Finite Element Analysis on Reinforced Concrete Beams Subject to Impact

by

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14850

Dissertation submitted in partial fulfilment of
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CERTIFICATION OF APPROVAL

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Civil Engineering Programme
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(CIVIL)

Approved by,

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(Dr. Teo Wee)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
January 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(NG SEH HUI)

ABSTRACT

The study of reinforced concrete beams under impact load has been conducted by many researchers previously with different methods. It is important to understand the behaviour of reinforced concrete beams during impact so that it can be used as a reference in designing the structures. Failure under this accidental load can be catastrophic if structures are under-designed due to lack of knowledge in the response of reinforced concrete under impact load. Finite element analysis is the common method used in solving explicit dynamic problems. LS-DYNA is utilised to conduct the numerical simulation using finite element analysis. This research aims to determine the failure mode of reinforced concrete beams as well as their responses after impact. Generally, two beams are being studied by varying the transverse reinforcement ratio. It was found that reinforced concrete beams subject to impact tend to fail in shear rather than flexure. The beam with stirrups is stiffer and becomes more ductile, exhibiting a more elastic behaviour and resists the shear force through larger displacement of beam. Dynamic increase factors are introduced to the material model as high strain rate causes strength enhancement in the concrete and steel reinforcement. High impact force from the impactor causes residual displacements of the beams and residual strains in the reinforcement because the materials have exceeded the yield point and enters plastic region where some elements have permanently deformed.

ACKNOWLEDGEMENT

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CHAPTER 1
INTRODUCTION

Reinforced concrete is the most common construction material used in the industry due to its properties, availability of material as well as its functional cost. It can be easily cast into different structural elements such as beams and columns to provide stability to a structure. In normal case, the structural elements are designed in such a way that the structure remains rigid under normal working condition. In other words, only dead load and live load are considered in the design. However, there is still a possibility that accident will happen which may cause the structural elements to fail. For example, bridge piers in the middle of highway and columns in car parks are vulnerable to impact loads from vehicles. The consequences can be catastrophic if the columns fail. To prevent severe consequences to happen, accidental loads are taken into consideration in the design of the structure. Prior to that, the behaviour of concrete subjected to impact load need to be understood. In fact, impact load is different from the usual dead and live actions as it involves dynamic which the results vary over time after impact.

1. BACKGROUND

The effects of dynamic loadings such as earthquake and impact load on reinforced concrete have become a discussion topic for many researchers throughout these years. Several researches include experiments and numerical simulations have been conducted to determine the reinforced concrete behaviour on dynamic loadings. For example, the effects of blast loadings on reinforced concrete column is assessed to determine the possibility of progressive collapse (Wu, Li, & Tsai, 2011). In addition, Saatci and Vecchio (2009b) evaluate the behaviour of reinforced concrete structure under impact loads using nonlinear finite element modelling. Nevertheless, only impact loading on reinforced concrete beam will be discussed in this paper.

Examples of impact loadings are such as vehicle collision on column, weight drop on slab or beam and transverse impact on wall. Previous researches have shown the significance of the research. For illustration, accidents of vehicles collide with bridge pier have occurred in the past which involved casualties as well as destruction of the impacted bridge. In fact, these accidental collisions have happened in other countries but there are not much similar cases in Malaysia. On May 23, 2003, an overpass collapsed followed by an impact of a semitrailer at the median support of a bridge crossing I-80 near Big Springs, Neb. The traffic on the Memorial Day was seriously affected and a person was killed in that accident ("Nebraska Overpass Will Be Rebuilt With Fewer Piers," 2003). Also, Dallas-News (2002) reported another news of a collapse bridge due to impact from a trailer on September 9, 2002.

In short, the two accidents illustrated before give some background of the study and researches that have been conducted previously to assess the dynamic responses of reinforced concrete. The behaviour of reinforced concrete under impact loading need to be understood so that it can be used as a reference to the design of any structures where dynamic loadings are the governing factor.

2. PROBLEM STATEMENT

The effects of impact loadings on reinforced concrete beam are closely related to the properties of materials, namely the strength of concrete and steel reinforcement. Based on previous researches, it was found that reinforced concrete beams failed in flexure under static load and by shear when subjected to dynamic loading (Miyamoto, King, & Bulson, 1994). According to Adhikary, Li, and Fujikake (2013), the information on the dynamic shear strength of reinforced concrete beam is limited. There is a need to investigate the effects of longitudinal and transverse reinforcement ratio on concrete behaviour.

Besides that, strain rate effect under impact condition may also affect the behaviour of concrete. Under blast effects, the response of concrete is different from a static loading condition. Hence, it can be noticed that dynamic loading can give high implication to the concrete structure. In summary, lack of understanding on the dynamic responses of reinforced concrete beam due to impact loadings can pose a major problem to the design of a structure. Next, the failure mode of the beam is not fully understood and finally the design of the structural members such as beams and columns.

3. OBJECTIVES

This research is initiated to assess the dynamic response of reinforced concrete beams under impact loadings. It is vital to understand the concept and can be used as a reference in the design of reinforced concrete beam subjected to impact loadings.in the future. Thus, the objectives of this research are:

- To simulate the impact on reinforced concrete beams using LS-DYNA and determine the failure mode of the beams.

- To evaluate the impact behaviour of reinforced concrete beams from beam displacement and reinforcement strain.

4. SCOPE OF STUDY

The research aims to evaluate the behaviour of reinforced concrete beam subjected to impact loadings. Although beam is used in the study, the same concept can be applied to other types of structural members such as column. Besides that, a nonlinear finite element (FE) program called LS-DYNA is used in this study to simulate the impact of a rigid body on the concrete beam. Experiment is not conducted for the study because concrete samples preparation requires more time. Casting of reinforced concrete requires few days for the beam to achieve its strength. However, the results from the software simulation are validated with a set of experimental data obtained from previous research. This is to ensure the reliability of the results. The validation procedures are described in the methodology section. In addition, computer simulation will be adequate to illustrate the real condition of reinforced concrete beam subjected to impact which will be explained in detail in the literature review.

The material properties of concrete are analysed as well as its interaction with the steel reinforcement. Same grade of concrete beams are adopted for easier comparison and analysis. Also, the beams are of the same sizes and uniform size of steel reinforcement and strength are defined in the model. Furthermore, the effects of shear reinforcement in the beam are also studied. The whole system is visualized as a single degree of freedom for simplicity.

CHAPTER 2
LITERATURE REVIEW

1. LS-DYNA AND LS-PREPOST SOFTWARE

LS-DYNA is a common program used to analyse the large deformation static and dynamic response of structures using finite element (FE) analysis (Hallquist, 2006). Basically, the program solves a problem based on explicit time integration. However, the solver has limited capabilities including structural analysis and heat transfer. Thus, a contact-impact algorithm is introduced that allows difficult contact problems to be easily treated with heat transfer included across the contact interfaces. With the help of this algorithm, such interfaces can be connected firmly without the need of mesh transition regions. Each element type has many element formulations. In fact, LS-DYNA currently has about one hundred models and ten equations-of-state to illustrate different material behaviour.

LS-DYNA software was started with another name called DYNA3D in the mid-seventies. Lawrence Livermore National Laboratory has released the first version of DYNA3D in 1976. This early applications were introduced mainly for the stress analysis of structures subjected to a variety of impact loading (Hallquist, 2007). These applications require a lot of computer resources to run the analysis. In addition, the basic sliding interface treatment could only treat logically regular interfaces that are unusual in most finite element discretization of complex three-dimensional geometries. As a result, manual definition of mesh to contact elements was very difficult. In 1979, a new version of DYNA3D that was created to offer optimal speed on the CRAY-1 supercomputers was released. It has an improved sliding interface treatment that allowed triangular segments and the speed was much higher than the previous contact treatment. By the end of 1988, Livermore Software Technology Corporation was founded to introduce a commercial version called LS-DYNA3D which was later called LS-DYNA. Throughout these years, the capabilities of the software have been improved. For example, it included hourglass energy calculations for solid and shell elements, keyword input, improved interactive graphics and others.

Apart from that, LS-PrePost is a free software that comes with LS-DYNA. As its name suggests, it is a software used for pre and post-processing after a problem is solved by the LS-DYNA solver. To be specific, the pre-processing function of the program allows users to create a three-dimensional model in the form of finite elements. In the program, users are required to assign parameters such as material properties, load data, outputs definitions and others using keywords function. Furthermore, it also includes the ability to import a model from other software such as AutoCAD. After the model has been solved by LS-DYNA solver, the outputs can be viewed using LS-PrePost post-processing function. Its main post-processing capabilities include states result animation, fringe component plotting and time-history plotting.

2. BEAM MODELLING

A nonlinear finite element analysis can be performed by using LS-DYNA software (Adhikary et al., 2013). It has been used by many researchers to study the impact behaviour of reinforced concrete structures. The software is capable of determine the dynamic shear resistance and its failure mechanism. Adhikary et al. evaluated the shear behaviour of reinforced concrete deep beams under dynamic loading condition. In terms of the structural model, the concrete beam is modelled using eight node solid hexahedron elements with single integration point. In addition, steel reinforcements are represented by two-node Hughes-Liu beam element formulation with 2x2 Gauss quadrature integration. The author suggested that the mesh size should be in the ratio smaller than 1.5.

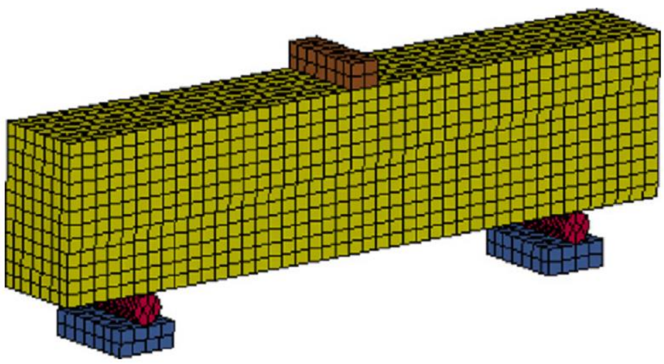


FIGURE 2.1 Finite Element Model of RC Deep Beam
(Adapted from Adhikary et al., 2013)

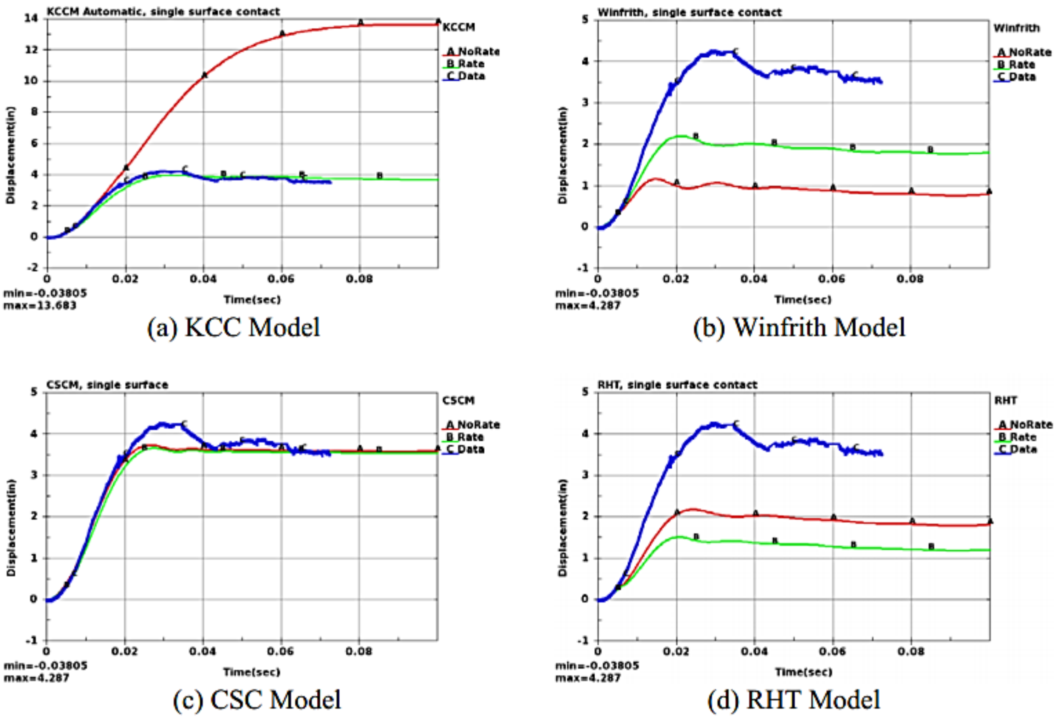
The finite element reinforced concrete beam model developed by the author is shown in FIGURE 2.1. Mesh size of 25mm in the span direction of beam is used because study showed that finer mesh has no significant effect on the results accuracy. Furthermore, the mesh pattern followed the location of steel reinforcement in such a way that the bars nodes coincide with the concrete nodes. Consequently, the shared nodes are merged to ensure perfect bonding between the two.

Besides that, the beam is supported on two rigid cylinders and constraints are applied to translation but able to rotate about their longitudinal axis. The contact between all parts of the model which include the loading plate, concrete and cylindrical supports are assigned with the contact algorithm AUTOMATIC_SINGLE_SURFACE. In addition, the concrete material type in the authors' study is MAT_CONCRETE_DAMAGE_REL3 which was the third release of Karagozian and Case (K&C) concrete model. On the other hand, for steel reinforcement, PIECEWISE_LINEAR_PLASTICITY material model is employed whereas the loading plate and cylindrical supports are rigid steel material (MAT_RIGID). Other than that, MAT_CONCRETE_DAMAGE_REL3 material type in LS-DYNA is also used to determine the residual axial compression capacity of blast-damaged reinforced concrete column (Wu et al., 2011).

3. CONCRETE MATERIAL MODEL

Several concrete material models are available in LS-DYNA. A suitable model that matches a particular type of problem should be used by understanding the characteristics of each model (Wu., Crawford, Shengrui, & Magallanes, 2014). It is costly to conduct a full scale blast loading test on a concrete sample, thus numerical simulation is always preferred by the researchers. LS-DYNA has shown a great potential in performing blast loading simulation. It contains a library of concrete model to capture the most basic characteristics of concrete. For example, there are MAT_CONCRETE DAMAGE_REL3 or known as KCC Model, MAT_WINFRITH_CONCRETE, MAT_CSCM CONCRETE and MAT_RHT concrete material model. In the study carried out by Wu et al., the performance of each model is assessed by varying the factors such as strain-rate enhancement, boundary condition and contact algorithm.

According to Wu et al., the strength of concrete is affected by the strain rate where an enhancement should be applied when the strain rate is high in the case of blast loading. A strain rate enhancement is input externally to the KCC model which the input data will be discussed later. Besides that, CSC and Winfrith models use an internal enhancement to account for the strain rate effect whereas RHT model depends on the reference strain rate on the input cards, namely E0C and E0T in LS-DYNA. As a result, the KCC model matched the experimental data well with strain rate effect but a huge discrepancies without the strain rate effect. For the CSC model, regardless of the definition of strain rate effect, both conditions suit well with the experimental data. However, the Winfrith and RHT model showed a lower displacement than the experimental data. FIGURE 2.2 shows the results of the simulation.



(a) KCC Model

(b) Winfrith Model

(c) CSC Model

(d) RHT Model

FIGURE 2.2 Lateral Deflection Histories at Central Mid-Height on Back Face.
(Adapted from Wu et al., 2014)

On the other hand, contact algorithm defines the interaction between each part of the model. There are many algorithms that have been implemented in LS-DYNA such as node to surface contact, surface to surface contact, single surface contact and others. Wu et al. claims that single surface or surface to surface contact is usually preferred for blast loading simulation.

In general, concrete can be characterised by a single parameter which is its uniaxial unconfined compressive strength, fc'. This is the basic properties of concrete that need to be known to evaluate the behaviour of concrete under various type of loading (Schwer & Malvar, 2005). In the LS-DYNA conference paper, the author claims that the concrete material model *MAT_CONCRETE_DAMAGE_REL3 is the best material type to simulate the behaviour of concrete when only minimum information of the concrete are known. For example, if only the compressive strength of the concrete is known, this material model is suitable to be used for the LS-DYNA simulation. Also, further information on the characteristics of the concrete can be input into the material cards.

As mentioned before, strain rate enhancement is an important factor in assessing the behaviour of concrete subjected to blast loading. Under the condition of rapid loading which in this case is impact loading, the response of concrete at high strain rate will be different. In fact, the strength of concrete increases significantly (Malvar & Crawford, 1998). The factor of enhancement of the concrete strength is called dynamic increase factor (DIF) which is defined as the ratio of dynamic to static strength. Malvar et al. reported that the DIF can be higher than two for compression (Bischoff & Perry, 1991) while greater than six for tension response . Besides that, the concrete structures tend to fail in tension under impact loading. Therefore, strain rate enhancement in tension provides a more accurate results on the dynamic behaviour of concrete as well as for compression. DIF is defined as a function of strain rate and the relationship between the two both in compression and tension are described in CEB Model Code (Comite Euro-International du Beton, 1990).

According to CEB formulation for compression, the relationship between DIF and strain rate is given as:

$$\frac{f_c}{f_{cs}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{1.026\alpha_s} \qquad for\ \dot{\varepsilon} \leq 30s^{-1}$$

$$= \gamma_s \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{1/3} \qquad for\ \dot{\varepsilon} > 30s^{-1}$$

where f_c = dynamic compressive strength

f_{cs} = static compressive strength

$\dot{\varepsilon}$ = strain rate ranges from 30 x 10^{-6} to 300 s^{-1}

$\dot{\varepsilon}_s$ = 30 x 10^{-6} s^{-1} (static strain rate)

$log\gamma$ = 6.156α - 2

α_s = 1/(5+9f_{cs}/f_{co})

f_{co} = 10 MPa

(Adapted from Comite Euro-International du Beton, 1990)

However, for tension, Malvar et al. has modified the CEB formulation based on several researches. It is believed that the modified relationship best represent the behaviour of concrete under impact loading. The proposed formulation becomes:

$$\frac{f_t}{f_{ts}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{\delta} \qquad for\ \dot{\varepsilon} \leq 1s^{-1}$$

$$= \beta\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{1/3} \qquad for\ \dot{\varepsilon} > 1s^{-1}$$

where f_t = dynamic tensile strength

f_{ts} = static tensile strength

$\dot{\varepsilon}$ = strain rate ranges from 10^{-6} to 160 s^{-1}

$\dot{\varepsilon}_s$ = 10^{-6} s^{-1} (static strain rate)

$log\beta$ = 6α - 2

δ = 1/(1+8f_{cs}/f_{co})

f_{co} = 10 MPa

(Adapted from Malvar et al., 1998)

4. ENERGY AND IMPACT FORCE MEASURES

Based on the law of conservation of energy, energy can neither be created nor destroyed. In an event of impact, the initial kinetic energy of the impacting body must be converted into residual kinetic energy, energy lost due to friction, internal energy absorbed by the deforming bodies and hourglass energy for finite elements (El-Tawil, Severino, & Fonseca, 2005). Hourglass modes are defined as non-physical and zero-energy modes of deformation that produce no stress and strain (LSTC, n.d.). It occurs typically in solid elements and also thick shell element which in this case is the concrete model. There are some stabilisation methods that are used in LS-DYNA modelling to reduce the hourglass effects which will be described in the methodology section. For example, an hourglass control keyword is defined in the model (Bala & Day, 2004). In simple words, hourglass effect is the deformation of individual element, while the overall body remains undeformed. In studying the impact behaviour of concrete, an energies plot is usually prepared to study the conversion of energies as well as the stability of the model due to hourglass effect. A research on crash analysis is taken as an example. The energies plot of vehicle collision on concrete pier is shown in FIGURE 2.33.

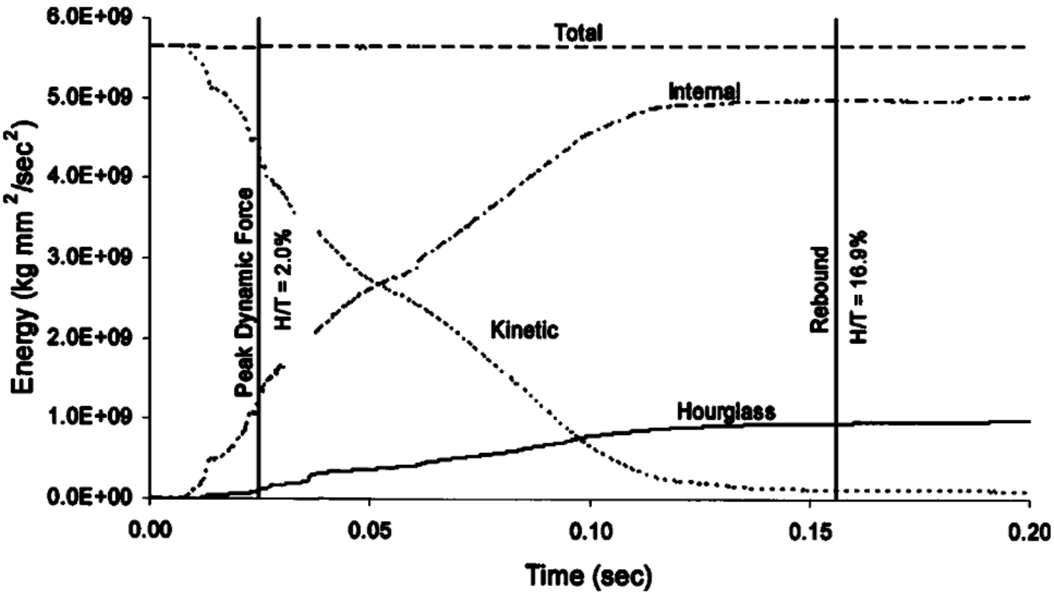


FIGURE 2.3 Evolution of Various Energy Quantities

(Adapted from El-Tawil et al., 2005)

In this study, it can be seen that the kinetic energy from the impacting vehicle is transformed into internal energy which is stored in the impacted pier or the deformed vehicle (El-Tawil et al., 2005). In the initial runs, it was found that the hourglass energy was excessive and affected the accuracy of the results. After that, the hourglass energy situation was solved by assigning fully integrated finite element formulations. The hourglass energy ratio is considered not very high and the value is acceptable. In fact, the hourglass energy need to be kept as low as possible. However, previous research claimed that in a validation of head-on collision experiment, 17% of hourglass energy is still acceptable (Zaouk, Bedewi, Kan, & Marzougui, 1996).

Additionally, another concern in an impact event is the impact force. In fact, the impact force is used to design the reinforced concrete beam for a particular condition, especially the dynamic properties of the concrete. During an impact, there are two peaks of impact force shown over the duration of experiment as shown in FIGURE 2.4 (Remennikov & Kaewunruen, 2006). The first peak indicates the initial impact from a rigid body, then the next peak is due to the bouncing of the body after the first impact. Following that, there is residual force on the concrete. Remennikov et al. conducted the experiment with three different drop heights. In general, at the first impact, the higher the drop weight, the larger the impact force due to higher impacting velocity.

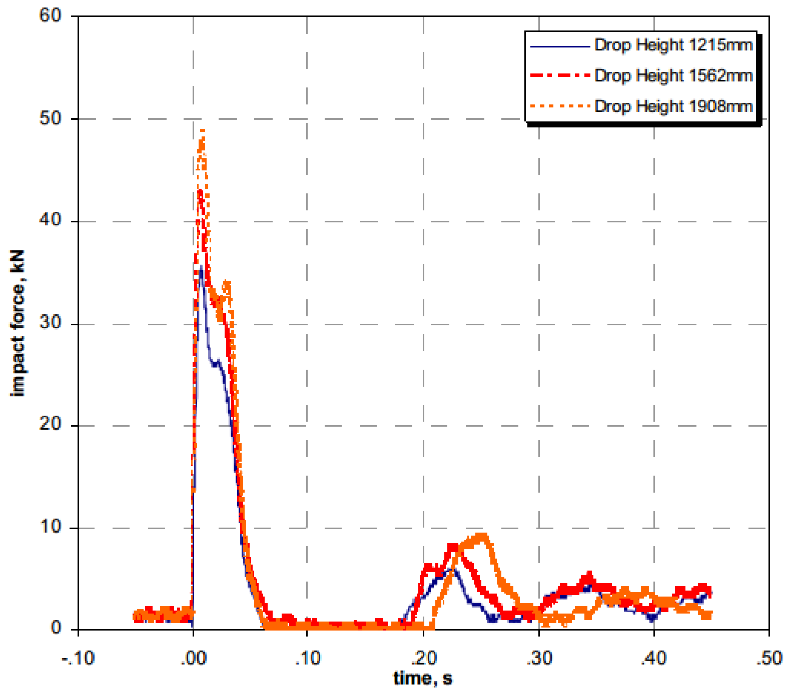


FIGURE 2.4 Time Histories of Impact Forces
(Adapted from Remennikov et al., 2006)

Relating to a vehicle crash event, the peak dynamic force which occurs in the early stage of impact has the highest amplitude of impact force. However, El-Tawil et al. claimed that this force does not represent the design structural demand as the great change in loading in very short period of time causes the structure has no time to respond. Therefore, the equivalent static force provides a more appropriate measure of the impact force and it is generally used in the design of reinforced concrete member (Chopra, 2001).

Besides that, some characteristic values can be obtained from the impact force graph. For example, impulse is the area under force-time curve, absorbed energy is the area under force-displacement curve and mean impact force is impulse over the duration of impact (Tachibana, Masuya, & Nakamura, 2010). The relationships between impact force, time of impact and displacement are shown in FIGURE 2.5.

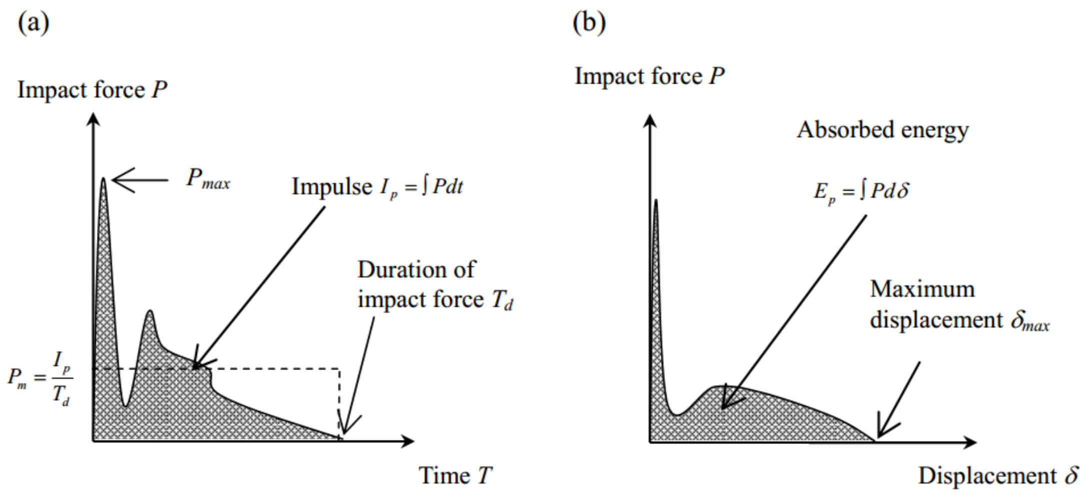


FIGURE 2.5 a) Force-Time Curve. b) Force-Displacement Curve.
(Adapted from Tachibana et al., 2010)

5. SHEAR FORCE DEMAND AND CAPACITY OF BEAM

The main factor for protection of structure is the calculation of dynamic shear force capacity at various performance levels (Sharma, Hurlebaus, & Gardoni, 2012). Reinforced concrete pier sustains damage during collision due to the transfer of large shear force over a short interval of time. This is because during short time interval, the resisting mechanism of the structure largely based on shear, inertia and local deformation at the point of impact rather than the global deformation of the entire structure. Hence, the dynamic shear capacity of the pier as well as its demand is more important than the static shear force. Also, different type and severity of impact such as the velocity of impacting body at the instant of impact and its mass also affect the damage state of the structure. Sharma et al suggests a performance based analysis to be carried out to minimize the damage to the reinforced concrete member.

Some experiments and simulations have been done in previous research. It showed that the dynamic shear force capacity during a collision can be higher than the values approximated by static procedures (Sharma, Hurlebaus, & Gardoni, 2009). This statement has also been proven by another research on the shear mechanism of reinforced concrete beam as shown in FIGURE 2.6 (Saatci & Vecchio, 2009a).

Test	Maximum dynamic reaction force, kN (kips)	Ratio of maximum dynamic reaction force to maximum static reaction force	Test	Maximum dynamic reaction force, kN (kips)	Ratio of maximum dynamic reaction force to maximum static reaction force
SS3a-1	431 (97)	2.2	SS3b-1	682 (153)	3.4
SS3a-2	822 (185)	4.1	SS3b-2	725 (163)	3.6
SS3a-3	783 (176)	3.9	SS3b-3	613 (138)	3.1
SS2a-1	327 (74)	1.7	SS2b-1	592 (133)	3.1
SS2a-2	651 (146)	3.4	SS2b-2	633 (142)	3.3
SS2a-3	779 (175)	4.0	SS2b-3	589 (132)	3.1
SS1a-1	356 (80)	2.4	SS1b-1	625 (141)	4.2
SS1a-2	517 (116)	3.5	SS1b-2	571 (128)	3.8
SS1a-3	314 (71)	2.1	SS0b-1	399 (90)	4.1
SS0a-1	305 (69)	3.1			
SS0a-2	190 (43)	1.9			

FIGURE 2.6 Ratio of Maximum Dynamic to Static Reaction Force.
(Adapted from Saatci et al., 2009a)

The ratio of maximum dynamic reaction force to maximum static reaction force showed that the response of reinforced concrete is higher when subjected to dynamic loading which in this case is impact loading. Apart from that, the shear characteristics of the concrete play an important role in its overall behaviour. In the experiment conducted by Saatci et al., the authors reported that all concrete beams developed diagonal shear cracks after the impacts, regardless of the amount of shear reinforcement in the beams. Furthermore, shear plug is also formed under the impact point (Ožbolt & Sharma, 2011). The increase in shear force capacity of the reinforced concrete beam during an impact can be due to various reasons such as strength enhancement due to strain rate effects, crack propagation, viscous damping, inertia effect, relative stiffness between impacting bodies and concrete-steel composite action.

6. CRITICAL REVIEW OF LITERATURE

Many researches have been done throughout these years to assess the behaviour of reinforced concrete under impact loadings. Strain rate enhancement of concrete has been debated by many researchers. In the finite element modelling by Saatci et al., the high strain rate due to impact loading has not been considered in the model. The authors stated that some researchers stressed on the significance of the strain rate effects in concrete but there are also academics who disagree with the statement. For example, the apparent dynamic strength enhancement is often interpreted wrongly as strain rate effect in structural design. In fact, the enhancement is due to the confinement stress caused by lateral inertia of the test specimens (Li & Meng, 2003). Hence, the strength of the concrete may be overestimated. Nevertheless, the authors added that strain rate enhancement is ignored in the model because VecTor2 is able to calculate the strength increase due to confining stress created by the inertia of the structure. In contrast, Wu et al. has shown the effects of inclusion of strain rate effects in four constitutive models in LS-DYNA which concluded that it is an important factor in the KCC model.

As has been said, the energy quantities of a collision simulation are plotted to determine the stability of the numerical model. The model is considered stable if the total energy is conserved and the hourglass energy is low. Basically, the total energy consists of the kinetic energy from impacting body, internal energy absorbed by the beam and deforming impacting body but in this case is a rigid body which assumed to be undeformable, and residual energies such as hourglass energy for finite elements. Hourglass energy is always monitored during the simulation and is kept as low as possible. Ideally, the hourglass energy should be less than 10% of the internal energy (Allemang, de Clerck, Niezrecki, & Wicks, 2013). However, in the research by El-Tawil et al., it is reported that the hourglass energy at the end of their test is 17% which is considerably higher than the ideal case.

CHAPTER 3
METHODOLOGY

A project schedule has been planned to ensure that the project can run smoothly and the objectives can be achieved within the time frame. Due to limited budget and time constraint, a computer simulation is adopted to represent the real condition of an impact on reinforced concrete beam by a rigid body. A real impact test can be conducted in the laboratory but the apparatus need to be set up carefully and the preparation of concrete samples require time for them to achieve the required strength. Hence, the test is replaced with a computer simulation and the beams, impactor and supports are modelled as close as possible to an experiment conducted previously by researchers to determine the behaviour of reinforced concrete subjected to impact loads (Saatci, 2007). In general, the simulation is conducted using a finite element program developed by Livermore Software Technology Corporation called LS-DYNA. In this study, LS-PrePost of version 4.2 (Beta) is used for modelling purpose and displaying the results whereas LS-DYNA is the solver for the simulation.

1. VALIDATION OF RESULTS

The research is conducted using software simulation to determine the behaviour of reinforced concrete beam when subject to impact. However, the results from a computer simulation may differ from the data obtained from a real impact condition. All the parameters required by the software need to be set correctly so that there will be no huge variation between both of the results. Therefore, the results from the finite element model analysis need to be validated before a conclusion is drawn. There are several ways to verify the simulation results such as experiment or theoretical approach. In this research, the results from simulation are compared with experimental data obtained from previous research which will be discussed in details in the following section.

On the other hand, theoretical approach proposed here is the single degree of freedom (SDOF). It is widely used in predicting the dynamic response of structures (Fallah & Louca, 2007). The damage criterion of SDOF approach proposed by Fallah et al. is based on the deflection of a structure. Based on this method, the reinforced concrete beam is idealised as an equivalent elastic-perfect plastic SDOF model. It can be used to produce pressure-impulse diagram for reinforced concrete beam. The diagram is then compared with the impulse diagram generated by LS-DYNA.

2. REVIEW OF EXPERIMENTAL TEST

According to Saatci, eight reinforced concrete beams are tested under falling impact weight at the University of Toronto with different shear reinforcement ratio. To be specific, the dimension of the beams are 250 mm by 410 mm and spanning 4.88 m. The beams are simply supported with effective span of 3 m as shown in FIGURE 3.1.

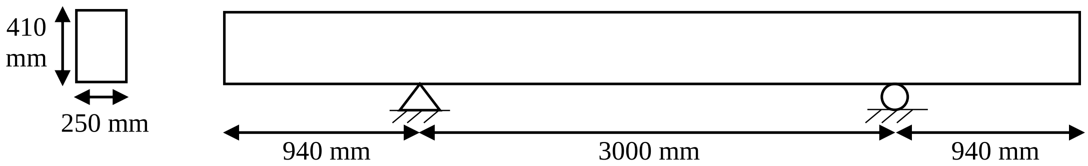


FIGURE 3.1 Specimen Dimension

(Adapted from Saatci, 2007)

The eight beams are grouped into four pairs with each pair having the same amount of reinforcement but different way of testing. For example, the first pair has no stirrup, the second pair has 0.1% transverse reinforcement, the third pair has 0.2% transverse reinforcement and the last pair has 0.3% transverse reinforcement. Furthermore, two specimens in each pair are subjected to different impact loads. In particular, one specimen is subjected to impact from a 211 kg weight once, followed by 600 kg weight twice; whereas another specimen is subjected to impact in the reverse order of the first one. Besides that, the beam is restrained by applying some amount of forces on the top surface of beam so that it will not bounce back after the impact. The setup of apparatus is shown in FIGURE 3.2.

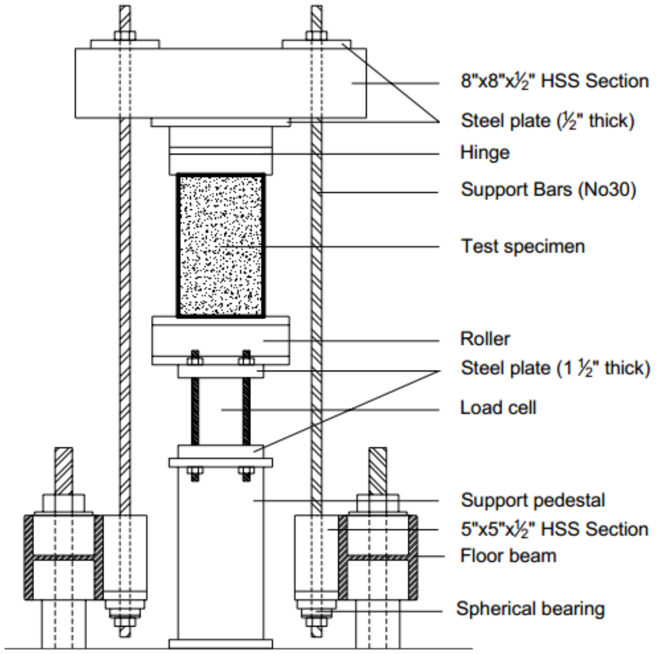


FIGURE 3.2 Cross-sectional of the Test Setup.

(Adapted from Saatci, 2007)

3. MODELLING PROCEDURES

In this research, two beams similar to the experiment are analysed. To be exact, the first beam consists of longitudinal reinforcement only and subjected to an impact from the 211 kg rigid body and it is called SS0a-1 hereafter following the naming of specimen in the experiment. On the other hand, the second beam has a stirrup ratio of 0.1% at 300 mm spacing subjected to the same impact loading and it is called SS1a-1 hereafter. It should be noted that, the beams are impacted once only which are different from the experiment that the specimens were impacted thrice. Having the same dimensions of beams illustrated in the previous section, the beams are modelled in LS-PrePost. Moreover, the beams are meshed into small elements following the locations of the steel reinforcement. This is to ensure that the beam elements for reinforcement and solid elements for concrete are sharing the same nodes and then merged to allow for perfect bonding. At each side of the supports, the beams are clamped by two thin plates which only allow rotation in the direction of the axis perpendicular to the span of the beam. The function of the top plates are to restraint the beam from bouncing back after the impact. The bottom plates resting on a fixed rigid cylindrical supports as shown in FIGURE 3.4 whereas FIGURE 3.3 illustrated the reinforcement in the beams as well as the mesh.

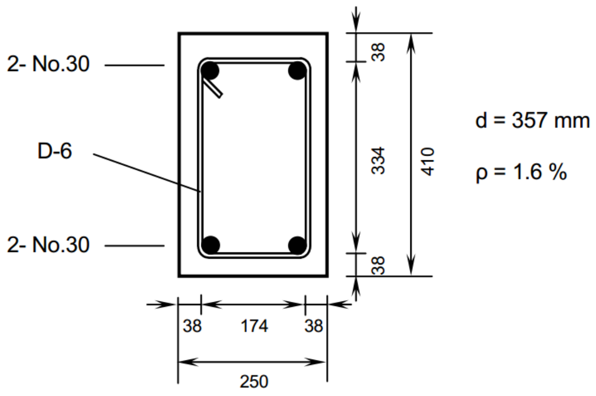


FIGURE 3.3 Beam Cross-section.
(Adapted from Saatci, 2007)

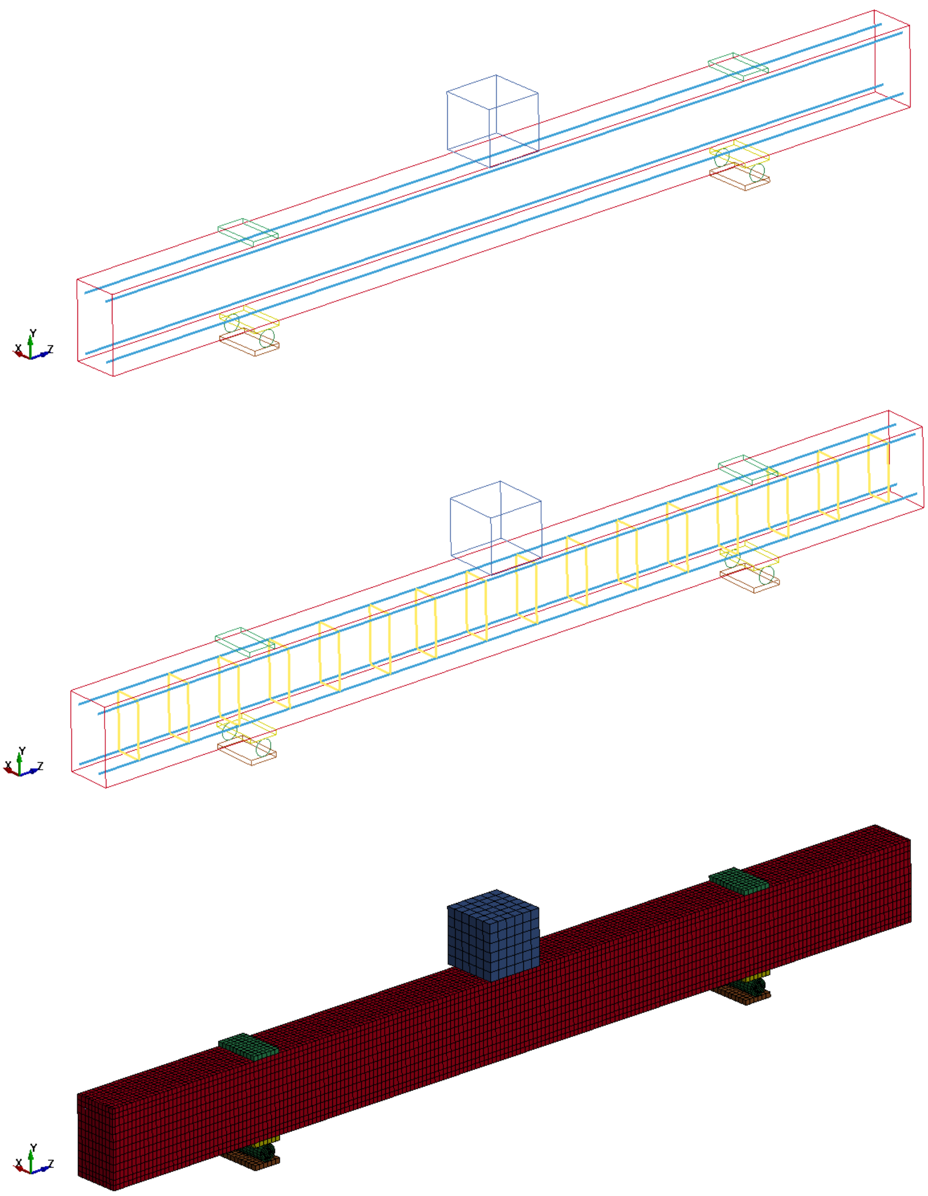


FIGURE 3.4 Beam SS0a-1 (top). Beam SS1a-1 (middle). FE Model (bottom)

As mentioned earlier, the mesh size of the beam depends on the locations of the reinforcement. It is ensured that the reinforcement passes through the nodes of the concrete elements as shown in FIGURE 3.5.

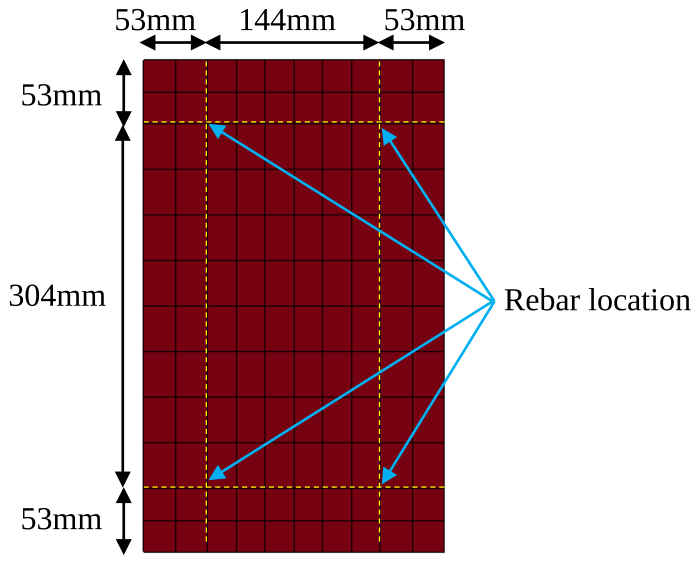


FIGURE 3.5 Mesh Size of Beam Cross-Section.

From the diagram, it can be noticed that each element has a size of approximately 25mm x 25mm and 25mm in the beam span direction, and the whole beam model is made up of these cuboid elements combined together.

Following that, the parts are assigned with different section and material properties using keywords function. All the parameters in the keywords are checked against the software keyword manual to ensure correct values are used. The concrete is modelled using eight-node hexahedron solid elements with a single integration point. Further, the material model of the concrete is *MAT_CONCRETE _DAMAGE_REL3 which is the best material model to be used as suggested by Schwer and Malvar. There are several parameters that are input to the material model. Prior to that, it should be noted that all the values inserted into LS-DYNA are unit-less, hence a consistent set of units is used to avoid confusion. TABLE 3.1 shows the set of units that is used in the model. Other derived units are derived from the basic units shown. After that, the properties of concrete beam are assigned according to the information given in the experiment by Saatci as shown in TABLE 3.2.

TABLE 3.1 Set of Consistent Units Used in LS-DYNA Model.

Parameters	Units
Length	millimetres (mm)
Time	millisecond (ms)
Mass	kilogram (kg)
Force	kiloNewton (kN)
Stress	GigaPascal (GPa)

TABLE 3.2 Properties of Concrete.

Beam	Properties	Values
SS0a-1	Mass density	2437 kg/m^3
	Unconfined compression strength	50.1 MPa
SS1a-1	Mass density	2473 kg/m^3
	Unconfined compression strength	44.7 MPa

Furthermore, strain-rate effect is also included in the concrete material model. A load curve is defined to represent the strain-rate enhancement of the concrete when subjected to impact. Both the strain-rate effects on compression and tension of concrete are included. The values of dynamic increase factor with respect to strain rate and the semi-logarithm graph can be found in APPENDIX 1. It is calculated using CEB formulation for concrete in compression and a modified formulation by Malvar for concrete in tension as shown in the previous research.

On the other hand, for the reinforcement bars, it is modelled using two-node beam element with material model of *MAT_PLASTIC_KINEMATIC. Besides that, the longitudinal reinforcement is formulated using Hughes-Liu formulation with 2x2 Gauss integration. However, using the same material model, stirrups are formulated using truss element which bending is assumed to be absent in the transverse reinforcement. The properties of reinforcement are summarised in TABLE 3.3.

TABLE 3.3 Properties of Reinforcement.

Reinforcement	Mass Density	Young's Modulus	Poisson Ratio	Yield Stress	Diameter
Longitudinal	7850 kg/m^3	195 GPa	0.3	464 MPa	30mm
Transverse	7850 kg/m^3	190.25 GPa	0.3	605 MPa	7mm

Furthermore, strain rate effects are also considered for the reinforcement. The strain rate sensitivity parameter is given in the Cowper-Symonds strain rate model which scales the yield stress with the factor

$$1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{p}}$$

The coefficients of C and p are determined from test data and depend on the type of material used. To be specific, the material for reinforcement used in this study is mild steel, thus the coefficients of C and p are 40.4 and 5 respectively (Paik & Thayamballi, 2003). All the shared nodes between concrete and reinforcement are merged to ensure perfect bonding and prevent slippage between them. Next, the contact interface between the beams and impacting body is defined. According to Ferrer, Ivorra, Segovia, and Irles (2010), the CONTACT_AUTOMATIC_SINGLE_SURFACE algorithm is the most suitable type of contact in LS-DYNA.

As mentioned previously, the beams are subjected to impact from a rigid body undergoing free-falling. In the experiment, the drop weight was placed at a height of 3.26m, resulted in a calculated impact velocity of 8 m/s using equations of motion. There were two weights being used in the experiment, but for the beams SS0a-1 and SS1a-1, the 211 kg weight is used and impact on the beam once only. With the same area of contact between drop weight and beam in the experiment, it is modelled in LS-PrePost as a rigid steel solid section with area of 300 mm by 300 mm. Then, the required height of the impactor is calculated using a steel density of 7850 kg/m^3 which resulted in a height of approximately 300 mm.

After all the keywords definition, the ".k" file is created. Next, the file is uploaded to LS-DYNA solver for the analysis and calculation. As a result, the "d3plot" file is created and the outputs are extracted using LS-PrePost. All the required outputs can be obtained from the fringe components, time-history plot as well as ASCII binary plot. It is important that the results from a simulation test need to be validated, therefore the results are compared against the experiment data and will be discussed in the following section.

4. PROJECT ACTIVITIES AND KEY MILESTONE

This project consists of various stages starting from preliminary studies until the final reporting stage. Each of the activities is important and need to be carry out so that the objectives of the study can be achieved. Nevertheless, the tasks to be performed are within the scope of study and they are specific enough, thus the desired outcomes can be achieved within the specified time frame. Besides, there are some activities or tasks which is critical in this project. These tasks need to be completed on time so that the objectives are achieved and the next tasks can be continued. In essence, these activities are called the project key milestones as summarised in this section.

A) Preliminary Research Work

After finalising the research topic, the project started with some preliminary research works. These include some searching of previous researches related to the project. Besides previous researches, the current design codes and standards are also reviewed. Based on the previous studies, their methodology and findings are noted for report references. After that, the problems statement with the objectives and scope of study are established. This is the first key milestone of the project as the problem statement states the problem faced nowadays and the objectives set will be able to solve the problem at the completion of the study. Moreover, the scope of study limits the author to a specific area so that the study area is not too wide and can be achieved within the specified period of time. More importantly, it conforms to the guide for setting objectives which are specific, measurable, attainable, realistic and within the time frame (S.M.A.R.T.). Next, the research gaps are also identified and included in the critical review of literatures. This critical review is also another key milestone that need to be achieved as it shows the differences and improvement of this research from the previous. Then, learning of software, specifically LS-DYNA is necessary as the method of this project is generally a numerical simulation of vehicular collision.

B) Preliminary Model

As described in the previous section, a preliminary model is produced using a simple beam subjected to an impact free falling rigid steel box at the mid span of the concrete section. All the keywords are defined and outputs are obtained. In this preliminary modelling, one of the key milestones that can be achieved is to know the basic rules of modelling in LS-DYNA. For example, the choice of the most suitable contact algorithm needs some trial and error. With a simple model, this can be easily determined and later can applied directly to the real model. Eventually, it can save a lot of time doing trial and error in the real model which requires longer time for the analysis run.

C) Preliminary Results

After the analysis run by the solver, the outputs can be obtained. Basically, the required outputs are such as the displacement of beam, stresses of concrete and reinforcement, energies plot and impact force. However, these results need to be validated because it is a computer simulation which might differ from an actual collision event. This is another key milestone as it affects the reliability of results. Without a proof to the results, the project may not be continued. There are several methods of validation such as experimental testing. Moreover, the results can also be validated using multiple software such as RCBlast and SeismoStruct. Both software are typically used in dynamic analysis. Accordingly, the similar model is run in other software the results are compared. However, in this study, the results from LS-DYNA simulation will be compared against experimental data obtained from previous research.

D) Review of Experiment Testing

The modelling of reinforced concrete beams are based on an experiment by Saatci. In the author's thesis, the apparatus set up and the testing procedures are well illustrated. Besides that, all the material properties such as concrete properties, reinforcement properties, weight of impactor and others are clearly defined. The model in LS-DYNA is created as close as the experiment set up so that the results can be compared and validated. The thesis is reviewed carefully to avoid any important parameters being missed out.

E) The First Beam Model

As mentioned previously, the beams are modelled according to the experiment following the naming convention in the experiment. For example, the first beam model is called SS0a-1 which is a reinforced concrete beam with longitudinal reinforcement only. The outputs such as beam displacement and reinforcement strain are extracted from LS-DYNA. It is then superimposed on the experimental data to see any discrepancies and inaccuracy of the results. The results of the simulation are discussed in the following section.

F) The Second Beam Model

To have a better understanding on the behaviour of reinforced concrete beam subject to impact, a second beam is generated which is called SS1a-1. In this model, stirrups are included with certain amount of shear reinforcement as described before. Likewise, the outputs such as beam displacement and reinforcement strain are extracted from LS-DYNA. Again, the graphs are superimposed on the experiment plotted graph to see any differences and inaccuracy of the results. The results of the simulation are also discussed in the following section.

5. PROJECT TIMELINE

A) GANTT CHART FOR FYP 1

No.	Activities / Details	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	**Selection of Project Topic**	■													
2	**Preliminary Research Work**														
	• Find sources and understand previous research works.		■	■											
	• Identify the problems, objectives and scope of study.			●											
	• Identify research gap and report in Literature Review.			■	●										
	• Learning of software modelling.				■	■									
3	**Submission of Extended Proposal**						●								
4	**Preliminary Modelling**														
	• Create model parts.							■							
	• Define keywords.								■						
	• Identify parameters.								■						
	• Run analysis and solve errors.									●					
5	**Preliminary Results**														
	• Obtain required outputs.										■				
	• Output analysis and results validation.											●			
6	**Proposal Defence**												●		
7	**Submission of Interim Draft Report**													■	
8	**Submission of Interim Report**														●

Project : Finite Element Analysis on Reinforced Concrete Beams Subject to Impact

As of Date : 5th December 2014

Legends: ● Key Milestone

■ Process

B) GANTT CHART FOR FYP 2

No.	Activities / Details	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	**Refine Scope of Study and Objectives**	■													
2	**Review Previous Research Experiment**														
	• Understand experimental set up.		■												
	• Note all material properties.		■												
3	**Create the First Model based on Experiment**														
	• Identify keywords and parameters involved.			■	■	■									
	• Results validation.					■	■								
4	**Submission of Progress Report**							●							
5	**Create the Second Model Based on Experiment**														
	• Identify keywords and parameters involved.								■	■	■				
	• Results validation.										■	■			
6	**Pre-SEDEX**												●		
7	**Submission of Draft Final Report**												●		
8	**Submission of Dissertation**													■	
9	**Submission of Technical Paper**														●
10	**Viva**														●

Project : Finite Element Analysis on Reinforced Concrete Beams Subject to Impact

As of Date : 26^{th} March 2015

Legends: ● Key Milestone ■ Process

CHAPTER 4

RESULTS AND DISCUSSIONS

In this section, the results of the simulation by LS-DYNA are shown. Some discussions on the results are also included as a reference for future works. Also, the results are compared or validated with the experimental data to access the reliability, accuracy and representative of the results in the real situation.

There are many outputs that can be extracted from LS-DYNA, depending on the keywords defined before the analysis. The main focus of the study is the dynamic response of reinforced concrete beam when subject to impact. Therefore, the results such as the stress, plastic strain of concrete, displacement of the beam and axial strain of the reinforcement are needed. Prior to that, energies plot is needed to determine the stability of the model. First, FIGURE 4.1 shows the contour of stress distribution in the concrete beam when impacted by the rigid steel box at different time. It can be seen that the stress distributed from the impacted point to the two ends of the beam.

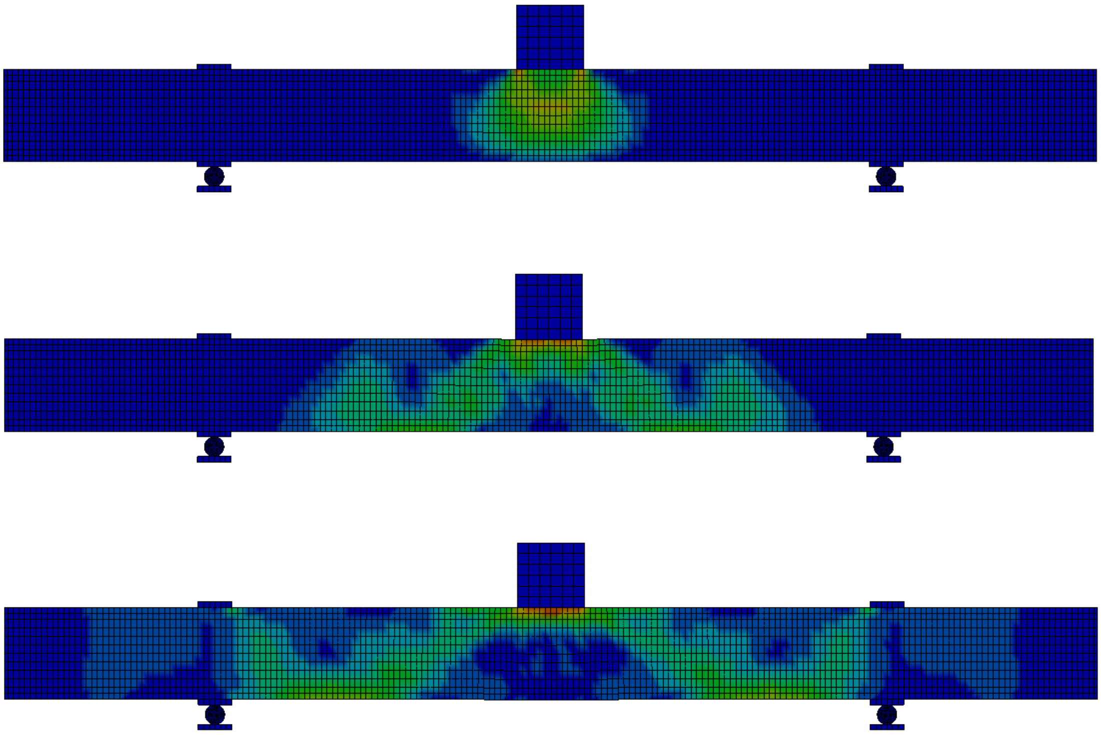
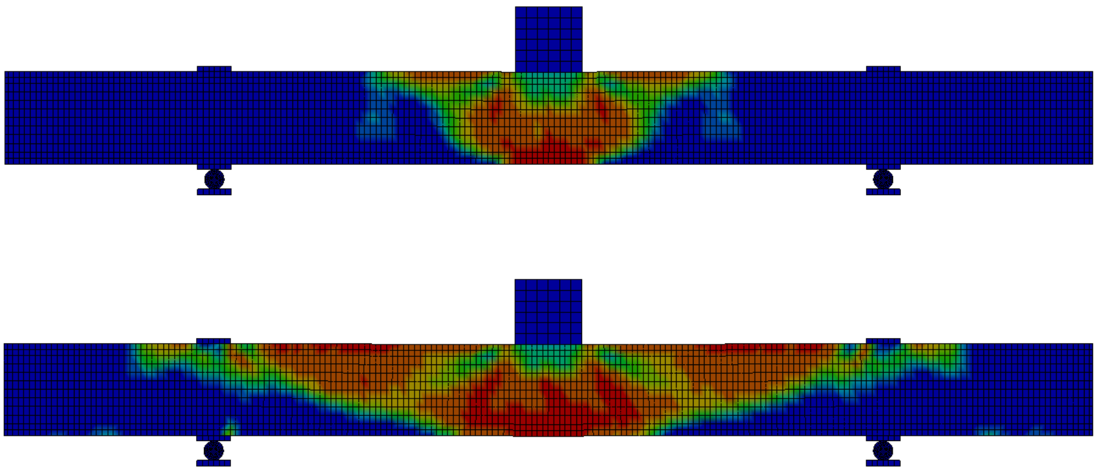


FIGURE 4.1   Stress Distribution of Concrete Beam.

In fact, the stress contour shown in FIGURE 4.1 is the von Mises stress of the element. Von Mises stress is also called the effective stress is an indication of which yielding will occur in a ductile material (Jong & Springer, 2009). In general, von Mises combined six components of stress into a single number for the yield strength checking. The six stress components are three normal stresses in three axes and shear stresses in three planes. Although some researchers argue that von Mises stress is only for ductile material such as steel, there are also several researches have been done on concrete using von Mises stress. The concrete is assumed to be elasto-plastic, hence von Mises criterion is applied to concrete in compression (Hendriks & Rots, 2002). Furthermore, von Mises yield surface is also adopted in the finite element analysis of reinforced concrete structures at an early application (Chen & Saleeb, 2013; Singh, 2007). Since concrete has limited compressive ductility, von Mises surface is combined with maximum crushing strain criterion. Once the concrete element reaches its critical value, crushing will occur and the material element loses its strength completely.

Apart from that, plastic strain can also be used as a graphical representation of the damage of concrete. In other words, it shows the crack patterns in the concrete provided that the mesh size is small enough or at least in the order of the crack width. Then, once the element reaches the maximum strain, it will be deleted from the model. However, the cracks on the beam is not shown in this result section as the mesh size is coarser than the crack width. Nevertheless, from FIGURE 4.2, it can be noted that the contours are spreading diagonally which means the beam has shear cracks instead of flexural cracks. The figure also shows the development of plastic strain of the concrete elements.



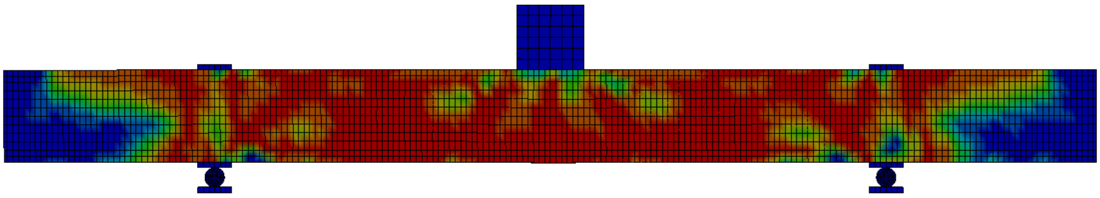


FIGURE 4.2   Plastic Strain of Concrete.

Other than that, it is important to determine the stability of model in finite element modelling. Energies plot usually gives an indication on the stability of the model. In essence, the hourglass energy is kept as low as possible or under 10% of the internal energy as suggested by Allemang et al. Other energies such as total energy, kinetic energy and internal energy are also plotted. These energies show the conversion or transformation of one type to another as shown in FIGURE 4.3 and FIGURE 4.4. The energies in both beam can be said to have the same pattern and magnitude. The total energy is constant and it is conserved. Initially, the kinetic energy has the same magnitude as the total energy which is 6560 Joules. This value can also be checked using the equation

$$E = \frac{1}{2}mv^2$$

$$= \frac{1}{2} \times 211kg \times (8m/s)^2$$

$$= 6752\, Joules$$

The calculated value is relatively close to the kinetic energy calculated by LS-DYNA. When the beam is impacted, the kinetic energy is absorbed by the beam as internal energy. Therefore, the kinetic energy drops whereas the internal energy rises. In addition, the hourglass energy or the zero-energy is always the main concern in finite element analysis. In this case, the hourglass energy (144 J) is considerably low which accounts for 2.3% of the internal energy (6170 J), hence this value is accepted and the model is stable.

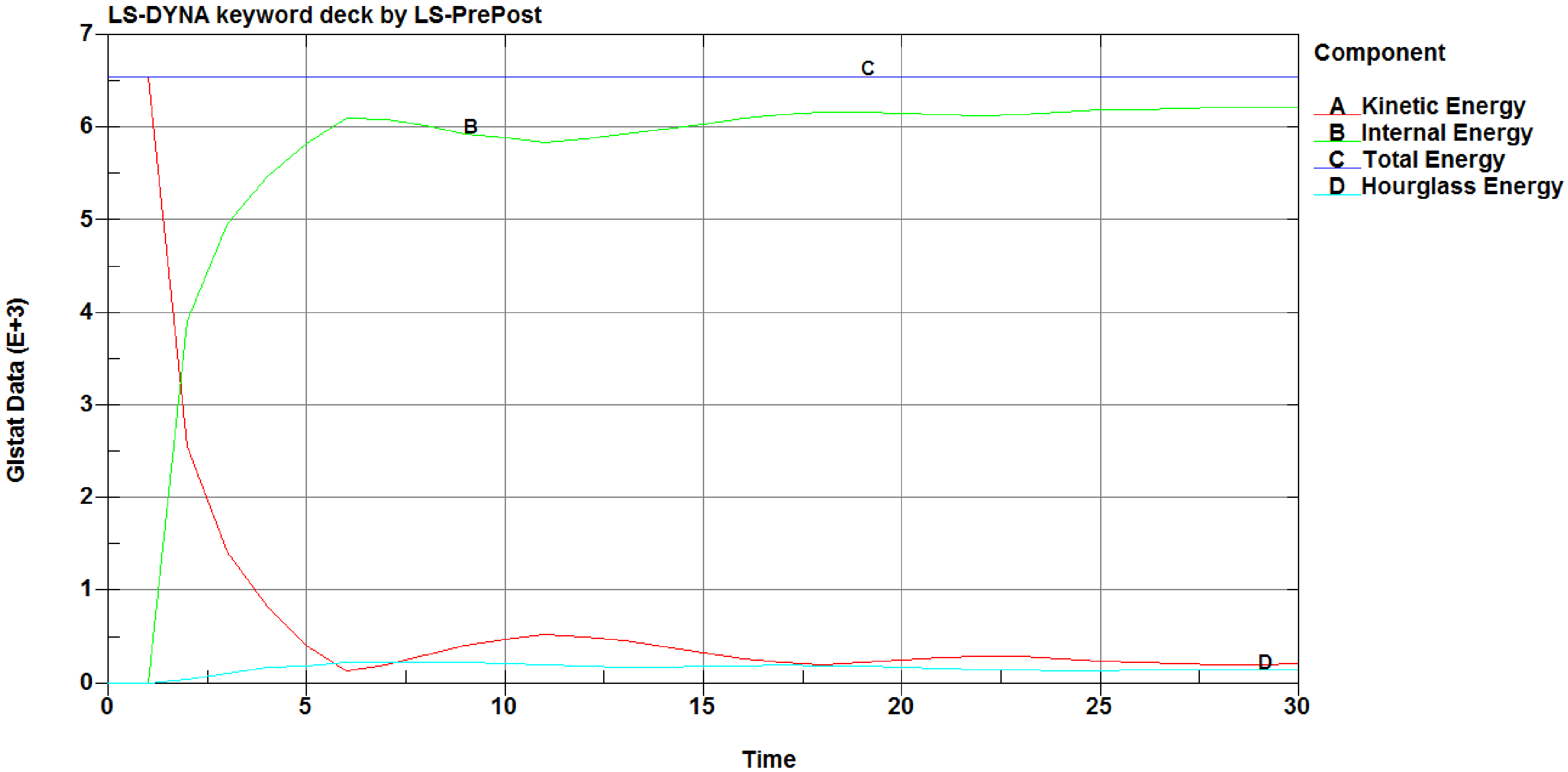


FIGURE 4.3 Energies Plot for SS0a-1 Beam.

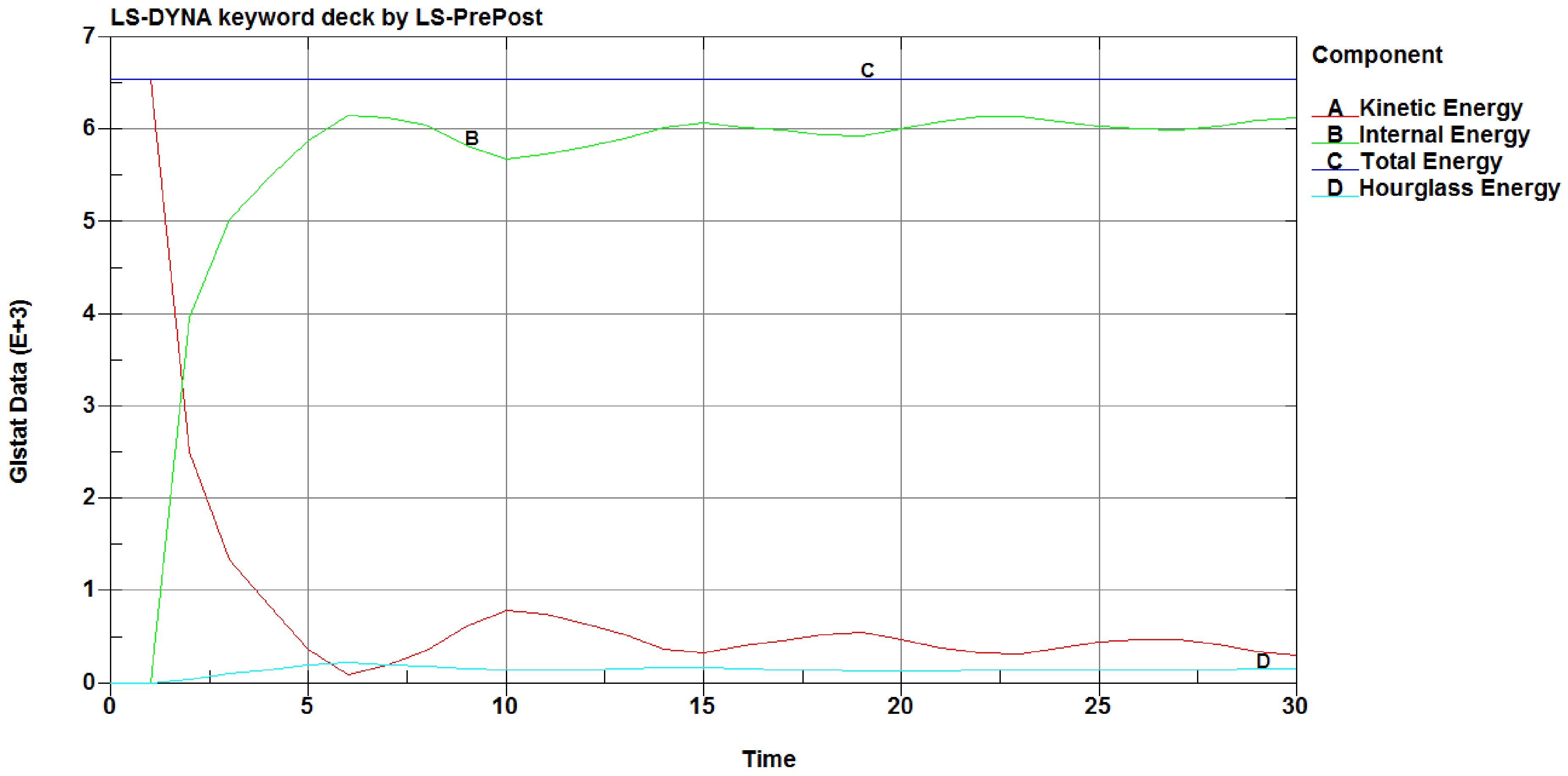


FIGURE 4.4 Energies Plot for SS1a-1 Beam.

At the most fundamental level, LS-DYNA finite element code solves the displacements for each nodes in an element, followed by strains and stresses. To understand the behaviour of reinforced concrete beams subject to impact, it is important to know the displacement of the beam after the impact. In the case of a beam, the mid-span displacement is the most critical. Therefore, only the mid-span displacement of the beam will be discussed in this section. In fact, there are two types of displacements that the designers usually concern. One is the maximum or peak displacement which occur at the instance when the beam is impacted while the other is the residual displacement. Since the concrete has certain elasticity, the displacement-time graph displays a wave type graph and damped to the residual displacement.

For the SS0a-1 beam as shown in FIGURE 4.5, the maximum displacement calculated by LS-DYNA is 10.19 mm compared to the experimental value of 9.1 mm with only a small difference. Hence, it can be said that both results are relatively close to each other. After that, the displacement is getting smaller over time due to damping force in the beam. The displacement calculated by LS-DYNA has larger damping force as compared to experimental data as the displacement graph becomes almost a straight line after 200 ms of the simulation. However, a wave graph can still be clearly seen in the experimental graph after 200 ms. Besides that, LS-DYNA predicted a higher residual displacement of beam which is 3.07 mm whereas the experiment data shows a beam residual displacement of around 1.6 mm.

For the SS1a-1 beam, the maximum displacement obtained from LS-DYNA is 8.84 mm which is lower than the experimental value of 12.18 mm as shown in FIGURE 4.6. This difference might due to simulation errors which will be discussed at the end of this section. However, when the displacement damped over time, LS-DYNA calculated displacement starts to capture the peaks of the experimental graph. It can also be noted that the amplitude of displacement for this beam is higher and the wave-shape graph lasts longer as the stirrups in the beam makes it stiffer and becomes more ductile, exhibiting a more elastic behaviour and resists the shear force through larger displacement of beam. Experimental data shows a residual displacement of 1.05 mm but the simulation in LS-DYNA is not long enough to predict the residual displacement.

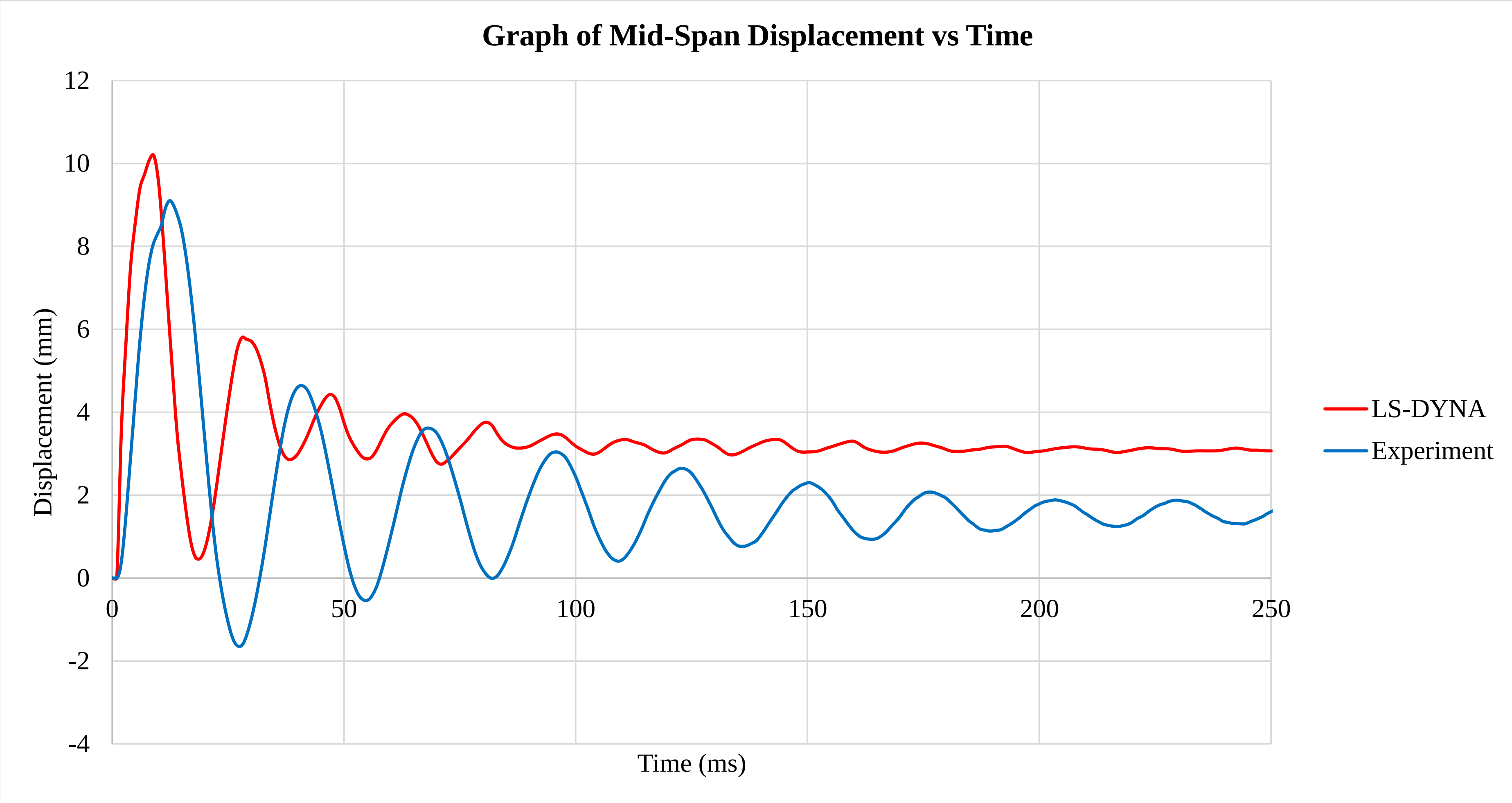


FIGURE 4.5 Displacement-Time Graph for SS0a-1 Beam.

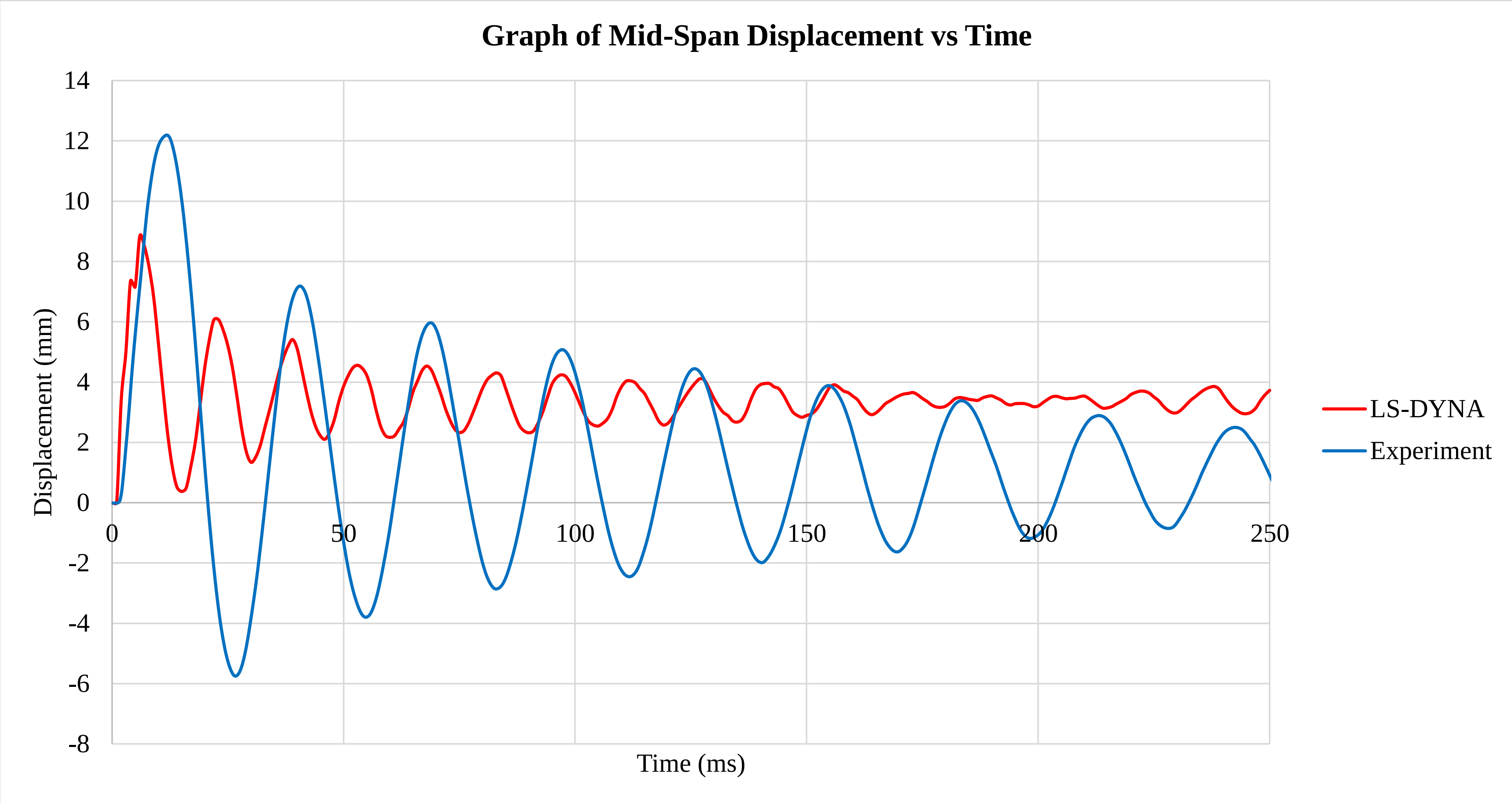


FIGURE 4.6 Displacement-Time Graph for SS1a-1 Beam.

FIGURE 4.7 and FIGURE 4.8 show the graph of longitudinal reinforcement strain over time. These results were taken from the one of the bottom reinforcement of the beams at their mid-span (Bar #3 Gauge #1 from the experiment) because the strain of reinforcement at mid-span is the largest due to largest displacement. As mentioned previously, LS-DYNA finite element code uses displacement to calculate strain and eventually the stress of an element. In general, the reinforcement shows positive strains which mean the rebar are in tension. For SS0a-1 beam, the maximum reinforcement strain obtained from LS-DYNA is 2462 mm/m whereas result from experiment was 2527 mm/m which is close to each other. In fact, these values have exceeded the elastic strain of the high yield steel bar. The maximum strain of the steel bar before it enters plastic region is

$$\varepsilon_y = \frac{f_y}{E_s}$$

$$= \frac{464}{195000} = 0.002379$$

Therefore, this causes some residual plastic strain in the steel bar as shown in the graph. However, LS-DYNA computed a higher residual plastic strain (≈ 545 mm/m) compared to experimental results (≈ 400 mm/m).

Whereas in the case of SS1a-1 beam, the maximum reinforcement strain obtained from simulation is 2683 mm/m whereas experiment gave a peak reinforcement strain of 2305 mm/m. The high strain output from simulation may be due to some errors in finite element analysis which will be discussed later. After that, the graph produced from simulation matches considerably well with the experimental graph. Also, it can be noted that the amplitude of strain of the reinforcement in this beam is higher than the beam without stirrups. The same explanation as for the displacement of beam can be applied. The beam is stiffer with the stirrups, making it resists the shear by bending. Consequently, larger displacement causes higher strain in the reinforcement. Again, it is hard to predict the residual plastic strain of the reinforcement because the wave-like graph will still continue. However, from the experiment, the residual plastic strain is 290 mm/m, thus it is can be hypothesised that the residual plastic strain of reinforcement in this beam is lower than the first beam due to the presence of stirrups.

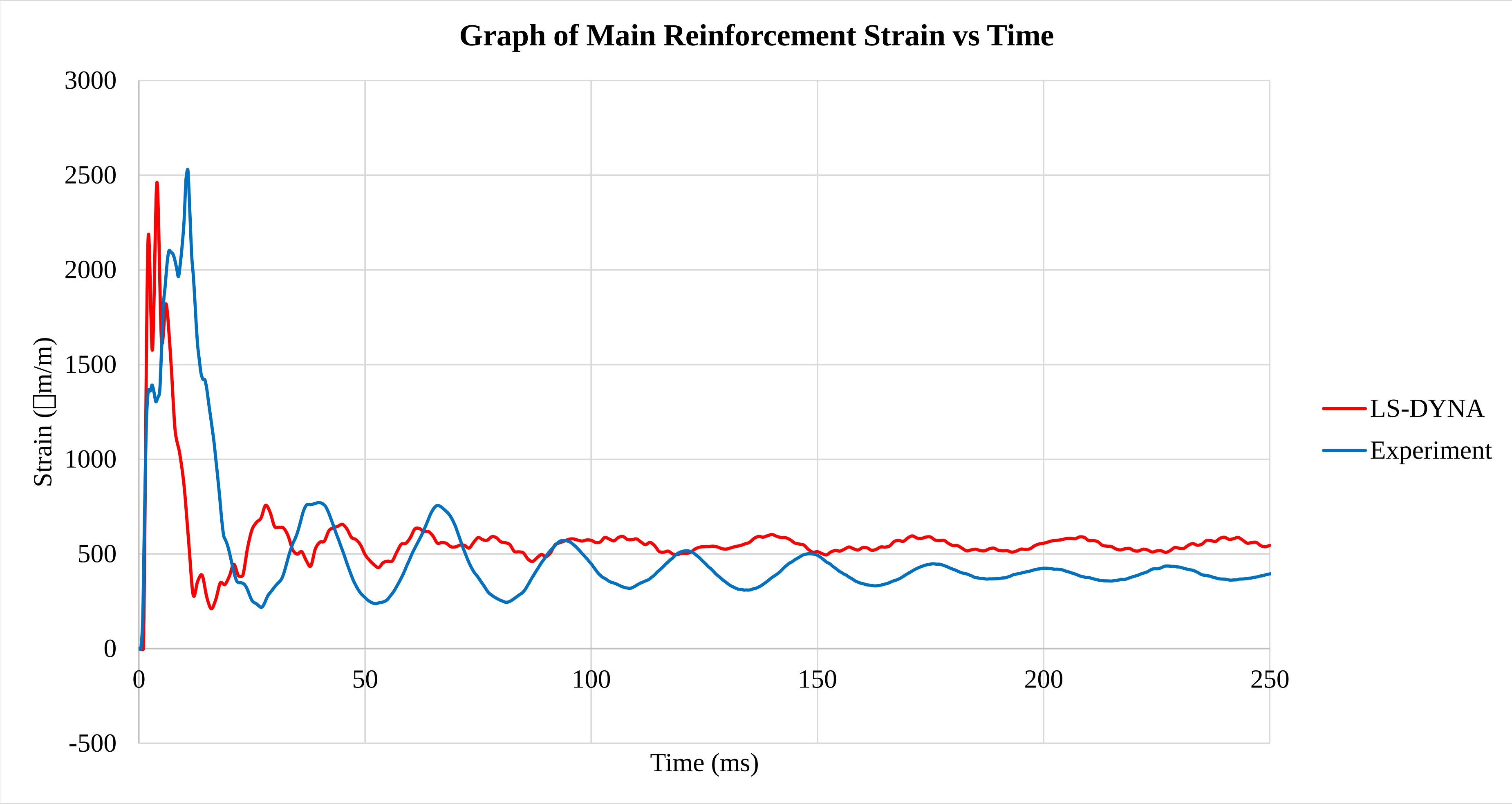


FIGURE 4.7 Rebar Strain-Time Graph for SS0a-1 Beam.

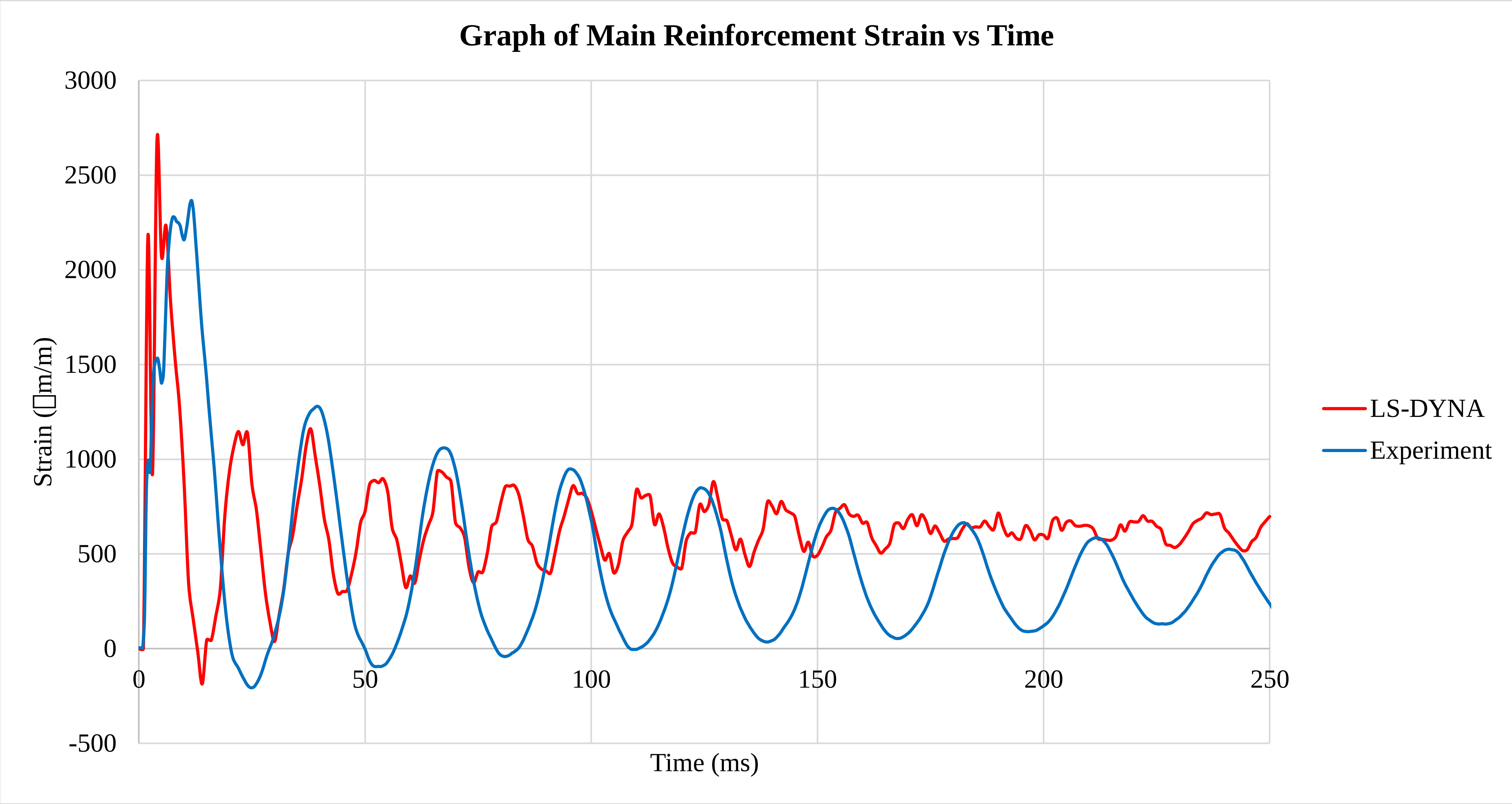


FIGURE 4.8 Rebar Strain-Time Graph for SS1a-1 Beam.

SS1a-1 beam contains 0.1% of shear reinforcement with the intention to compare the results with the beam without stirrups. As shown previously, the displacement and longitudinal reinforcement in this beam is lower due to extra stiffness from stirrups. The beam with stirrups is able to sustain plastic deformations or increased ductility (Said & Elrakib, 2013). According to Sharma et al., reinforced concrete under impact load sustains large shear force and tends to fail in shear rather than flexure. Hence, shear reinforcement in beam aids in resisting shear stresses in the beam. From FIGURE 4.9, the maximum stirrup strains calculated or measured by LS-DYNA and experiment are 1956 mm/m and 2153 mm/m respectively. These values are close to the yield strain of stirrups which implies that the stirrups are successful in resisting shear stress in the beam. After the first impact, the stirrups strains decrease and left with residual plastic strain in the stirrups. Moreover, it is important to note that the effect of high strain rate in concrete and reinforcement. Due to the high strain rate caused by impact load, the strength of concrete and steel reinforcement increase significantly. This strength enhancement allows the materials to sustain higher stress beyond their ultimate strength. All in all, the simulation results fits quite well with the experimental data.

On top of all the results discussed previously, it is necessary to understand the accuracy or reliability of finite element analysis. In every software simulations using finite element code, validation of results is important in order to know whether the results are representative enough of the real situation. Hence, the outputs from LS-DYNA in this study are validated with the experimental data. Although there might have some errors or uncertainties in the experiment which will affect the results, the accuracy in finite element modelling cannot be ignored too. With all these factors, it causes differences between simulation and experimental results. The common sources of errors in finite element simulation can be due to modelling errors, numerical errors and others (Tekkaya & Martins, 2009).

In terms of modelling errors, it is important for a researcher to select a suitable material model for analysis. For example, in LS-DYNA there are several material model for concrete. Some models are not suitable because certain parameters are ignored. As mentioned in the literature, concrete material model in LS-DYNA such as Winfrith model ignores the strain rate effects, thus it cannot be used as strain rate enhancement is an important parameter in an impact analysis for concrete structures.

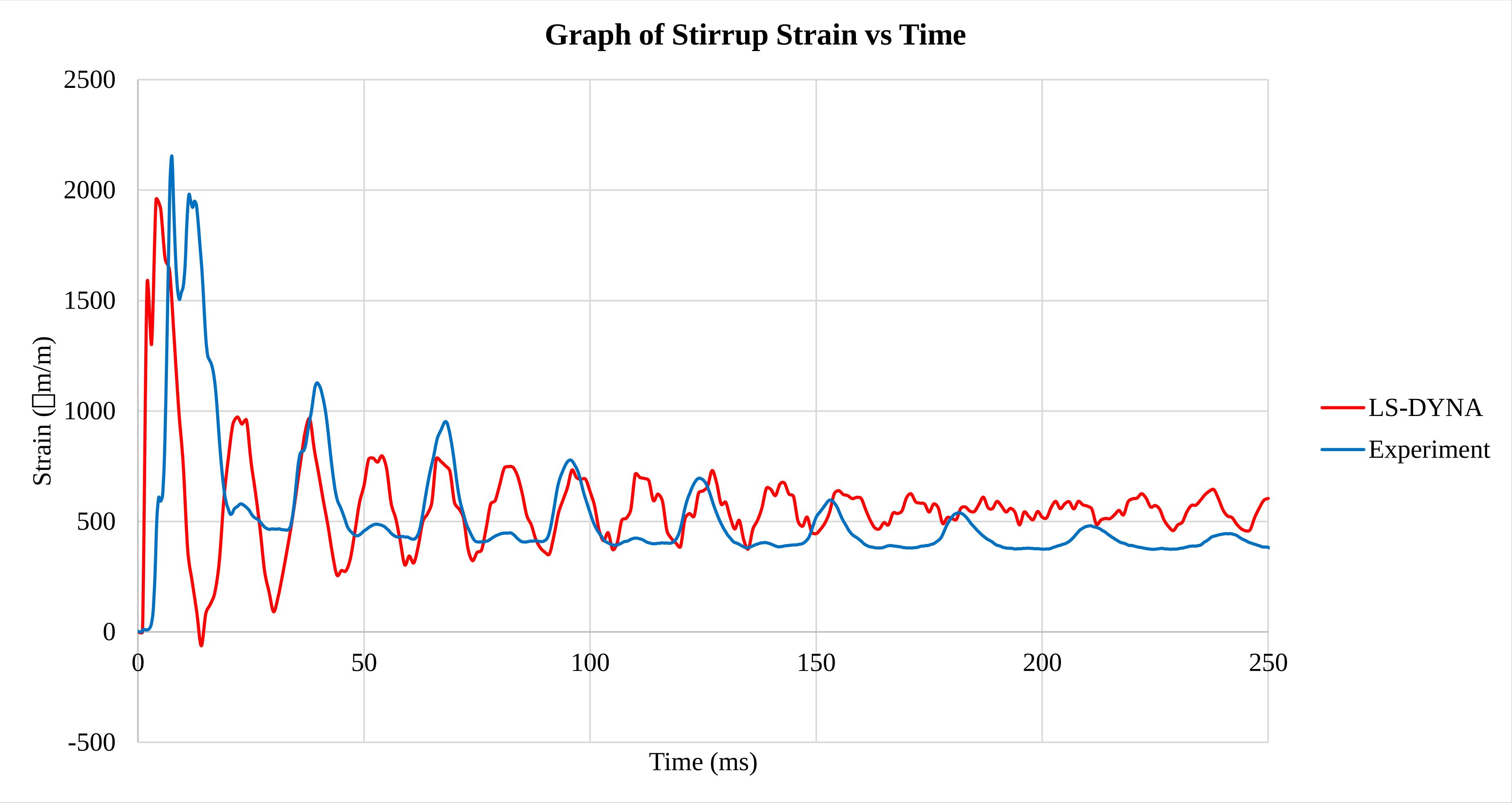


FIGURE 4.9 Stirrup Strain-Time Graph for SS1a-1 Beam.

Second, the common issue in numerical errors is mesh size and shape. Irregular pattern of mesh shape or elements with acute and obtuse angle generally affect the accuracy of the results due to their unconformities. In fact, a finer mesh produces a more accurate results but increases the computation time substantially. According to Tekkaya et al., a mesh convergence study needs to be carried out to obtain the optimum mesh size for analysis. However, in this study, a typical mesh size of 25 mm is used as suggested by Adhikary et al. that any finer mesh has no significant effect on the accuracy of the results. Besides that, time step is another issue which contributes to numerical errors. Time steps in explicit dynamic formulations are usually smaller than quasi-static implicit formulations. For example in an impact analysis, smaller time step provides advantage in showing the development and distribution of stresses in concrete as the event happens in the order of milliseconds. However, this also increases the computation time. Other errors in finite element analysis are due to wrong interpretation of finite element results. Inexperience users might extract the wrong information from the post-processing software.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

Reinforced concrete is the most common construction material used in the industry due to its properties, availability of material as well as its functional cost. In normal case, the structural elements are designed in such a way that the structure remains rigid under normal working condition. To prevent severe consequences to happen, accidental loads are taken into consideration in the design of the structure. In this study, the behaviour of reinforced concrete beams under impact load is analysed. Several researches have been done previously on the behaviour of reinforced concrete beams subject to impact. It was found that the beams failed in shear rather than flexure when subjected to high dynamic loadings. LS-DYNA and LS-PrePost are used in this study to simulate the condition in an event of impact on reinforced concrete beams. The results are validated by experimental data.

The experiment was conducted by Saatci to analyse the dynamic response of reinforced concrete beams subject to impact and their shear mechanisms by varying shear reinforcement ratio and impact load sequence. Two beams namely SS0a-1 and SS1a-1 are selected for the simulations in LS-DYNA. From the results, the simulation outputs match considerably well with the experimental data, although there are slight differences between the results which might be due to the errors in the experiment or errors in finite element analysis as explained previously. The first objective of the study is to simulate the impact on reinforced concrete beam and determine its failure mode. From the contour of plastic strain shown in the result section, the contours spreading out diagonally from the point of impact. This indicates diagonal shear cracks are likely to be formed on the concrete beam. In other words, reinforced concrete beams subject to impact tends to fail in shear due to high dynamic loading.

Besides that, the study also aims to evaluate the behaviour of reinforced concrete beams under impact loading. This is explained in terms of the beam displacement as well as the reinforcement strain. In general, the peak displacement and reinforcement strain occur at the instance when impactor hits the beam. Then, the displacement and reinforcement strain reduce over time due to damping force of the beam and eventually leave some residual displacement and strain as the beam and reinforcement have exceeded the plastic region of material. High strain rate due to impact loading causes strength enhancement in the concrete and steel reinforcement. This enhancement allows the structural members to sustain higher stress beyond their ultimate resistance under static loading.

This study focuses on two reinforced concrete beams from the experiment which one contains longitudinal reinforcement only while the other contains certain ratio of additional reinforcement in the transverse direction or stirrups. The behaviour of reinforced concrete beams are also analysed from their displacement and reinforcement strain. To have a deeper understanding on the beam behaviour, other aspects of the beam can be assessed such as the acceleration and support reactions on the beam. Also, the failure mode of this study was determined by looking at the contour of plastic strain of concrete. This might not give a clear indication on the crack pattern. Therefore, it is recommended to include an erosion function to the concrete model in LS-DYNA. This allows the elements which have exceeded the failure criteria to be deleted from the model and the cracks can be seen in the post-processing software. To do that, a finer mesh in the order of crack width will be needed. On the other hand, the study of reinforced concrete structures under impact loading is useful in the design of reinforced concrete members subject to accidental load. For example, vehicles collide with car park columns or bridge piers. As a continuation of this research, a vehicle model can replace the rigid steel impactor to analyse the response of reinforced concrete column collided by vehicles. This makes a great contribution to the society as the failure of these members may lead to severe consequences. In conclusion, the simulation is successful and the objectives are achieved.

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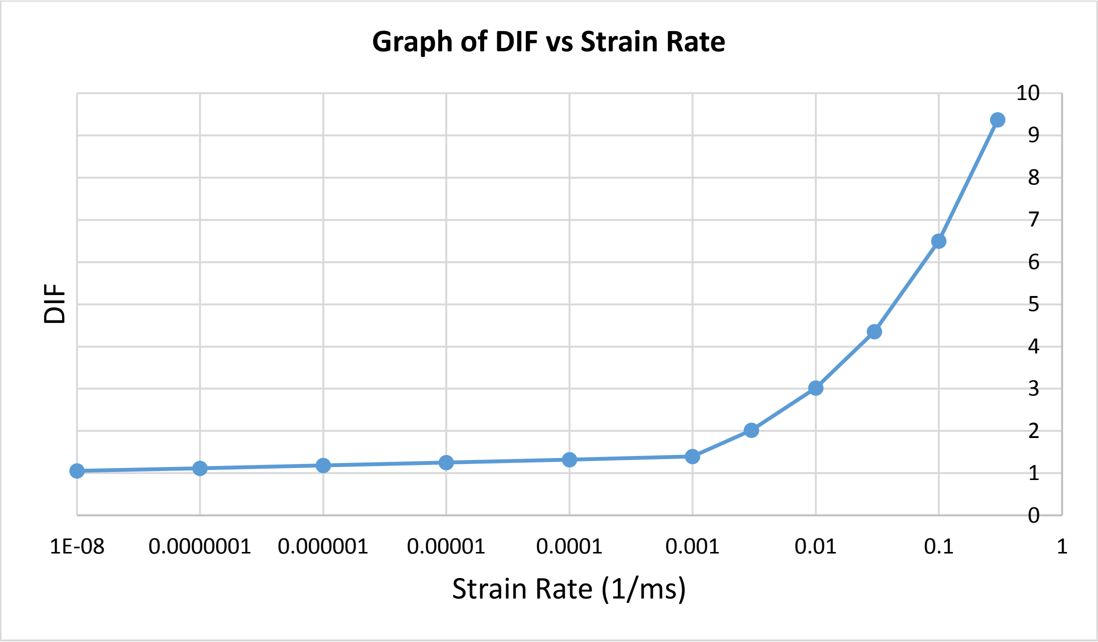
APPENDICES

APPENDIX 1: DYNAMIC INCREASE FACTOR FOR CONCRETE

TABLE A.1 Enhancement Factors for SS0a-1 Beam.

Strain Rate (1/ms)	Enhancement
-3.00E-01	9.370517155
-1.00E-01	6.497153716
-3.00E-02	4.349408779
-1.00E-02	3.015711614
-3.00E-03	2.018816722
-1.00E-03	1.399769335
-1.00E-04	1.323468866
-1.00E-05	1.251327484
-1.00E-06	1.183118479
-1.00E-07	1.1186275
-1.00E-08	1.05765188
0.0E+00	1
3.00E-08	1
1.00E-07	1.024967733
1.00E-06	1.074467599
1.00E-05	1.126358016
1.00E-04	1.180754433
1.00E-03	1.237777873
3.00E-03	1.265947373
1.00E-02	1.297555209
3.00E-02	1.327085128
1.00E-01	1.982401864
3.00E-01	2.859118236

a) Tension



b) Compression

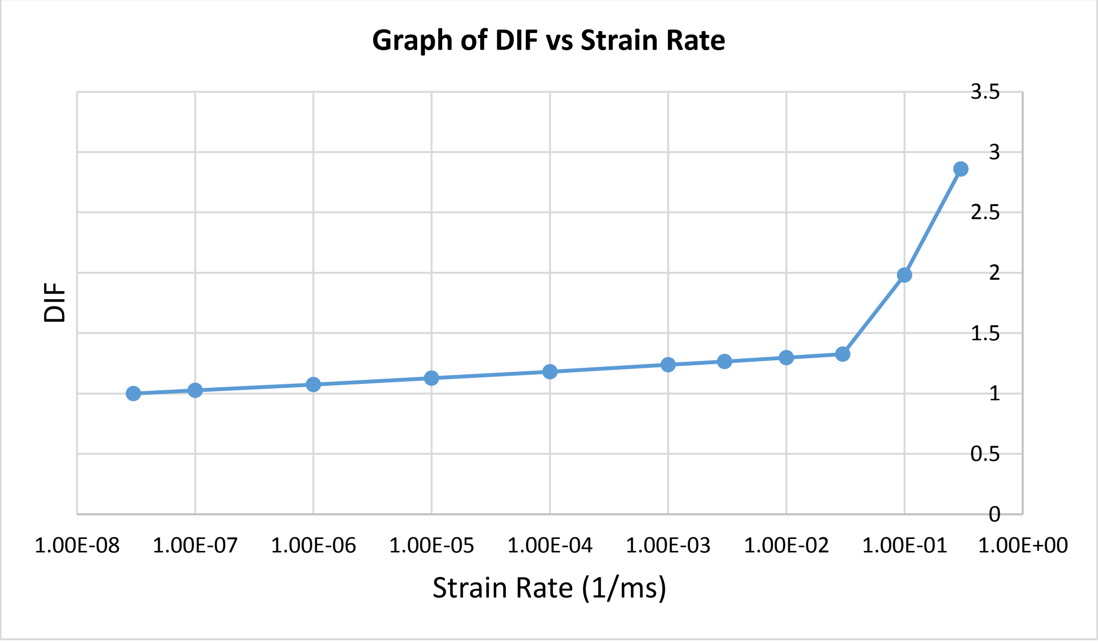
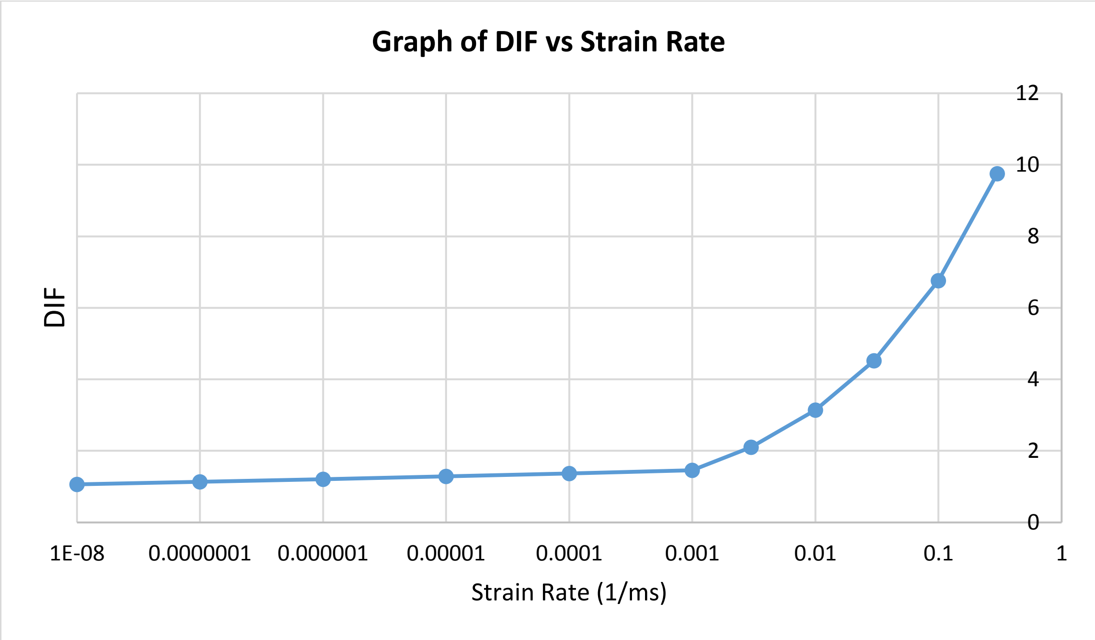


FIGURE A.1 Enhancement Curve for Concrete – SS0a-1.

TABLE A.2 Enhancement Factors for SS1a-1 Beam.

Strain Rate (1/ms)	**Enhancement**
-3.00E-01	9.748279601
-1.00E-01	6.759079567
-3.00E-02	4.524750574
-1.00E-02	3.137286824
-3.00E-03	2.100203174
-1.00E-03	1.456199549
-1.00E-04	1.367783657
-1.00E-05	1.284736102
-1.00E-06	1.206730935
-1.00E-07	1.133461998
-1.00E-08	1.064641723
0.0E+00	1
3.00E-08	1
1.00E-07	1.027687354
1.00E-06	1.082792083
1.00E-05	1.140851535
1.00E-04	1.202024142
1.00E-03	1.266476832
3.00E-03	1.298435247
1.00E-02	1.334385483
3.00E-02	1.368057513
1.00E-01	2.043606478
3.00E-01	2.947390564

a) Tension



b) Compression

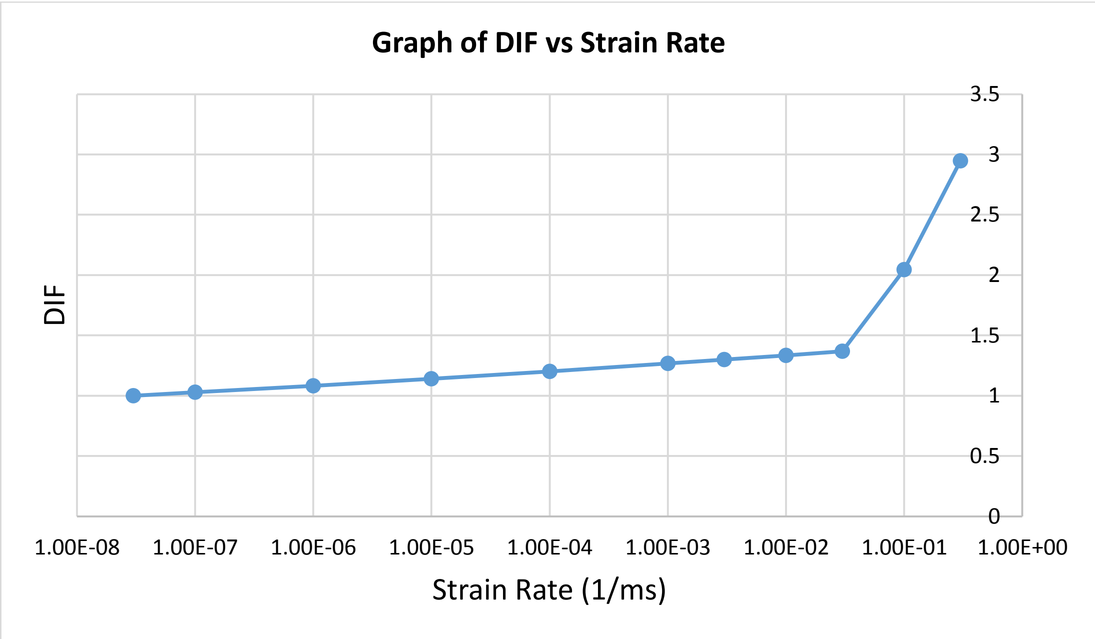


FIGURE A.2 Enhancement Curve for Concrete – SS1a-1.