Predicting the Response of RC Beam from a Drop-Weight Using Gene Expression Programming

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Abstract: For structures and load-bearing beams under extreme impact loading, the prediction of the transmitted peak impact force is the most challenging task. Available numerical and soft computing-based methods for finding peak impact force are not very accurate. Therefore, a simple and user-friendly predictive model is constructed from a database containing 126 impact force experiments of the simply supported RC beams. The proposed model is developed using gene expression programming (GEP) that includes the effect of the impact velocity and the impactor weight. Also identified are other influencing factors that have been overlooked in the existing soft computing models, such as concrete compressive strength, the shear span to depth ratio, and the tensile reinforcement quantity and strength. This allows the proposed model to overcome several inconsistencies and difficulties residing in the existing models. A statistical study has been conducted to examine the adequacy of the proposed model compared to existing models. Additionally, a numerical confirmation of the empirical model of the peak impact force is obtained by reference to 3D finite element simulation in ABAQUS. Finally, the proposed model is employed to predict the dynamic shear force and bending moment diagrams, thus rendering it ideal for practical application.

Keywords: gene expression programming (GEP); reinforced concrete beam; impact loading; statistical analysis; numerical simulation

1. Introduction

The complex behavior of reinforced concrete (RC) beams under impact loading has received significant attention over the past few decades [1–4]. Various response parameters are responsible for characterizing the dynamic response of impacted RC beams [5–9]. One of the most important parameters is the peak impact force, whose correct prediction is essential to designing optimized structural elements that can mitigate the hazardous effects [10–14]. A laboratory test method to measure the peak impact force is the drop weight impact test, in which the contact force between the impactor and the beam is determined by a load cell [15–17]. Once the peak impact force is known, the bending moment and the shear force can be easily determined [18]. So the knowledge of peak impact force determines the whole dynamic behavior of impacted RC beams. Recognizing the significance of the peak impact force, several analytical and computation models have been developed in the past to reliably predict this force. However, most of the available techniques require expertise and are computationally expensive [19,20]. Evolutionary algorithms have proven to be a pertinent technique for developing efficient predictive models that are also user-friendly.

Developing an efficient and accurate predictive model requires an in-depth understanding of key influencing parameters. To establish these parameters concerning the peak impact force, it is increasingly important to understand the overall behavior of impacted RC beams. When impact load is applied to these beams, they undergo two response phases, namely a local phase and a global phase. The local response is identified by a localized shear plug resulting in local deformation at the point of impact, whereas the global phase
is identified by a flexure plastic hinge at the point of impact resulting in global deflection of the beam [3,10,20–33]. From this standpoint, two fundamental response parameters sufficient for adequate prediction of the dynamic response of RC beams can be emphasized: (1) the impact force submitted to the beam and (2) the maximum deflection of the beam. The impact force and the maximum deflection are normally predicted by using various numerical, analytical, or empirical methods. One of the most simple and accurate methods of predicting the response of structures under extreme dynamic loading is based on the rigid-plastic theory [20].

Several experimental investigations have been carried out on RC elements [4,13,15,21–24] under impact loading. These results are also verified by employing commercial software packages, such as ABAQUS and LS-DYNA [10,18,25–29], which can be computationally expensive and time-consuming [1]. Computational processes based on evolutionary algorithms have grown out of a recognition of these inadequacies of traditional design techniques. Genetic algorithms, evolutionary computing, and neural networks have made significant inroads into the analysis and design of structural systems. These techniques can be successfully employed to develop equations that can forecast the important response parameters, such as peak impact force.

Pham et al. [3] developed a neural network-based impact force model for reinforced concrete beams. Similarly, Zhao et al. [7] proposed an analytical model based on the contact laws and the conservation of energy to predict the peak impact response of RC beam under impact loading. Additionally, Tachibana et al. [23] proposed an equation to predict the maximum displacement of RC beam and compared the results with experiments and FEM simulation. In addition, Kishi and Mikami [2] proposed empirical relations for flexural load-carrying capacity and the maximum displacement for the reinforced concrete beam. Ando et al. [30] and Kishi et al. [31] carried out an experimental investigation and concomitant empirical analysis of RC beams subject to input impact energy.

Nevertheless, all foregoing soft computing models [3] have been developed using limited influencing factors, and the available numerical models [21–24] pose excessive computational complexity, which prevents the common application of these models. Similarly, the drawback of the available analytical models [7] is that they are too simplistic, mainly based on single degree of freedom dynamic systems. These considerations require the development of a feasible and efficient model that can predict the response in the spirit of the available experimental data. The current study aims to create a robust model using gene expression programming for predicting the peak impact force on the RC beam from drop-weight. The accuracy of the model is assessed using experimental observations contained in an extensive database containing 126 impact force experiments. This study proceeds by providing a parametric equation of the peak impact force whose results are compared with the existing models in the literature. Additionally, a numerical simulation is presented for two of the experimental tests on the RC beam and its predictions compared with the proposed empirical model of the impact force. This force can also be employed to predict the shear force and the bending moment diagrams for the RC beams under impact loading. For this reason, it is asserted that the drawbacks in the existing models are overcome by developing the current user-friendly GEP model that incorporates additional influencing parameters, such as the shear span to depth ratio, the tensile reinforcement, and the shear reinforcement.

2. Research Significance

One of the most important response parameters is the peak impact force, which is generated within a beam as a result of the applied impact and governs the overall dynamic response of the impacted beam. The peak impact force from a laboratory experiments is calculated using an expensive load cell and sensor assembly. Once the peak impact force is obtained, the dynamic shear force and the bending moment diagrams can be easily determined, thereby offering all the necessary information to design the impacted beam. To avoid the expensive impact force assembly, very limited models [4,13,15,21–24] are
available to predict the peak impact force but with insufficient accuracy. The current study aims at identifying some key factors that the available models have overlooked, such as concrete compressive strength, the shear span to depth ratio, and the tensile reinforcement quantity and strength. Hence, a robust regression-based model [3] is built that incorporates all these key parameters, resulting in an accurate prediction of peak impact force, which compensates for the inconsistencies of the available models. The predictive ability of the proposed gene expression programming-based model is ensured by comparing the results with the existing soft computing models and single degree of freedom analytical models [7].

3. Assumptions

The proposed method is intended for predicting the peak impact force transferred to a simply supported beam subjected to midspan drop weight impact. The following assumptions are made during the development of the new model:
1. The shape of the impactor is considered not to influence the impact behavior of RC beams;
2. The impact event is so fast that the damping of the impacted component can be neglected;
3. The bearing plates are normally provided to distribute the impact load and avoid localized failure. This influence of the bearing plate is ignored;
4. The impact force is applied perpendicular to the longitudinal axis of the beam;
5. No provision is made in the proposed model for incorporating special anchored reinforcement.

4. Discussion of Influencing Parameters

In setting up an empirical model for the impact force on RC beams, the knowledge of various influencing parameters is essential. Therefore, various important factors are identified [8,11,32–34], such as the concrete compressive strength, the longitudinal tensile reinforcement, the yield strength of longitudinal reinforcement, the vertical shear reinforcement, the mass, the velocity of the drop-weight, and different geometric properties of the RC beam. The significance of these variables has been demonstrated by extensive experimental studies by Hughes and Mahmoud [35], Louw et al. [36], May et al. [37], Zhan et al. [38], and Goldston et al. [13]. From these precedents, Zhan et al. [38], May et al. [37], and Louw et al. [36] pointed out that the concrete compressive strength shows a positive correlation with the impact force from a drop-weight. A similar increasing trend has been observed by Adhikary et al. [32] through numerical simulation. This trend follows intuition since as the compressive strength is increased, the beam capacity and the stiffness are increased, thereby resulting in an increased peak impact force because stiffer elements attract more force. In the same context, increasing the width or depth of the beam will attract more impact force than increasing the length of the beam.

Longitudinal tensile reinforcement is another important parameter affecting the peak impact force on the RC beam. In this instance, Goldston et al. [13], Hughes and Mahmoud [35], Adhikary et al. [11], and Zhan et al. [38] observed the influence of the longitudinal tensile reinforcement on the impact force because as the tensile reinforcement increases, both the ultimate bending moment capacity as well as the ultimate load-carrying capacity increases. Zhan et al. [38] and Fujikake et al. [4] also observed that the stiffness of the RC beam increases with the increase in the longitudinal tensile reinforcement, which tends to rise the peak impact force. The yield strength of the longitudinal reinforcement also contributes to the impact force as it increases the brittleness of the RC beam. Similar behavior has been produced by Adhikary et al. [32] with the help of a numerical study. Adhikary et al. [11] and Bhatti et al. [8] have shown the increasing trend of the peak impact force with the increasing vertical shear reinforcement. This trend is due to the transverse reinforcement providing additional confinement to the core concrete, thereby supplementing lateral restraint capacity against the buckling of the longitudinal reinforcements.

Input kinetic energy \((K.E = \frac{1}{2}MV^2)\) has a vital role in the impact analysis of the RC beam under drop-weight. By increasing the input kinetic energy, the increase in the peak impact load has been reported by various researchers [8,33,34].
5. Experimental Database

The peak impact force prediction model has been developed using an extensive database of 126 experimental tests from the previous studies [2,4,8,23,24,38–42], summarized in Tables A1 and A2. This database comprises RC beams of rectangular cross-sections subjected to impact, where the impactor’s contact surface is either flat or spherical. For GEP analysis, only a randomly selected portion of 84 experiments is used to develop the model and the remaining 42 experiments are used to validate the model.

Distribution of Key Influence Parameters

The dataset comprises various influencing parameters that are essential for developing a robust predictive model. The determination of these parameters requires an in-depth review of experimental investigations. The parameters influencing the peak impact force and their validity ranges are derived from the literature [4,13,15,21–24]. These key parameters are the impact velocity, the impact mass, the geometric size of the beam, the concrete compressive strength, the longitudinal reinforcement, and the shear reinforcement. These parameters, along with their respective ranges within the dataset, are listed in Table 1.

| Parameters                     | Ranges             |
|-------------------------------|--------------------|
| Velocity (V)                  | 1–16 (m/s)        |
| Mass (M)                      | 33–1700 (kg)      |
| Compressive strength (f'_c)   | 20–42 (MPa)       |
| Net span length (L_n)         | 1000–5000 (mm)    |
| Beam width (b)                | 100–300 (mm)      |
| Beam height (h)               | 120–500 (mm)      |
| Tensile reinforcement ratio   | 0.29–3.1 (%)      |
| Shear reinforcement ratio     | 0–1.4 (%)         |

6. Previous Models to Evaluate the Peak Impact Force on RC Beam

The reliability and validity of any model can be demonstrated by comparing it with the existing analytical and numerical models. Hence, the models proposed by Zhao et al. [7] and Pham and Hao [3] are selected for this purpose.

6.1. Zhao et al. Model

Zhao et al. [7] proposed a peak impact force model using the contact law and the conservation of energy. In this model, the energy-balance equation for predicting the peak impact force for both spherical and flat nose drop-weight impactors can be given by the following equations, respectively:

\[ F_P = \left[ \frac{9MV^2}{8 \left( \frac{M}{m+1} \right)} \left( \frac{\pi EA}{d} \right)^{\frac{1}{2}} \right]^{\frac{1}{2}} \]  

\[ F_P = \left( \frac{3MV^2}{4 \left( \frac{M}{m+1} \right)} \times \frac{EA}{d} \right)^{\frac{1}{2}} \]

where \( F_P \) is the impact force, M and V are the mass and velocity of the impactor, m is the effective mass of the beam (calculated using the approximate design method proposed by Biggs), E is the elastic modulus of concrete (where \( E = 5000 \times \sqrt{f'_c} \)), d is the depth of the beam, and R and A are the respective radius and area of the impactor.
6.2. Pham and Hao Model

Pham and Hao [3] introduced an artificial neural network (ANN)-based empirical model. The simplified form of the model is given below;

\[ P = W \times X + e \] (3)

where \( W \) is a proportional matrix, \( X \) is the input matrix, and \( e \) is scalar, which is calculated as follows:

\[ e = LW \times b_1 + b_2 \] (4)

\[ W = LW \times IW = \begin{bmatrix} w_1 & w_2 & w_3 & w_4 & w_5 & w_6 \end{bmatrix} \] (5)

\[ X = [x_1 \ x_2 \ x_3 \ x_4 \ x_5 \ x_6]^T = \begin{bmatrix} f'cEI & Ln & m & m_2 & M & V \end{bmatrix}^T \] (6)

where \( IW \) is the input weight matrix, \( b_1 \) is the bias matrix of layer 1, \( LW \) is the layer weight matrix, \( b_2 \) is the bias matrix of layer 2, \( f'c \) is the concrete compressive strength, \( \frac{EI}{Ln} \) is the flexural stiffness parameter with \( EI \) as flexural rigidity and \( Ln \) as the net span, \( m \) is the beam weight, \( m_2 \) is the weight of the overhanging ends of beam, \( M \) is the impactor mass, and \( V \) is the impactor velocity. Additionally, \( x \) means the cross product.

The above model can be simplified in the following form:

\[ P = \sum_{i=1}^{6} k_i x_i + c \] (7)

where \( k_i \) are proportional factors and \( c \) is a constant. In this model, it is derived that \( c = 21,119 \) and

\[ k = \begin{bmatrix} 7.63 & -0.02 & 1.93 & -3.17 & 1.34 & 186.09 \end{bmatrix} \] (8)

7. GEP Algorithm

Gene expression programming (GEP) is a type of genetic algorithm (GA) that generates mathematical models from the input data and processes them in a domain-independent manner. In terms of chromosome representation, GEP differs from the genetic algorithms GAs and the genetic programming GP. In GAs, chromosomes are linear strings of fixed length, whereas in GPs, they are nonlinear entities of varying sizes and shapes. GEP, on the other hand, encompasses both a fixed-length linear string and a ramified structure of various sizes and shapes.

As with other evolutionary algorithms, several trials were carried out to execute the evolutionary process by iteratively changing the number of chromosomes, the number of genes, the size of the head, and the linking functions. Thus, GEP optimizes solutions by selecting the best candidates from the provided initial population based on their fitness. Notably, increasing the number of genes and chromosomes can result in a complicated function but the function can precisely fit the results. There is a trade-off between achieving a simplified mathematical model by controlling the number of genes and chromosomes and achieving the desired level of accuracy.

Convergence to the global optimal solution is a critical step in the GEP algorithm. The algorithm may fail to select an optimal solution from among several competing candidate solutions at times. In this state, the algorithm can lead to an indefinite sequence of steps, which can result in either a non-terminating program or an illogical expression. This problem can be solved by adjusting the linking function or changing the number of genes and chromosomes.

Over the last decade, the advantages of the GEP have attracted widespread application in the field of structural engineering. Several authors [3] have used the GEP to develop models for estimating the capacity of various structural components elegantly. In the present work, the GEP was used successfully to predict the behavior of an RC beam from a drop-weight.
Figure 1 depicts the various stages of GEP optimization. The optimization procedure begins with the selection of control parameters, such as the function set, the terminal set, the fitness function, the control parameters, and the stop condition. The fitness function is specified before the execution of the evolutionary algorithm, which results in the creation of a random string of initial population, also known as ‘chromosomes’ in genetic programming parlance. These strings are translated into an expression tree, the results of which are compared to each chromosome’s fitness score. If the fitness criterion is not met, a roulette-wheel sampling method is used to select some chromosomes, which are then mutated to produce new generations. In contrast, if the variables are optimally tuned to the fitness function, the chromosomes are optimized [49].

Figure 1. Flow chart for GEP model construct.

8. Proposed GEP Model for Estimating Peak Impact Force

In this section, a GEP model is proposed for the peak impact force on the RC beam. The GEP models generated from the previously mentioned dataset can be represented by the following equation extracted from genetic sub-elemental tail (Sub ET):

\[ F_p(kN) = G_1 + G_2 + G_3 \]  

\[ G_1 = \left( \frac{1}{3.07 + 2V} \right)^5 + \left( \frac{V}{L_n + \frac{A_s f_y}{f_c'}} + s - 2390.26 \right) \]  

\[ G_2 = \left\{ \left( \frac{f_c'}{\frac{V}{2} - 2.93} + (\ln(V) \times (b - \rho_v f_y + 40.27)) \right) - (f_c' \times \sqrt{V}) \right\} \]  

\[ G_3 = \left\{ \left( (6.83 + f_c') \times V \right) + b + 3h - \frac{a}{d} - \frac{M}{V} - 2s - d - 404.96 \right\} \]

where \( b, h, \) and \( d \) are the respective width, height, and effective depth of the beam; \( V \) and \( M \) are the velocity and the mass of drop-weight, respectively; \( L_n \) and \( \frac{V}{2} \) represent...
the respective net span and shear span to depth ratio of the beam; $A_s f_y$ is the product of area and yield strength of longitudinal reinforcement; In is the natural log; $f'_c$ is the concrete compressive strength; $\rho_v f_y$ is the product of reinforcement ratio and yield strength of transverse reinforcement; and $s$ is the mid-span deflection.

The expression tree of the estimation model is also given in Figure 2, along with the model construction parameters shown in Table 2.

Figure 2. Gene expression for the peak impact force. (a) Sub ET-1 (b) Sub ET-2 (c) Sub ET-3.
Table 2. Model Construction Parameters.

| Function Set          | ln, +, −, /, x, sqrt, x^{2,3,4,5} |
|-----------------------|-----------------------------------|
| Chromosomes           | 110                               |
| Head size             | 11                                |
| Linking function      | Addition                          |
| Number of genes       | 3                                 |
| Mutation rate         | 0.0014                            |
| Inversion rate        | 0.1                               |
| One-point recombination rate | 0.0027                     |
| Two-point recombination rate | 0.0027                    |
| Gene recombination rate | 0.0027                         |
| Gene transposition rate | 0.0027                       |
| Constants per gene    | 10                                |
| Lower/upper bound of constants | −20/20                     |

9. Accuracy of the Proposed Model

The accuracy of any empirical model is inextricably linked to the training and validation of these models using the available dataset [45]. In the case of the current model, a random sample of 60% from the designated RC beam experiments is used as training data (for model creation), while a random sample of 40% from each category is used for validation. After the model development, several statistical performance checks, such as the performance factor (PF), coefficient of variation (CoV), average absolute error (AAE), and coefficient of determination are used to gain quantitative insight into the model. The coefficient of variation (CoV) measuring dispersion around data mean is the precision testing measure that can be presented by

\[ CoV(\%) = \left( \frac{\text{Standard Deviation (σ)}}{\text{Mean (μ)}} \right) \times 100 \] (13)

The average absolute error (AAE) between the proposed model and the experimental data can be expressed as

\[ AAE(\%) = \frac{1}{n} \times \sum \left( \frac{|\text{Experimental value} - \text{predicted value}|}{\text{Experimental value}} \right) \times 100 \] (14)

where \( n \) is the number of test specimens.

The coefficient of determination \((R^2)\) testing the model reliability can be determined by the expression

\[ R^2 = 1 - \frac{\sum[\text{Experimental value} - \text{predicted value}]^2}{\sum[\text{Experimental value} - \text{Experimental value}_{\text{mean}}]^2} \] (15)

where the value of \( R^2 \) close to 1 is considered an accurate prediction.

The slope of the best fit line \((m')\) measures the accuracy of the developed model. This slope can be readily obtained from

\[ m' = \tan^{-1} \left( \frac{y_2 - y_1}{x_2 - x_1} \right) \] (16)

where \( x \) and \( y \) represent the abscissa and ordinate values, respectively.

The statistical comparison of the proposed model with the experimental results is shown in Figure 3. The observation of the coefficient of determination \((R^2)\) suggests that its value is 0.98 for both training, validation, and overall data. Surely the close proximity of the \( R^2 \) value to 1.0 suggests an accurate prediction. Furthermore, the best-fit line for the predicted peak impact force is \( y = 0.96x \) for all data, which is just under the 45° benchmark, indicating a superior correlation between experimental and predicted results.
Figure 3. Comparison of predicted and experimental results of peak impact force. (a) training data; (b) validation data; (c) all data.
Understanding the influence of all the variables in the proposed model is useful for evaluating the model efficiency. Figure 4a,b show that increasing the width and depth of the beam increases the stiffness of the beam, thereby attracting more impact force. Similarly, Figure 4c shows that increasing the compressive strength of concrete increases the modulus of elasticity and the stiffness of the RC member, thus attracting more impact force. On the contrary, the peak impact force reduces as the span of the beam increases, as shown in Figure 4d. The effect of the tension force of the longitudinal reinforcement follows the pattern akin to that of Figure 4a–c,e because the ultimate bending moment capacity and the load-carrying capacity increase with the increase in the longitudinal reinforcement. The influence of input kinetic energy on the impact force is featured in Figure 4f. It can be seen that the higher magnitude of the imparted kinetic energy results in a larger impact force.

![Figure 4. Parametric study. (a) Peak impact force vs. beam width; (b) Peak impact force vs. beam height; (c) Peak impact force vs. concrete compressive strength; (d) Peak impact force vs. beam span; (e) Peak impact force vs. steel tension force; (f) Peak impact force vs. input kinetic energy.](image-url)
The predicted to the experimental ratio (PER) is an important factor in the determination of the sensitivity of various parameters in the proposed model. It is clear from Figure 5 that the PER is close to the benchmark value of 1.0 for the core variables, namely the impactor velocity \( V \), the impactor mass \( M \), the beam width \( b \), the beam height \( h \), the concrete strength \( f'_c \), and the ratio \( \frac{A_s}{f'_c} \). This clearly shows the adequacy of the proposed model for the various ranges of these core variables.

![Figure 5](image_url)

**Figure 5.** Evaluating the predictive performance of the proposed model. (a) Velocity of Drop, (b) Mass of Drop Weight, (c) Breath of Beam, (d) Depth of beam, (e) Concrete Compressive Strength, (f) Normalized Reinforcement Ration.

10. Development of a Numerical Model

This section compares the proposed empirical model with a numerical model developed using finite element code ABAQUS (Version 2022, Dassault Systemes, Waltham, MA, USA). First, the experimental results of Bhatti [8] are employed to calibrate the ABAQUS model, then the impact force given by the finite element simulation is compared with the proposed GEP model. Notably, the experimental results considered herein are neither used in training nor the validation of the GEP model.

10.1. Experimental Program Bhatti

As per the experimental study reported by Bhatti [8], a series of 2400 mm long beams were tested under impact loading of 400 Kg. The RC beam was of 41.2 MPa compressive strength having a square cross-section of 400 × 200 mm and 50 mm cover all around.
Further, the longitudinal and transverse bars were of 35 and 6 mm diameters, respectively, with the yield and ultimate strength of 395 MPa and 501 MPa, and the spacing of stirrups was 150 mm. Following Bhatti’s classification of tested specimens, the beam with stirrups spacing of 150 mm is named Type-A.

10.2. Response of RC Beam Predicted by ABAQUS

A 3-D finite element model, Figure 6, was constructed to simulate the dynamic response of the RC beam. The model was developed in ABAQUS using its contact element capability. C3D8R brick elements were used for the beam, T3D2 wire elements were used to model the steel in the beam, and isoparametric elements were used to model the striker. A perfect bond between the concrete and reinforcement was ensured by adopting the embedded method. The impactor and the beam were permitted to stay in contact by employing frictionless interfacial elements. The concrete had a prescribed density of 2400 kg/m$^3$, a Poisson’s ratio of 0.19, and a Young modulus of 25.7 GPa. Similarly, the reinforcement had a density of 7850 kg/m$^3$, a Poisson’s ratio of 0.3, and a Young modulus of 206 GPa. The number of elements implemented for the beam was 7371 and for the impactor was 1771. The dynamic behavior was evaluated by an explicit time integration scheme with automatic control of time steps.

![ABAQUS model of a beam subjected to central transverse impact. (a) FE baseline model; (b) FE mesh model.](image)

**Figure 6.** ABAQUS model of a beam subjected to central transverse impact. (a) FE baseline model; (b) FE mesh model.

Mechanical properties of concrete were modeled using concrete damage plasticity, and the properties of the reinforcing bars were described by the elastic–plastic material model. Concrete damage parameters are shown in Table 3. As per the experimental study, the support conditions were simulated as simply supported. Geometrical nonlinearity was taken into account, and a convergence study was carried out to optimize the mesh size. The ABAQUS was calibrated based on the available test results of a 384 kg impactor striking the beam at midspan. ABAQUS peak impact force was determined for two test cases of impactor striking velocities, namely 6.52 m/s and 7.42 m/s.

| Parameters                                      | Values |
|-------------------------------------------------|--------|
| Tensile strength of concrete $0.1 \times f'_c$ (MPa) | 4.12   |
| Dilation angle (degrees)                         | 35     |
| Eccentricity                                     | 0.10   |
| Bi-axial to uni-axial strength ratio             | 1.16   |
| Second stress invariant ratio                    | 0.667  |
| Viscosity parameter                              | 0.01   |

Table 3. Parameters of concrete damage plasticity model.
11. Results and Discussions

The capability of the proposed empirical model is compared with the existing models using various statistical performance measures pointed out in Section 9. A dataset of 126 experiments was employed to examine these performance indicators.

11.1. Peak Impact Force on RC Beam

The prediction accuracy of the proposed model can be assessed by comparing it with the available models. Therefore, the Pham and Hao [3] and Zhao et al. [7] models are selected, and the predicted results are shown in Figure 7. The prediction of Pham and Hao [3] results in the $R^2 = 0.80$, the average PER is 1.1, the coefficient of variation (CoV) is 116%, and the average absolute error (AAE) is 109%. Similarly, the coefficient of determination ($R^2$) of the Zhao et al. [7] model is 0.93, with an average absolute error of 55.4%. Zhao’s model gives the average value of PER 1.43 and CoV = 41%. The proposed model has an average PER of 1.01, with a coefficient of variation (CoV) of 19% and $R^2 = 0.98$. Having PER and $R^2$ close to 1, and the least coefficient of variation, demonstrates the effectiveness of the GEP tool for the efficient prediction of impact force. Moreover, the average absolute error (AAE) for the proposed model is 14%, which is considerably less than the previously proposed models.

![Figure 7. (a) Predicted and experimental impact force using the Pham and Hao [3] and Zhao et al. [7] models.](a)
Figure 7. Predicted and experimental impact force proposed using the (a) Pham and Hao [3] and (b) Zhao et al. [7] models.

Figure 8. Response of RC beam model in ABAQUS: peak impact force.

Table 4. Comparison of GEP result with experimental and ABAQUS results.

| Peak Impact force on the beam (kN) | Experimental Results | ABAQUS Results | GEP Results |
|----------------------------------|----------------------|----------------|------------|
| [Striker velocity 6.52 m/s]      | 1110                 | 1113           | 1150       |
| [Striker velocity 7.42 m/s]      | 1290                 | 1229           | 1240       |

11.2. Practical Implementation

The practical implementation of the peak impact force is described herein. The empirical formulation (9) can be further used for determining the dynamic shear and the
bending moment diagrams of impacted RC beams. The full procedure shown in Figure 9 for generating this response is given by Pham et al. [18]. According to this procedure, these diagrams can be reasonably predicted provided the maximum impact force and the location of the plastic hinges are known. Having the maximum impact force determined from (5) and the hinge locations estimated from the model proposed by Pham et al. [44], the shear force and bending moment diagrams can be easily generated. These diagrams can be readily implemented to design beams under extreme dynamic loading.

Figure 9. Calculation of the shear force and bending moment diagram. \( M \): Impactor mass; \( V_0 \): Impactor velocity; \( V \): Shear force diagram; \( M \): Bending moment diagram; \( P \): Magnitude of shear at the point of impact; \( L_n \): Length of beam between two supports.

12. Conclusions

The peak impact force is one of the most important response parameters governing the overall dynamic response of the impacted beam. An evolutionary genetic model is developed to predict this important force that is transferred to the RC beam under impact loading. The key contribution of this model is the implementation of key influencing factors including concrete compressive strength, the shear span to depth ratio, and the tensile reinforcement quantity and strength, which has considerably improved the accuracy as compared to the other available models. Based on the available literature, 126 experiments were compiled, of which 42 experiments were employed for validation purposes. The proposed machine learning model is benchmarked against two existing models, one analytical and the other regression-based. The following conclusions are drawn:

- An increase in the influencing factors, such as the concrete compressive strength, the steel bar tensile strength, the longitudinal reinforcement ratio, the geometric dimension of beam cross-section, and the input kinetic energy results in attracting more impact force. Contrarily, an increase in the beam span results in attracting less impact force;
- The proposed empirical equation can accurately determine the impact force by incorporating all the aforementioned influencing factors. In addition, the influencing parameters in the model are consistently related to the experimental data;
- The predictive ability of the proposed model is indicated by the coefficient of determination, performance factor, and the average absolute error (98%, 1.01, and 15.2%, respectively).
• The proposed model can approximate the transmitted impact force to the RC beam more closely than an available analytical model and an artificial neural network-based model. A comparison is made with two different models to evidence the predictive ability of the developed model;

• The proposed model is also validated by comparing the results with the FE simulation, using an ABAQUS/Explicit solver, which was developed on existing experimental results. The model gives good agreement with the numerical results showing less than 4% error;

• Overall, the proposed regression model offers an excellent predictive tool for determining the peak impact force transmitted to RC beams subjected to impact. Surely, the predictability of the current model has been improved by incorporating the important influencing parameters, such as the properties of shear and longitudinal reinforcement. This impact force can be employed for determining the bending and shear design of these beams, which is useful design information in terms of sizing and detailing of RC beams under impact loading;

• In future work, experiments will be performed to further validate the empirical formulation with varying impactor mass, striking velocity, and steel reinforcement in an RC beam. Additionally, the ABAQUS formulation will be improved by adopting actual stress–strain curves to accurately simulate the tested beams.

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Appendix A

Table A1. Beam geometry and reinforcement details of RC beams.

| ID    | b (mm) | h (mm) | L (mm) | L_n (mm) | a (mm) | F'c (Mpa) | f (Mpa) | A_f (mm²) | f_y (Mpa) | A_f (mm) | F_y (Mpa) | V (Mpa) | Ratio % |
|-------|--------|--------|--------|----------|--------|-----------|---------|-----------|-----------|----------|-----------|---------|---------|
| A37   | 200    | 400    | 2400   | 2000     | 50     | 41.2      | 1924    | 373       | 1924      | 373      | 373       | 0.21    |
| A46   | 200    | 400    | 2400   | 2000     | 50     | 41.2      | 1924    | 373       | 1924      | 373      | 373       | 0.21    |
| A56   | 200    | 400    | 2400   | 2000     | 50     | 41.2      | 1924    | 373       | 1924      | 373      | 373       | 0.21    |
| A65   | 200    | 400    | 2400   | 2000     | 50     | 41.2      | 1924    | 373       | 1924      | 373      | 373       | 0.21    |
| A74   | 200    | 400    | 2400   | 2000     | 50     | 41.2      | 1924    | 373       | 1924      | 373      | 373       | 0.21    |
| A84   | 200    | 400    | 2400   | 2000     | 50     | 41.2      | 1924    | 373       | 1924      | 373      | 373       | 0.21    |
| B37   | 200    | 400    | 2400   | 2000     | 50     | 41.2      | 1924    | 373       | 1924      | 373      | 373       | 0.21    |
| B46   | 200    | 400    | 2400   | 2000     | 50     | 41.2      | 1924    | 373       | 1924      | 373      | 373       | 0.21    |
| B65   | 200    | 400    | 2400   | 2000     | 50     | 41.2      | 1924    | 373       | 1924      | 373      | 373       | 0.21    |
| B74   | 200    | 400    | 2400   | 2000     | 50     | 41.2      | 1924    | 373       | 1924      | 373      | 373       | 0.21    |
| B84   | 200    | 400    | 2400   | 2000     | 50     | 41.2      | 1924    | 373       | 1924      | 373      | 373       | 0.21    |
| B93   | 200    | 400    | 2400   | 2000     | 50     | 41.2      | 1924    | 373       | 1924      | 373      | 373       | 0.21    |
| S1616 | 300    | 600    | 6000   | 5000     | 40     | 42.0      | 402     | 426       | 402       | 426      | 426       | 1.40    |
| S1616 | 300    | 600    | 6000   | 5000     | 40     | 42.0      | 402     | 426       | 402       | 426      | 426       | 1.40    |
| S1616 | 300    | 600    | 6000   | 5000     | 40     | 42.0      | 402     | 426       | 402       | 426      | 426       | 1.40    |
| ID     | Geometric Size | Concrete               | Longitudinal Reinforcement | Shear Reinforcement |
|--------|----------------|------------------------|-----------------------------|---------------------|
|        | b (mm)         | h (mm)                 | L (mm)                      | $A_c$ (mm²)         | $f_y$ (Mpa)         | $f_y'$ (Mpa) | $f_y''$ (Mpa) | $f_y'''$ (Mpa) | Ratio % |
| G1-1   | 200 300 400 3000 40 | 34.7                    | 265 373                     | 265 373            | 295 0.071           |
| G1-2   | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G1-3   | 200 300 400 3000 40 | 34.7                    | 265 373                     | 265 373            | 295 0.071           |
| G1-4   | 200 300 400 3000 40 | 34.7                    | 265 373                     | 265 373            | 295 0.071           |
| G1-5   | 200 300 400 3000 40 | 34.7                    | 265 373                     | 265 373            | 295 0.071           |
| G2-1   | 200 300 400 3000 40 | 34.7                    | 265 373                     | 265 373            | 295 0.071           |
| G2-2   | 200 300 400 3000 40 | 34.7                    | 265 373                     | 265 373            | 295 0.071           |
| G2-3   | 200 300 400 3000 40 | 34.7                    | 265 373                     | 265 373            | 295 0.071           |
| G2-4   | 200 300 400 3000 40 | 34.7                    | 265 373                     | 265 373            | 295 0.071           |
| G3-1   | 200 300 400 3000 40 | 34.7                    | 265 373                     | 265 373            | 295 0.071           |
| G3-2   | 200 300 400 3000 40 | 34.7                    | 265 373                     | 265 373            | 295 0.071           |
| G3-3   | 200 300 400 3000 40 | 34.7                    | 265 373                     | 265 373            | 295 0.071           |
| G3-4   | 200 300 400 3000 40 | 34.7                    | 265 373                     | 265 373            | 295 0.071           |
| G4-1   | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G4-2   | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G5-1   | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G5-2   | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G6-1   | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G7-1   | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G7-2   | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G8-1   | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G9-1   | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G9-2   | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G10-1  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G10-2  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G10-3  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G10-4  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G11-1  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G11-2  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G11-3  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G11-4  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G11-5  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G11-6  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G12-1  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G12-2  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G12-3  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G12-4  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G13-1  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G13-2  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G14-1  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G15-1  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
| G16-1  | 200 300 400 3000 40 | 34.7                    | 265 373 265 373            | 295 0.071           |
### Table A1. Cont.

| ID     | Geometric Size | Concrete | Longitudinal Reinforcement | Shear Reinforcement |
|--------|----------------|----------|----------------------------|--------------------|
|        |                |          | b (mm) | h (mm) | L (mm) | Ln (mm) | a (mm) | f'c (Mpa) | f'r (Mpa) | As (mm²) | fy (Mpa) | A's (mm) | fy (Mpa) | Ratio% |
| B-1700-4.60 | 200 | 500 | 6000 | 5000 | 40 | 27.0 | 1257 | 495 | 402 | 495 | 344 | 0.09 |
| B-1052-6.40 | 200 | 500 | 6000 | 5000 | 40 | 27.9 | 1257 | 495 | 402 | 495 | 344 | 0.09 |
| C-1700-4.60 | 200 | 500 | 4000 | 3000 | 40 | 32.1 | 1257 | 495 | 402 | 495 | 344 | 0.09 |
| C-1300-5.56 | 200 | 500 | 4000 | 3000 | 40 | 26.3 | 1257 | 495 | 402 | 495 | 344 | 0.09 |
| D-1700-4.60 | 200 | 500 | 4000 | 3000 | 40 | 26.5 | 1257 | 495 | 402 | 495 | 344 | 0.19 |
| D-1300-5.56 | 200 | 500 | 4000 | 3000 | 40 | 25.6 | 1257 | 495 | 402 | 495 | 344 | 0.19 |
| BD1  | 150 | 310 | 2700 | 1860 | 33 | 28.1 | 603 | 477 | 603 | 477 | 550 | 0.22 |
| BD2  | 150 | 310 | 2700 | 1860 | 33 | 26.9 | 603 | 477 | 603 | 477 | 550 | 0.22 |
| BD3  | 150 | 310 | 2700 | 1860 | 33 | 41.4 | 603 | 477 | 603 | 477 | 550 | 0.22 |
| BD4  | 150 | 310 | 2700 | 1860 | 33 | 41.4 | 603 | 477 | 603 | 477 | 550 | 0.22 |
| B-0-00 | 200 | 400 | 2800 | 2400 | 42.5 | 41.3 | 1473 | 460 | 402 | 460 | 0 | 0.00 |
| B-0-25 | 200 | 400 | 2800 | 2400 | 42.5 | 41.9 | 1473 | 460 | 402 | 460 | 314 | 0.25 |
| B-0-50 | 200 | 400 | 2800 | 2400 | 42.5 | 41.9 | 1473 | 460 | 402 | 460 | 314 | 0.50 |
| BD1  | 150 | 310 | 3000 | 1860 | 33 | 45.8 | 603 | 477 | 603 | 477 | 550 | 0.22 |
| BD2  | 150 | 310 | 3000 | 1860 | 33 | 45.8 | 603 | 477 | 603 | 477 | 550 | 0.22 |
| BD3  | 150 | 310 | 3000 | 1860 | 33 | 45.8 | 603 | 477 | 603 | 477 | 550 | 0.22 |
| BD4  | 150 | 310 | 3000 | 1860 | 33 | 45.8 | 603 | 477 | 603 | 477 | 550 | 0.22 |
| B1   | 200 | 400 | 2800 | 2400 | 42 | 20.1 | 982 | 429 | 402 | 429 | 0 | 0.00 |
| B2   | 200 | 400 | 2800 | 2400 | 42 | 20.1 | 982 | 429 | 402 | 429 | 314 | 0.50 |
| B3   | 200 | 400 | 2800 | 2400 | 42 | 20.1 | 982 | 429 | 402 | 429 | 314 | 0.50 |
| B4   | 200 | 400 | 2800 | 2400 | 42 | 20.1 | 982 | 429 | 402 | 429 | 314 | 0.50 |
| B5   | 200 | 400 | 2800 | 2400 | 42 | 20.1 | 982 | 429 | 402 | 429 | 314 | 0.50 |
| 10-C27-4 | 120 | 120 | 1800 | 1200 | 27 | 157 | 235 | 157 | 235 | 235 | 0.25 |
| 6-C40-5 | 120 | 120 | 1800 | 1200 | 40 | 56.52 | 235 | 56.52 | 235 | 235 | 0.25 |
| 6-C40-6 | 120 | 120 | 1800 | 1200 | 40 | 56.52 | 235 | 56.52 | 235 | 235 | 0.25 |
| 6-C40-7 | 120 | 120 | 1800 | 1200 | 40 | 56.52 | 235 | 56.52 | 235 | 235 | 0.25 |
| 8-C40-2 | 120 | 120 | 1800 | 1200 | 40 | 101 | 235 | 101 | 235 | 101 | 235 | 0.25 |
| 8-C40-3 | 120 | 120 | 1800 | 1200 | 40 | 101 | 235 | 101 | 235 | 101 | 235 | 0.25 |
| 8-C40-4 | 120 | 120 | 1800 | 1200 | 40 | 101 | 235 | 101 | 235 | 101 | 235 | 0.25 |
| 8-C40-5 | 120 | 120 | 1800 | 1200 | 40 | 101 | 235 | 101 | 235 | 101 | 235 | 0.25 |

### Table A2. Impact response characteristics.

| ID     | Hammer Test Results | Reference |
|--------|---------------------|-----------|
| A37    | V (m/s) | M (kg) | Fp (kN) | Smax (mm) | Failure Model | Reference |
| 3.67   | 400 | 750 | 8.1 | Flexure | [8] |
| A46    | 4.58 | 400 | 880 | 10.1 | Flexure |
| A56    | 5.61 | 400 | 1000 | 13.1 | Flexure-shear |
| A65    | 6.52 | 400 | 1110 | 16.0 | Shear |
| A74    | 7.42 | 400 | 1290 | 22.0 | Shear |
| A84    | 8.4 | 400 | 1400 | 24.4 | Shear |
| B37    | 3.67 | 400 | 760 | 7.5 | Flexure |
| B46    | 4.58 | 400 | 900 | 11.3 | Flexure-shear |
| B65    | 6.52 | 400 | 1200 | 16.0 | Shear |
| B74    | 7.42 | 400 | 1280 | 19.8 | Flexure-shear |
| B84    | 8.4 | 400 | 1416 | 24.0 | Flexure-shear |
| B93    | 9.3 | 400 | 1575 | 28.0 | Flexure-shear |
| ID     | Hammer Test Results | Reference |
|--------|---------------------|-----------|
|        | V (m/s) | M (kg) | Fp (kN) | Smax (mm) | Failure Model |
| S1616-1 | 1.73    | 400    | 125     | 5.9       | None         |
| S1616-2 | 2.45    | 400    | 180     | 11.0      | None         |
| S1616-3 | 3.46    | 400    | 248     | 20.1      | Flexure      |
| S1616-4 | 4.85    | 400    | 317     | 36.2      | Flexure      |
| S1322-1 | 2.45    | 400    | 190     | 7.8       | None         |
| S1322-2 | 3.46    | 400    | 260     | 11.4      | Flexure      |
| S1322-3 | 4.85    | 400    | 305     | 23.5      | Flexure      |
| S1322-4 | 6.86    | 400    | 340     | 27.0      | Flexure      |
| S2222-1 | 2.45    | 200    | 7.0     | None      | None         |
| S2222-2 | 3.46    | 400    | 260     | 11.0      | Flexure      |
| S2222-3 | 4.85    | 400    | 313     | 21.4      | Flexure      |
| S2222-4 | 6.86    | 400    | 388     | 31.8      | Flexure      |
| A1     | 5       | 300    | 434     | 24.1      | n/p          |
| A2-1   | 3.46    | 150    | 321     | 13.6      | Flexure      |
| A2-2   | 2.45    | 300    | 293     | 25.4      | Flexure      |
| A2-3   | 2       | 450    | 245     | 37.0      | Flexure      |
| A2-4   | 4.9     | 150    | 453     | 16.3      | Flexure      |
| A2-5   | 3.5     | 300    | 417     | 31.6      | Flexure      |
| A2-6   | 2.8     | 450    | 346     | 43.7      | Flexure      |
| A2-7   | 6       | 150    | 573     | 17.9      | Flexure      |
| A3-1   | 4.24    | 300    | 513     | 33.3      | Flexure      |
| A3-2   | 3.46    | 450    | 445     | 48.4      | Flexure      |
| A2-10  | 1       | 300    | 65      | 4.5       | Flexure      |
| A2-11  | 2       | 300    | 253     | 12.6      | Flexure      |
| A2-12  | 3       | 300    | 426     | 26.9      | Flexure      |
| A2-13  | 4       | 300    | 489     | 41.4      | Flexure      |
| A2-14  | 5       | 300    | 466     | 58.3      | Flexure      |
| A4     | 5       | 300    | 452     | 114.9     | n/p          |
| B      | 5       | 300    | 667     | 77.0      | n/p          |
| C      | 5       | 300    | 650     | 42.4      | n/p          |
| D      | 5       | 300    | 639     | 94.0      | n/p          |
| E      | 5       | 300    | 742     | 29.1      | n/p          |
| F      | 5       | 300    | 664     | 43.9      | n/p          |
| G1-1   | 7       | 300    | 1496    | 64.3      | n/p          |
| G1-15  | 7       | 300    | 1601    | 58.0      | n/p          |
| G2-1   | 4       | 300    | 510     | 28.3      | n/p          |
| G2-2   | 5       | 300    | 779     | 44.0      | n/p          |
| G2-3   | 6       | 300    | 854     | 57.0      | n/p          |
| G2L-1  | 4       | 400    | 447     | 44.2      | Flexure      |
| G2L-2  | 5       | 400    | 668     | 66.8      | Flexure      |
| G2L-3  | 6       | 400    | 787     | 89.7      | Flexure      |
| G3-1   | 4       | 300    | 609     | 36.7      | n/p          |
| G3-2   | 5       | 300    | 770     | 52.0      | n/p          |
| G3-3   | 6       | 300    | 839     | 70.6      | n/p          |
| G4-1   | 4       | 300    | 800     | 39.7      | n/p          |
| G4-2   | 5       | 300    | 986     | 56.1      | n/p          |
| G4-4   | 6       | 300    | 1313    | 63.5      | Flexure      |
| G5-1   | 6       | 400    | 1557    | 83.4      | Flexure      |
| G5-2   | 7       | 400    | 1336    | 26.4      | n/p          |
| G6-1   | 5       | 300    | 1243    | 45.8      | n/p          |
| G7-1   | 6       | 300    | 1588    | 60.9      | n/p          |
| G8-1   | 6       | 300    | 1192    | 36.5      | n/p          |
| G9-1   | 5       | 300    | 931     | 43.2      | n/p          |
| G9-2   | 6       | 300    | 1103    | 57.9      | n/p          |
| G10-1  | 4       | 300    | 751     | 33.7      | None         |
| G10-2  | 5       | 300    | 922     | 49.5      | Flexure      |
| G10-3  | 6       | 300    | 1017    | 67.8      | Flexure      |
| G10-4  | 7       | 300    | 1042    | 83.9      | Flexure      |
| G11-1  | 3.13    | 500    | 703     | 20.5      | n/p          |
| G11-2  | 4.2     | 500    | 971     | 33.2      | n/p          |
| G11-3  | 5.05    | 500    | 1462    | 43.1      | n/p          |
| G11-4  | 5.78    | 500    | 1878    | 55.5      | n/p          |
| G11-5  | 6.42    | 500    | 1765    | 67.2      | n/p          |
| G11-6  | 7       | 500    | 1907    | 83.4      | n/p          |
| G12-1  | 7.67    | 500    | 1675    | 85.4      | n/p          |
| G13-1  | 7.67    | 500    | 2150    | 60.6      | n/p          |
| G14-1  | 7.67    | 500    | 2258    | 63.7      | n/p          |
| G15-1  | 7.67    | 500    | 2063    | 40.5      | n/p          |
| G16-1  | 7.67    | 500    | 2023    | 52.9      | n/p          |
Table A2. Cont.

| ID          | Hammer | Test Results | Reference |
|-------------|--------|--------------|-----------|
|             | V (m/s) | M (kg)       | Fp (kN)  | S_{max} (mm) | Failure Model |
| B-1700-4.60 | 4.6    | 1700         | 1360     | 83.7         | Flexure      |
| B-1052-6.40 | 6.4    | 1052         | 1900     | 79.3         | Flexure-shear |
| B-868-7.14  | 7.14   | 868          | 1450     | 209.0        | Shear        |
| C-1700-4.60 | 4.6    | 1700         | 1380     | 118.0        | Shear        |
| C-1300-5.56 | 5.56   | 1300         | 1500     | 67.4         | Shear        |
| C-868-7.14  | 7.14   | 868          | 1780     | 67.9         | Shear        |
| D-1700-4.60 | 4.6    | 1700         | 1380     | 41.5         | Flexure      |
| D-1300-5.56 | 5.56   | 1300         | 1500     | 48.0         | Flexure      |
| D-868-7.14  | 7.14   | 868          | 1780     | 47.5         | Flexure-shear |
| BD1         | 4.15   | 253          | 891      | 12.0         | Flexure      |
| BD2         | 7.11   | 253          | 1396     | 24.0         | Flexure      |
| BD3         | 11.96  | 253          | 1940     | 75.0         | Shear        |
| BD4         | 7.81   | 578          | 1466     | 80.0         | Flexure      |
| BD5         | 5.1    | 578          | 983      | 38.0         | Flexure-shear |
| A-1         | 3.12   | 968          | 260      | 81.0         | Flexure      |
| A-2         | 4      | 587          | 420      | 74.0         | Flexure      |
| A-3         | 5.7    | 392          | 790      | 83.6         | Flexure      |
| A-4         | 8.5    | 197          | 800      | 89.5         | Flexure      |
| B-0-00      | 7.2    | 393          | 2014     | 142.6        | Shear        |
| B-0-25      | 7.2    | 393          | 2214     | 31.4         | Flexure-shear |
| B-0-50      | 7.2    | 393          | 1948     | 20.3         | Flexure      |
| BD1         | 4.43   | 333          | 912      | n/p          | Shear        |
| BD2         | 8.65   | 333          | 1708     | n/p          | Shear        |
| BD3         | 5.71   | 200          | 1184     | n/p          | Shear        |
| BD4         | 4.43   | 200          | 768      | n/p          | Flexure      |
| BD5         | 5.71   | 200          | 1360     | n/p          | Flexure-shear |
| B1          | 5.9    | 253          | 1500     | 12.4         | Flexure-shear |
| B2          | 15.2   | 253          | 2203     | 79.8         | Flexure      |
| B3          | 7.2    | 393          | 1689     | 44.8         | Flexure      |
| B4          | 7.2    | 393          | 2014     | 142.6        | Shear        |
| B5          | 7.2    | 393          | 1948     | 20.3         | Flexure      |
| B6          | 7.2    | 393          | 2214     | 31.4         | Flexure-shear |
| 10-C27-4    | 8.85   | 33.6         | 141.97   | 28.66        | n/p          |
| 6-C40-5     | 9.9    | 33.6         | 202.2    | 62.65        | n/p          |
| 6-C40-6     | 10.84  | 33.6         | 267.7    | 87.74        | n/p          |
| 6-C40-7     | 11.71  | 33.6         | 230.71   | 119.07       | n/p          |
| 6-C40-8     | 12.52  | 33.6         | 224.75   | 119.11       | n/p          |
| 8-C40-2     | 6.26   | 33.6         | 151.73   | 22.94        | n/p          |
| 8-C40-3     | 7.67   | 33.6         | 182.59   | 35.65        | n/p          |
| 8-C40-4     | 8.85   | 33.6         | 203.26   | 35.14        | n/p          |
| 8-C40-5     | 9.9    | 33.6         | 234.5    | 38.82        | n/p          |
| 10-C40-5    | 9.9    | 33.6         | 245.8    | 33.7         | n/p          |
| 10-C40-6    | 10.84  | 33.6         | 248.56   | 45.22        | n/p          |
| 10-C40-7    | 11.71  | 33.6         | 183.3    | 62.5         | n/p          |

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