocity Impact Simulations

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1 Introduction

The performance of reinforced concrete structural components under impact loading has received significant attention over the past decade, with high fidelity numerical simulations supplementing the available experimental test data. Several studies have evaluated the prediction of impact force and displacement time histories, as well as cracking and spalling, using a number of constitutive models in LS-DYNA. Under-integrated hexahedral elements are typically used in these analyses with hourglass control introduced to suppress hourglass modes. Prior studies have demonstrated that finite element analysis of reinforced concrete beams to impact loading is sensitive to the hourglass coefficient, however several studies have limited their basis of selection of appropriate hourglass coefficients to relative hourglass energy and comparison of model predictions with experimental measurements of displacement and force time histories. Furthermore, studies contrasting the performance of different constitutive models have routinely used a single hourglass coefficient for all models [1, 2]. This may be problematic if individual constitutive models demonstrate unique sensitivity to the hourglass control.

To provide detailed insight into the effect of hourglass control type and coefficient on the simulated response of reinforced concrete to low velocity impacts, a numerical study was conducted using experimental data from a series of three different reinforced concrete beam specimens subjected to drop hammer impact loading of different intensities. Several prevailing constitutive models for dynamic analysis of reinforced concrete, including Continuous Surface Cap Model (CSCM), Winfrith, Karagozian and Case Concrete (KCC), and Riedel-Hiermaier-Thoma (RHT), are included in the investigation to examine the sensitivity of each constitutive model to the hourglass control parameters. The study quantifies the influence that the Flanagan-Belytschko stiffness form of hourglass control with exact volume integration has on relative hourglass energy, displacement response, and impact force across a range of different hourglass coefficients. Furthermore, the significant effect of hourglass control on fringes of maximum principal strain, which are typically used as an indicator for location and severity of cracking in reinforced concrete, is investigated. It is recommended that comprehensive sensitivity analysis be performed prior to establishing parameters for hourglass control in the simulation of reinforced concrete beams under low velocity impact and that unique hourglass coefficients be considered for different constitutive models.

2 Modeling of Experimental Case Studies

This paper is based on finite element analysis of the set of twelve drop hammer impact tests detailed in Fujikake et al. [4]. This experimental program included three reinforced concrete beam specimens each having the same nominal cross-sectional dimensions, span length, and shear reinforcement, but varying in longitudinal reinforcement. The beam dimensions, longitudinal reinforcement locations, and stirrup spacing for all specimens is presented in Figure 1. The series of specimens denoted S1616 and S2222 were doubly reinforced with 16 mm and 22 mm diameter deformed bars, respectively, while the longitudinal reinforcement in the series of specimens denoted S1322 consisted of 13 mm diameter bars on the compression side and 22 mm diameter bars on the tension side. All specimens were flexure controlled under static loading conditions, with the ratio of shear resistance to flexural resistance under concentrated load at the midspan being reported as 2.55 for the S1616 series and 1.51 for the S2222 and S1322 series. A 400 kg hammer with a hemispherical contact surface was used to impart the impact loading with the S1616 series including drop heights of 15, 30, 60, and 120 cm and the the S2222 and S1322 series including drop heights of 30, 60, 120, and 240 cm. Failure in all specimens in the S1616 series was classified as flexural, with flexure-shear cracking being more prevalent as the impact intensity increased. The S2222 and S1322 specimens were reported to exhibit flexural failure for the 30 cm and 60 cm drop heights, while a combination of local crushing of concrete around the impact location and flexural failure was reported for the 120 and 240 cm drop heights. Flexure-shear and shear cracks were also evident in photographs of the failed specimens provided in the referenced paper. The S1322 specimen was noted as exhibiting local concrete crushing over a larger relative length of the beam than the S2222 specimen, which is anticipated due to the reduced longitudinal reinforcement on the compression side.

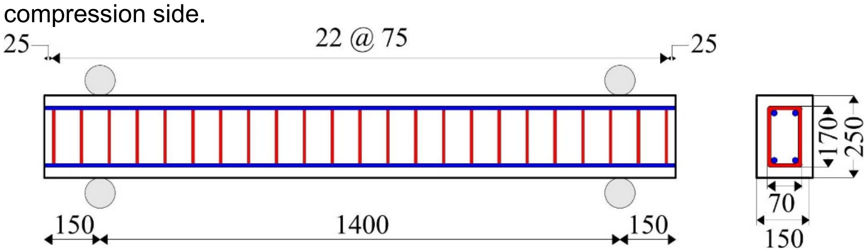

Fig.1: Dimensions and reinforcement details for beam specimens in Fujikake et al. [4]

The beam specimens from this experimental program were selected for the analysis conducted for this paper due to the extensive use of these beam specimens, in particular the S1616 beam series, as a benchmark for assessing and validating the performance of high-fidelity finite element modeling techniques for impact analysis of reinforced concrete beams. Furthermore, the beams in the experimental program encompassed a range of reinforcement ratios and impact energies resulting in several different failure modes and extents of damage.

2.1 Finite Element Modeling

All finite element analysis presented in this paper was conducted using LS-DYNA release 13.0.0. Since all of the beam specimens share the same cross sectional dimensions, span length, shear reinforcement, and locations of longitudinal reinforcement, a common mesh was used to model all of the specimens. Figure 2 presents the finite element model that was developed. The concrete was represented with constant stress hexahedral solid elements with a uniform edge length of 10 mm. This mesh size was informed by convergence studies disclosed in prior numerical studies of these beam specimens [1,3]. The longitudinal reinforcement and stirrups were modeled with Hughes-Liu beam elements and assumed to maintain perfect bond with the concrete. The **CONSTRAINED_BEAM_IN_SOLID** constraint was used as an alternative to shared nodes to connect the beam elements representing the reinforcement to the solid elements representing the concrete. The reinforcement was modeled with **MAT_003** to represent the constitutive behavior of the steel with a piecewise linear elastic-plastic response with isotropic hardening. The yield stress of the reinforcement was prescribed according to the values detailed in the experimental program. The Cowper Symonds strain rate model was used to invoke strain rate effects and the parameters for the model were established based on the guidance in [5]. The drop hammer was modeled as a spherical part with the same diameter as the hemispherical surface described in the experimental test program. A rigid material model was assigned to the hammer with the stiffness of steel for contact and the mass density was adjusted to reproduce the total mass of the hammer. Cylindrical supports below and above the beam specimen were similarly modeled as rigid materials. Following the recommendation in Adhikari et al. [3], a gap of 1 mm was introduced between the beam and the cylindrical supports above the beam to minimize any potential development of moment restraint near the beam ends. The **CONTACT_AUTOMATIC_SURFACE_TO_SURFACE** algorithm with Coulomb coefficients of 0.3 for both static and dynamic friction was employed to define contact between the drop hammer and the beam as well as between the cylindrical supports and the beam. Dynamic relaxation was performed prior to the impact simulation to initialize gravitational effects prior to the transient analysis of the impact.

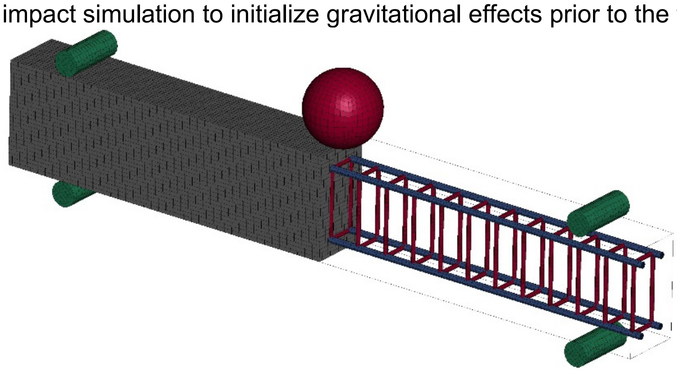

Fig.2: Finite element mesh with concrete elements to the right of the midspan of the beam hidden to show the reinforcement

2.2 Constitutive Models

Parameters for the CSCM material model were established using the automatic parameter generation capability of **`MAT_159`** with an unconfined compressive strength of 42.0 MPa and maximum aggregate size of 10 mm, which correspond to the mechanical properties disclosed in the experimental test program. With the exception of the rate effects option that was turned on to account for strain rate enhancement, the default assignments for other options were used, resulting in full recovery of the modulus in compression and no retraction of the hardening cap. Erosion was not included in the simulations. The KCC material model was similarly implemented with the unconfined compressive strength and maximum aggregate size using the automatic parameter generation feature of **`MAT_072R3`** and strain rate effects were included using the internal formulation. The Winfrith concrete model was implemented using **`MAT_084`** with strain rate effects included. The initial tangent modulus of concrete, Poisson's ratio, uniaxial compressive strength, uniaxial tensile strength, and fracture energy were assigned as 30.46 GPa, 0.2, 42 MPa, 3.644 MPa, and 0.143 N/mm, respectively. The fracture energy assumption was informed by the empirical equation for normal weight concrete provided in the CEB-FIP [6]. Parameters for the RHT material model were established using the automatic parameter generation option in **`MAT_272`** based on unconfined compressive strength and the default formulation for strain rate enhancement was used.

2.3 Hourglass Control

All simulations performed for this study used the Flanagan-Belytschko stiffness form of hourglass control with exact volume integration for solid elements. The stiffness form of hourglass control has been commonly used for finite element analysis of reinforced concrete beams subject to low velocity impact [1,2], although some studies have also reported success using a viscous form of hourglass control [3,7]. The exact volume form of integration was selected over the one point quadrature method based on analysis in Schwer et al. [8] demonstrating that the one point quadrature method does not pass the 3D Patch Test. Using each of the four concrete constitutive models, the four drop height scenarios for all three of the beam series were simulated using hourglass coefficients of 0.1, 0.05, 0.01, 0.005, 0.001, 0.0005, and 0.0001. Part energies were written to the matsum file every 10 µs to monitor hourglass and internal energies within the concrete elements of the model throughout the duration of each simulation. The ratio of the hourglass energy to the internal energy was analyzed as a time history to arrive at the maximum instantaneous value for this ratio for each simulation.

3 Results

The effect of hourglass coefficient on the ratio of maximum hourglass energy to internal energy for each concrete constitutive model is presented in Figure 3 for the S1616 series of drop hammer impact scenarios. In general, the maximum relative hourglass energy tended to increase with the hourglass coefficient, as expected. The maximum relative hourglass energy typically increased with the intensity of the impact for the CSCM and KCC models, while tending to decrease with the intensity of the impact for the Winfrith and RHT models. The sensitivity of the relative hourglass energy to the hourglass coefficient varied significantly by concrete constitutive model, with the RHT model exhibiting the least sensitivity and the KCC model exhibiting the greatest sensitivity. A conventional rule-of-thumb is that the hourglass energy should not exceed approximately 10% of the internal energy. Notably, the hourglass energies were around or below a maximum of 10% of the internal energy for all of the constitutive models when an hourglass coefficient of 0.005 or less was used. The reported maximum relative hourglass energies were found to change very little when the beam model was changed from S1616 to S2222 or S1322.

The vertical displacement of a centrally located at the underside of the beam at the midspan was written to a nodout file every 10 µs to examine the sensitivity of the beam displacement to hourglass coefficient and compare the predicted responses to the reported time histories from the experimental test program. Figure 4 illustrates the effect of the hourglass coefficient on the displacement time histories obtained for the S1616 beam specimen subjected to the 120 cm drop height. In this figure, the experimentally measured response is shown as a dashed line in black for reference. Due to space constraints and the similarity of results obtained for other impact intensities and for the S2222 and S1322 series, the results presented are limited to this single case for the S1616 series. As shown in the figure, an increase in the hourglass coefficient results in a decrease in the predicted peak displacement at the midspan for the CSCM, Winfrith, and RHT models. The trend toward lower peak displacement with increased hourglass coefficient is expected due to the stiffening effect of the hourglass control. The peak displacement obtained with the KCC model for this impact scenario does not exhibit a clear trend with the hourglass coefficient. Similar results were obtained for the other impact intensities and across the models for the other beam series. In general, the displacement time histories obtained with the KCC model exhibited the greatest sensitivity to the hourglass coefficient, with generally significant and irregular changes in the displacement time history occurring from relatively small changes in the hourglass coefficient. Across all of the beam series and drop height scenarios, the displacement time histories obtained with the Winfrith concrete model exhibited the least sensitivity to hourglass coefficient. Although the intent of this paper is not to comprehensively investigate the performance of each of the concrete constitutive models, it is notable that all of the models generally predict the experimentally measured mid-span displacement well, particularly when lower hourglass coefficients are used. The CSCM and KCC models exhibited greater agreement for this impact scenario of this beam series, but these constitutive models did not universally perform better at predicting the displacement time histories across all beam series and impact scenarios.

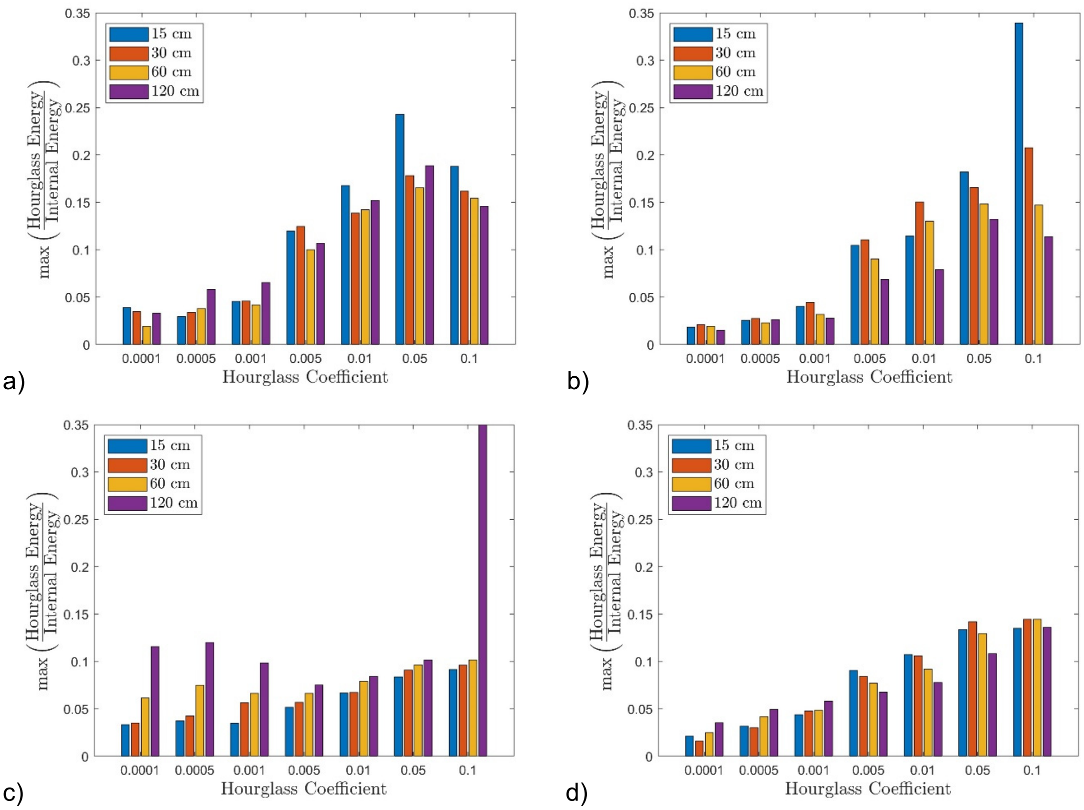

Fig.3: Maximum relative hourglass energies for S1616 beam specimens by hourglass coefficient: a) CSCM; b) Winfrith; c) KCC; d) RHT

The vertical force component for the contact between the drop hammer and the beam was written to an rcforc file every 10 µs to similarly investigate the influence of the hourglass coefficient on the impact force time history. Figure 5 presents the impact force time histories for the S1616 beam subject to the 120 cm drop height for each constitutive model across the range of hourglass coefficients included in the study. Neither the peak force nor the total impulse were generally found to be significantly affected by the hourglass coefficient used. This observation was consistent across all of the beam series and drop height scenarios. However, the hourglass coefficient is observed to noticeably affect the amplitude of oscillations in the contact force associated with stress wave reflections, particularly for the CSCM model. In general, higher hourglass coefficients increase the peak-to-peak amplitude of these force oscillations. Across all of the constitutive models, the contact forces predicted when lower hourglass coefficients are used more accurately reflect the experimentally measured force time history. Overall, the predicted impact force time histories correlated well with the experimental data for all constitutive models, except for the KCC model, which significantly overpredicted the peak impact force. The overprediction of peak impact force when the KCC model is used was consistently observed across all three beam series and all drop height scenarios.

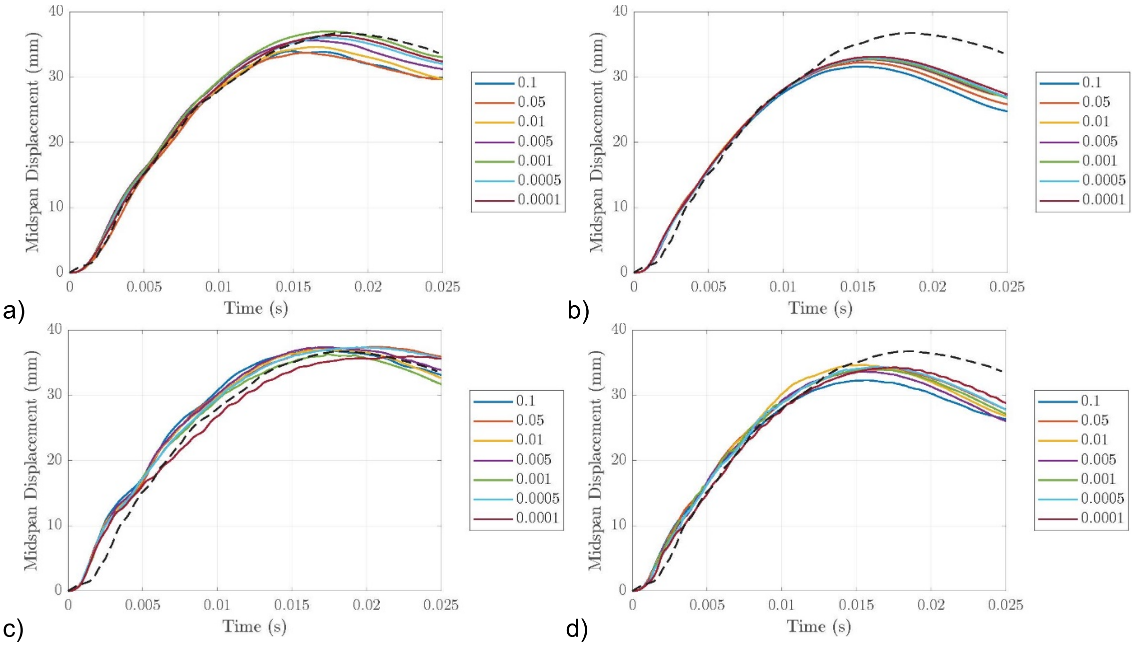

Fig.4: Displacement time history by hourglass coefficient for S1616 beam with 120 cm drop height impact: a) CSCM; b) Winfrith; c) KCC; d) RHT

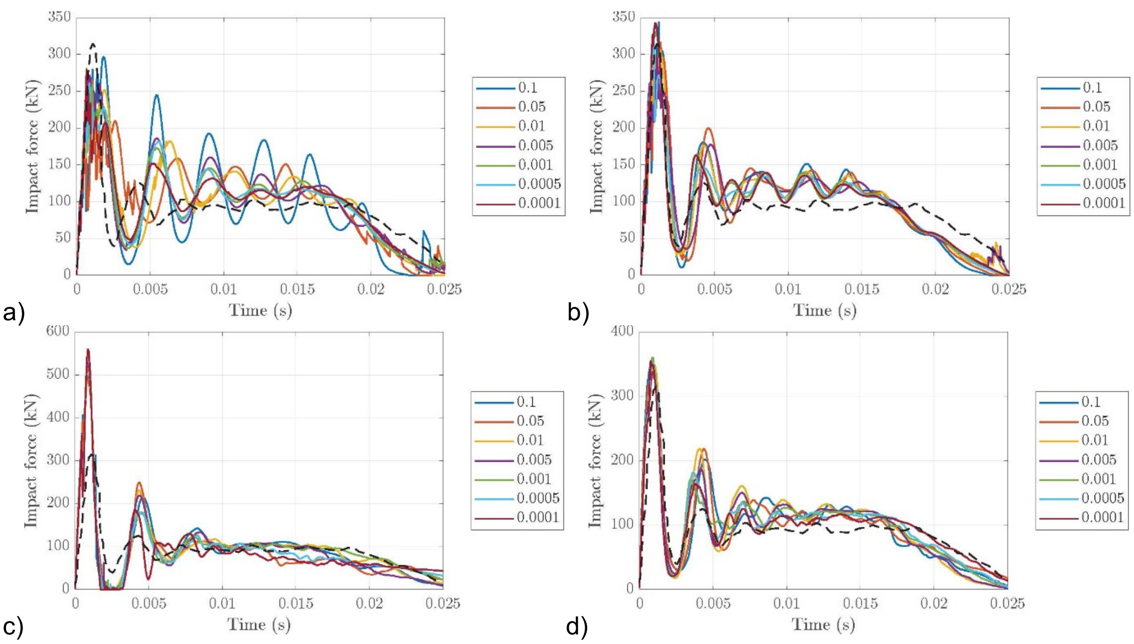

Fig.5: Impact force time history by hourglass coefficient for S1616 beam with 120 cm drop height impact: a) CSCM; b) Winfrith; c) KCC; d) RHT

In general, the displacement and force time history results presented for the S1616 beam exhibit sensitivity to the hourglass coefficient, but all of the individual model predictions are generally reasonable estimates for the midspan displacement and contact force. Furthermore, limiting the evaluation of the model to just these displacement and force time histories, which has been typical practice in prior studies [1,2], may incompletely assess the significance of the hourglass control on the behaviors exhibited within the model. To explore in more detail the influence of the stiffness form of hourglass control on behavior produced by the constitutive models, the maximum principal strain distributions were plotted at the end of the termination time for each simulation. Figure 6 presents the maximum principal strain distributions obtained for the S1616 beam subjected to the 120 cm drop height for each of the constitutive models with each of the hourglass coefficients included in the study. In this figure, the upper limit on the color map for the maximum principal strain fringe was set to 0.1 for all of the subfigures. A mapping of the visible surface cracks and extent of concrete crushing in the vicinity of the impact location observed in photographs from the experimental test program are provided in this figure for reference. The failure mode for this specimen was reported as flexural, with flexural and flexure-shear cracks visible in the photograph of the specimen. A limited region of spalling near the top of the beam at the midspan where the impact occurred was also present. In contrast to the relatively mild variation in displacement time history with the hourglass coefficient, the maximum principal strain distributions are observed to be significantly affected by the hourglass coefficient. For all four constitutive models, higher hourglass coefficients led to smearing of the damage within the concrete, while lower hourglass coefficients produced maximum principal strain distributions that more clearly reflect individual cracks. For this scenario, all constitutive models produced the most favorable comparisons with the experimental observations when the hourglass coefficient is either 0.0005 or 0.001. For the CSCM model, the use of a lower coefficient leads to an indication of some shear cracking originating near the supports, while the use of higher coefficients smear the damage near the midspan and attenuate the severity of the localized damage near the impact. The Winfrith model indicates a similar flexural mode of failure, but does not suggest significant localized damage near the impact. This may be attributed to the lack of compression softening in the Winfrith model. The nature of the damage is most significantly influenced by the hourglass coefficient for the KCC and RHT models. With lower hourglass coefficients, both models appear to suggest formation of flexural cracks as well as the formation of a local shear plug. While shear plug failures are known to occur during impact loading of reinforced concrete beams that are flexure-controlled under static loads due to the influence of inertia forces [9], the formation of a shear plug was not noted in the experimental test program upon which these models were based.

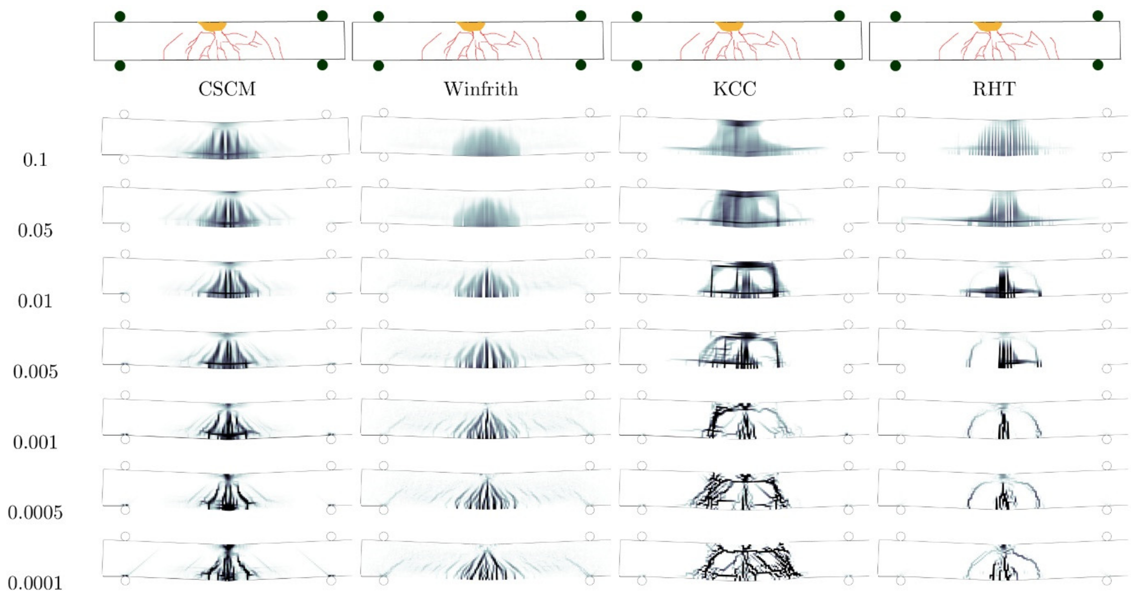

Fig.6: Maximum principal strain distributions for S1616 beam with 120 cm drop height impact by concrete constitutive model and hourglass coefficient

As noted, the effects of hourglass coefficient on the results obtained for the S2222 and S1322 beam series were generally similar to those observed with the S1616 beam model. One notable difference was that instabilities developed when using the CSCM model with the lower hourglass coefficients for the higher intensity impact scenarios. In addition, the RHT model terminated with a negative volume error when the lowest hourglass coefficient was used to simulate the S1322 beam subjected to the largest drop height. Figure 7 presents the displacement time histories obtained for the 120 cm drop height scenario of the S2222 beam specimen with different hourglass coefficients and concrete constitutive models. Although the impact intensity for this case is the same as for the S1616 results previously presented, the higher longitudinal reinforcement ratio of the S2222 beam led to more extensive local crushing of the concrete near the location of the impact. As the extent of local damage in the compression region increased, the effect of the hourglass coefficient on the simulation results became more significant, except for the Winfrith concrete model that does not include compression softening. Furthermore, the typical trend of lower amplitude peak displacements with increased hourglass coefficients was no longer observed. The displacement time histories presented for the

CSCM model with the two lowest hourglass coefficients reflect the occurrence of instabilities that were suppressed with the use of higher hourglass coefficients.

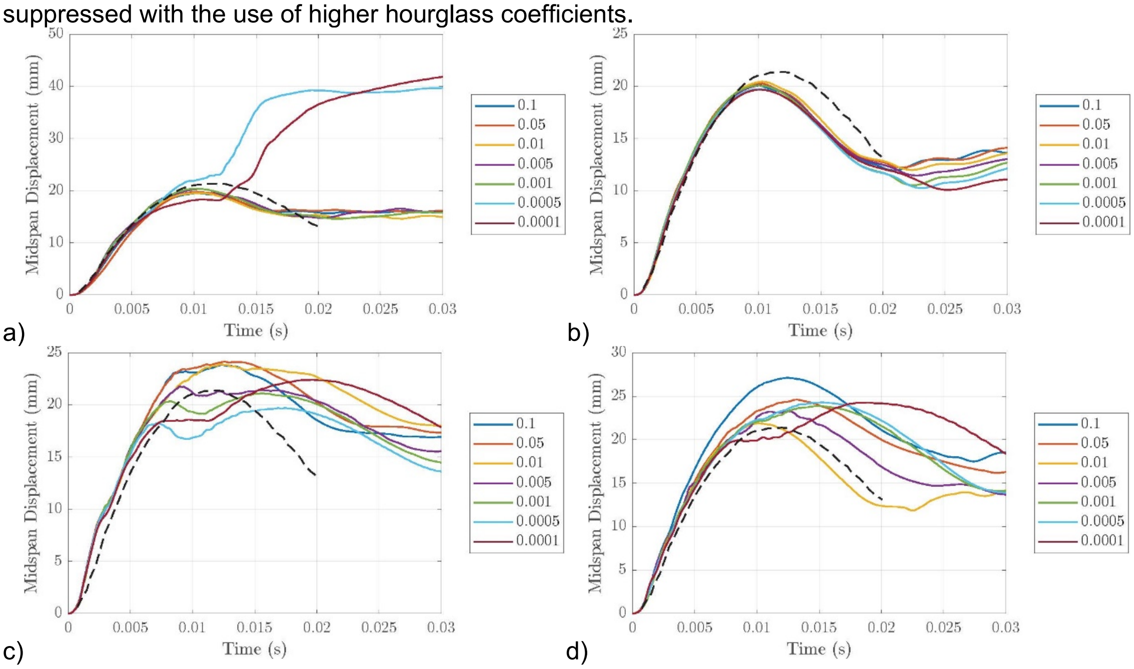

Fig.7: Displacement time history by hourglass coefficient for S2222 beam with 120 cm drop height impact: a) CSCM; b) Winfrith; c) KCC; d) RHT

The maximum principal strain distributions obtained for the S2222 beam model with the 120 cm drop height are presented in Figure 8 for each of the constitutive models with each of the hourglass coefficients. Similar to the previous figure, the upper limit on the color map for the maximum principal strain fringe was set to 0.1 for all of the subfigures. Instabilities are apparent in the results obtained with the CSCM model when lower hourglass coefficients were specified. Furthermore, the use of higher hourglass coefficients had a more pronounced effect on the damage patterns reflected in the simulations performed with the KCC and RHT models. As the impact intensity was increased to 240 cm and as the longitudinal reinforcement in the top layer was reduced in the model for the S1322 specimen, the severity of the instabilities increased and, ultimately, extended to all CSCM simulations with hourglass coefficients less than 0.01. Consequently, the lowest hourglass coefficient leading to stable results across all beam series and impact scenarios for the CSCM model was 0.01. In contrast, the Winfrith, KCC, and RHT models continued to produce stable results with hourglass coefficients down to 0.0005 through all cases, including those where an increased severity of local concrete crushing near the impact was experimentally observed. For these constitutive models, the use of an hourglass coefficient in the range of 0.0005 to 0.001 minimizes the ratio of hourglass energy to internal energy, while suppressing instabilities and producing maximum principal strain distributions that correspond most closely to the experimentally observed crack patterns.

4 Summary

Maximum principal strain distributions reveal that hourglass control can significantly affect the damage prediction within reinforced concrete beams using the CSCM, Winfrith, KCC, and RHT concrete constitutive models, even when the maximum ratio of hourglass energy to internal energy is below the conventionally recommended threshold of 10%. Any finite element analysis aimed at predicting the nature and extent of damage in reinforced concrete beams should carefully examine the sensitivity of the result to the hourglass coefficient. Studies aimed at evaluating or comparing the performance of different concrete constitutive models for low velocity impact analysis should first carefully select hourglass coefficients to minimize the effect of the hourglass control on the result, while ensuring adequate suppression of instabilities. It may be warranted to select different hourglass coefficients for different concrete constitutive models.

The beam specimens modeled in this study were limited to flexure-controlled sections, with modes of failure from impact loading being characterized only by flexural cracks, flexure-shear cracks, and, in some instances of higher impact intensity, localized crushing of concrete at the region of impact. For cases where the damage was limited primarily to flexural and/or flexure-shear cracks, all of the constitutive models produced the strongest agreement with the measured midspan displacement, impact force time history, and observed damage when the hourglass coefficient was in the range of 0.0005 to 0.001. However, for the beam series and impact scenarios where significant localized crushing of concrete was experimentally observed, higher hourglass coefficients were required when using the CSCM model to suppress instabilities. The use of an hourglass coefficient of 0.01 sufficiently suppressed instabilities when using the CSCM model and did not appear to be detrimental to the damage prediction, although the use of such a high coefficient with either the KCC or RHT models would significantly change the maximum principal strain distribution. Consequently, comparison of the relative performance of these concrete constitutive models in predicting the behavior and response of the reinforced concrete beams modeled in this paper should be performed using different hourglass coefficients across the constitutive models. If a single hourglass coefficient were to be specified for each constitutive model to simulate all twelve of the beam experiments modeled in this study, then a coefficient of 0.01 would be most appropriate for the CSCM model to ensure adequate suppression of instabilities, while a coefficient in the range of 0.0005 to 0.001 appears to yield the best prediction of damage, beam response, and impact force characteristics for the Winfrith, KCC, and RHT models.

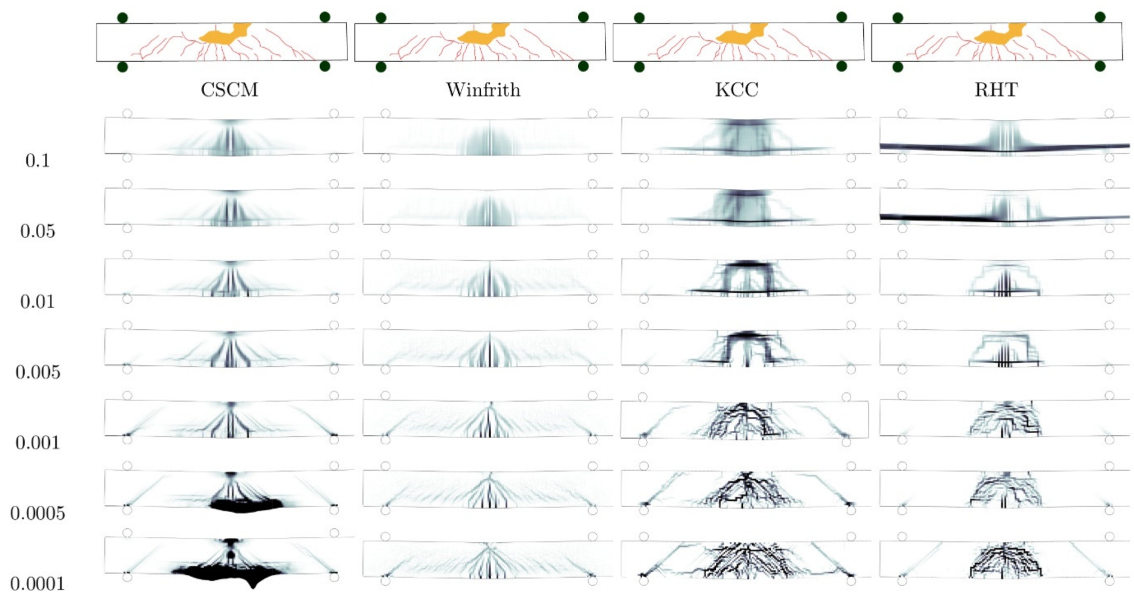

Fig.8: Maximum principal strain distributions for S2222 beam with 120 drop height impact by concrete constitutive model and hourglass coefficient

It should be noted that hourglass is affected by mesh size and that the relative hourglass energies associated with specific hourglass coefficients presented in this paper are dependent on the model. The paper does not aim to recommend a specific set of hourglass coefficients for any concrete constitutive model, but rather seeks to provide insight into the sensitivity of the constitutive models to the stiffness form of hourglass control. The results are also limited to a relatively small set of reinforced concrete beam specimens with no variation in cross sectional dimensions, span length, or shear reinforcement. Additional research should be conducted to examine the effects of hourglass control on beams exhibiting support shear or local shear plug failures under impact loading. Furthermore, the study should be extended to include the viscous form of hourglass control with exact volume integration to offer guidance on the most appropriate form of hourglass control to use when analyzing reinforced concrete beams subject to low velocity impact.

5 Literature

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