XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

Different methodologies for shear-building impact analysis

Rodrigo E. A de Souza[1], Graciela Doz[2], Marcus V. G de Morais[3], Suzana M Avila[4], Maura A. M. Shzu[4]

[1]*University of Brasilia*
St. Leste Projeção A, 72444-240, Gama/Federal District, Brazil
180130366@aluno.unb.br
[2]*Dept. of Civil Engineering, University of Brasília*
Faculdade de Tecnologia(UnB), 70910-900, Gama/Federal District, Brazil
graciela@unb.br
[3]*Dept. of Mechanical Engineering, University of Brasília*
Faculdade de Tecnologia(UnB), 70910-900, Gama/Federal District, Brazil
mvmorais@unb.br
[4]*Dept. of Engineering, University of Brasília*
Faculdade do gama(FGA),72444-240, Gama/Federal District, Brazil
avilas@unb.br, maura@unb.br

Abstract. In structural analysis, the great important topic concerns the safety and stability of the structure when it is subject to an impact load. The science of mechanical shock used to be a complex analysis in structural dynamics area. Thus, it is proposed to investigate different methodologies of impact analysis in a shear-building. The modelling of the problem consists of applying a short load and linear solid finite elements with 3 degrees of freedom per node. Before, to validate the computacional analysis, one beam was evaluated. The results were also compared with the analytical calculation. The response history shows a good agreement and some of the advantages and disadvantages of each numerical method were highlighted.

Keywords: Impact, Shear-building, Implicit Method, Explicit Method

1 Introduction

Collisions, in most cases, are accidental and usually affect the integrity of the structures. It may be mentioned collisions between vehicles, vessels at great depths, against bridge posts or iceberg, shocks of tectonic plates in earthquakes, etc. Sometimes intentional actions can also put the structure at risk, as the September 11 attacks, 2001. Structures most subject to this phenomenon are designed with impact mitigating elements, as is the case of vehicles. These elements become essential to provide protection to drivers and passengers.

The impact problem can be classified according to the conservation, or not, of kinetic energy. If energy is conserved, it is called elastic collision, otherwise collisions are inelastic [1]. They can also be partially elastic or inelastic, when only part of the kinetic energy is conserved so that the final energy is less than the initial. This last behavior, configures most of the collisions, where after the shock the bodies move away and the final relative speed is less than the initial [2]. Mohammad [3], for example, explored the concepts of impact in the analysis of steel and composite safety devices on the side door of a vehicle, in which the composite one demonstrated better energy absorption capacity.

The impact is conditioned to the application of a high intensity loading in a short period of time, with non-uniform stress distribution on the material [4]. There are many studies already carried out in this area. Teixeira [5] used the explicit integration method to analyze, in Ansys, the longitudinal and transversal impact, in addition to the elastic stress wave propagation in beams. Norton [6] also studied the non-linearity for impact problem. Fujikake et al [7] carried out the impact responses in reinforced concrete beams by experimental study and developed an analytical model to estimate the maximum impact load and deflection. The results were consistent with each other.

The implicit and explicit methods were evaluated by other researchers, among them stands out HU [8], which sought to understand the disadvantages of the Newmark integration method in impact problems, to implement improvements in the algorithm using Lagrange multipliers. On the other hand, Sánchez [9] used the Ansys's explicit method to analyze a container impact onto rigid target.

Several researchers have been studying different solutions to improve the numerical integration procedure for impact problems. Carpenter [10] proposed a different type of simplification and modelling based on the Newmark algorithm; Taylor [11] proposed an algebraic development based on deformation gradients. Solberg [12] used an approach based on the Hamiltonian combination with Lagrange multipliers.

Impact problems involving shear-buildings have been the focus by other authors. Among them, we mention Varanis et al [13], who carried out an experimental study to analyse a vibro-impact model of two shear-buildings positioned side by side. Carrs and Moss [14] evaluated parameters affected by the impact of adjacent shear-buildings subject to seismic excitation using a two-dimensional inelastic dynamic analysis.

Thus, it is proposed here to verify, in a preliminary approach, the performance of the implicit and explicit numerical methods in an impact problem involving a shear-building, but above all it is surrounded by guarantees that determine the reliability of the analysis process. Therefore, the initial study is conducted on a cantilever beam and its results are compared with analytical solution.

2 Objective

The present work aims to check the performance of different methods applied to impact problems. It is proposed here compare the results observing the computational costs, the accuracy of the results and the advantages and disadvantages of each. Since the computational cost is directly related to machine configuration, it is important to put that all analysis were performed on a computer with Windows 10 Operating System, 64GB, Intel Core i7-7500U processor and 8GB RAM.

3 Methodology

Discussing about methods and parameters considered in this work will guide the reader about the path taken to reach the conclusions obtained. Thus, ANSYS was the tool chosen to study the impact problem on shear-building, where the performance of the numerical methods available in this package are the object of analysis of this work. These methods can be based on implicit or explicit integration. According to Gavin [15], both procedures use the central finite difference method to integrate the equation of motion. The basic idea of the integration methods is to solve the dynamic equation of the problem assuming that the vectors of displacement, speed and acceleration vary within discrete intervals of time [16]. It is important to note that the damping has been neglected.

The use of implicit integration is advisable in the analysis of quasi-static or low-frequency problems. In highly non-linear problems, it is said that their convergence is not guaranteed. For both explicit and implicit formulation, Lagrangian multipliers are used. The implicit method also has the advantage of converging regardless of the time step, Δt, adopted, unlike the explicit method. On the other hand, the cost per time step is immeasurable, since the speed depends much more on the convergence of interactions that varies from case to case. It is worth mentioning that its structuring allows a more complete solution, without simplifications.

The singular stiffness matrix affects the implicit integration stability, however, this problem is overcome when diagonalized mass and damping matrices are used, which result in an effective diagonal stiffness matrix. So, it transforms equations into a system of decoupled equations, making it unnecessary to invert the effective stiffness matrix at each time-step [17].

The basic formulation of the implicit scheme adopted by the ANSYS package is based on Newmark's integration[18]. The equation of motion is defined as a function of α and δ, which are the Newmark parameters and which define the stability of the method.

Problems that are faced by large deformations and contacts have a better response when simulated by the explicit dynamic method. The method uses diagonal mass and damping matrices to provide more efficiency to the algorithm. On the other hand, their convergence depends on the time-step size.

Analysis were divided into two stages: Validation and Application. The first, the Validation Stage, consists of in a first and necessary step to understand and to go on with the analysis process and its variables, as well as the setting of the tools used. In this way, an elastic cantilever beam was subjected to an impact load. The results of the analysis were also compared with analytical solution.

The second, the Application Stage, it was analysed a shear-building under an impact load. It is believed that the evaluation of a little more complex structure will reveals the methods performance even further, confirming and making clear the conclusions listed in this work. The same numerical procedure was applied for the new structure, which also received a unidirectional charge.

The maximum deflection of the structures was observed from the ABNT NBR8800: 2008. It advises that the maximum deflection should be in the range of L/120 to L/350, where L is the length of the beam.

In computational analysis, the structures were modelled by a linear 3D solid element, defined by 8 nodes having 3 degrees of freedom at each node in Cartesian directions. The time increments, Δt, defined to guarantee the stability and precision of the results, were based on Clough [17] and Chopra [19] and its value was limited by computer performance. Therefore, it was adopted, for implicit end explicit analysis, a time increment equal to 0.02s and 10^{-12} s, respectively.

The Newmark parameters, $\gamma = 0.5$ and $\beta = 0.25$, were adopted in the implicit analysis. In the explicit analysis, mass and damping matrices are used in their diagonalized form, thus making it more efficient.

The objects of study were also analysed in the plastic range, in which the material nonlinear constitutive curve was described by the bilinear isotropic hardening model, highly recommended for large deformations analysis. This material behaviour uses the von Mises yield.

4 Object Description

3.1 Validation Stage – Beam

The adopted rectangular beam is found in the renowned solid mechanic book [20]. It has a cross section of 0.20m x 0.40m and a length of 5m. It is made of steel, whose Young's modulus, density and Poisson's ratio are, respectively, 200GPa, 7850 kg/m^3 and 0.31. The allowable stress is 250Mpa. The problem describes a block of mass157 kg that moves with a speed of 2 m/s and collides with the free edge of the beam, Figure 1.

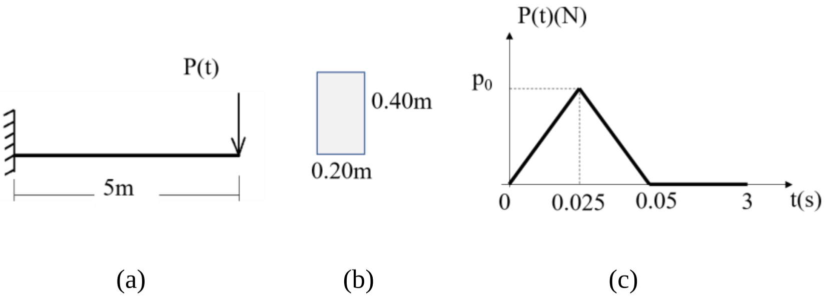


Figure 1: a) Cantilever beam subjected to impact load; b) Cross section; (c) impact load

The load time, t_d, of 0.05s was adopted. The load variation in a triangular shape, Figure 1c, is the most suitable for impact problems. The maximum impact load value of 56704N was obtained considering that the block's kinetic energy is all transferred to the beam. Thus, the deformation work corresponds to the maximum deformation of the static analysis and the beam inertia is neglected in the face of the body inertia. The friction or damping effect is disregarded throughout the analysis.

The analyticalresponse in an elastic range is given by equation (1) which describes the response to a triangular load [19], where $A = \frac{t}{t_d}$, $B = \frac{t}{T_n}$, $S = \frac{T_n}{2\pi t_d}$ e $X = \left(t - \frac{t_d}{2}\right)$.

$$u(t) = \begin{cases} -2(u_{st})_0(A - S\sin(2\pi B)), & 0 \le t \le \frac{t_d}{2} \\ -2(u_{st})_0\left\{1 - A + S\left[2\sin\left(\frac{2\pi}{T_n}X\right) - \sin(2\pi B)\right]\right\}, & \frac{t_d}{2} \le t \le t_d \\ -2(u_{st})_0\left\{S\left[2\sin\left(\frac{2\pi}{T_n}X\right) - \sin\left(\frac{2\pi}{T_n}(t - t_d)\right) - \sin(2\pi B)\right]\right\}, & t \ge t_d \end{cases} \quad (1)$$

The displacement responses depends on time load (t_d), the most relevant natural frequency of vibration (ω_n) and accordingly the natural period (T_n) and also the magnitude of the impact load (p_0), since the maximum static displacement , $(u_{st})_0$, is $^{p_0}/_k$ and k is the flexural stiffness of the beam.

3.2 Application Stage – Shear-building

The problem deals with the collision of a block of mass 157 kg that moves at speed of 5 m/s and hits the top of the shear-building, as shown in Figure 2.

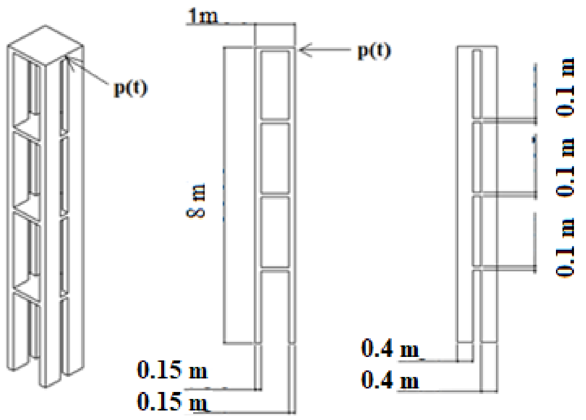


Figure 2: Shear-building subjected to the impact load: a) isometric view b) front view; c) side view

For shear-building, in view of its geometric characteristics, the analytical procedure was carried out simplifying the model to an equivalent beam length of 8m with constant cross section side of 0.59 m. The same material as the validation beam was considered, as well as the same time load and the maximum load obtained was 215513N.

5 Results and discussion

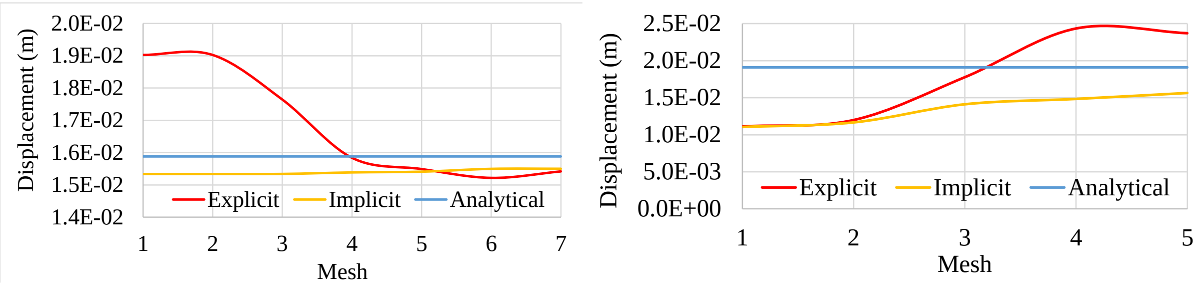
The convergence of the results depends on both the mesh density and quality. Ansys attributes the score 1 to define the best mesh. To assess the reliability of the results, critical displacement values are evaluated for the beam and the shear-building. Tables 1 and 2 show the numerical values for this study and Figure 3 illustrates the convergence curves for the two cases in elastic range.

Table 1: Convergence analysis and average time of running simulation – Beam

			Implicit Method		Explicit Method	
Mesh	Numbers of elements	Mesh quality index	Displacement (m)	Time of running simulation (s)	Displacement (m)	Time of running simulation (s)
1	5	0.34	0.015341	67	0.019023	5
2	10	0.69	0.015341	62	0.019023	6
3	40	0.96	0.015344	80	0.017643	9
4	240	0.95	0.015390	219	0.015839	29
5	1440	0.99	0.015413	1511	0.015490	151
6	12480	0.99	0.015500	10800	0.015216	860
7	108160	0.99	0.015503	21682	0.015417	5577
Maximum displacement- analytical solution (m):				0.015883		

Table 2: Convergence analysis and average time of running simulation - Shear-building

			Implicit Method		Explicit Method	
Mesh	Numbers of elements	Mesh quality index	Displacement (m)	Time of running simulation (s)	Displacement (m)	Time of running simulation (s)
1	110	0.54218	0.011042	59	0.011119	69
2	112	0.55153	0.011660	64	0.011982	69
3	324	0.,84950	0.014117	117	0.017770	90
4	2320	0.89331	0.014840	586	0.024355	268
5	79824	0.99915	0.015647	30060	0.023717	5086
Maximum displacement- analytical solution (m):				0.019098		

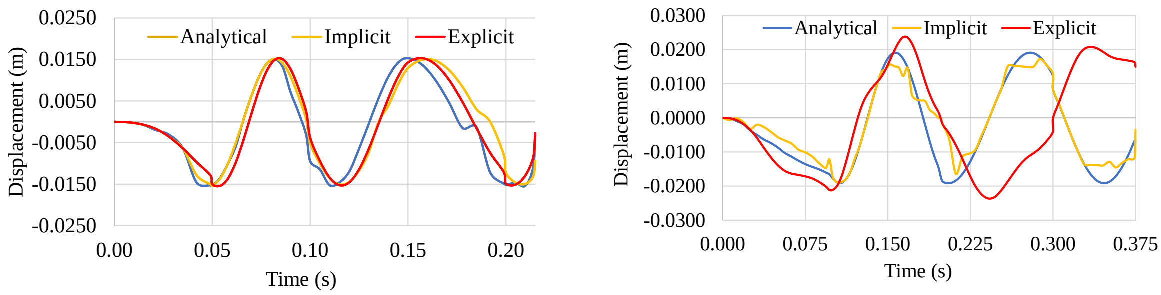


(a) (b)

Figure 3: Convergence analysis (a) Beam and (b) Shear-building.

In the convergence analysis, it was observed that the explicit method presented a higher sensitivity to the mesh density, while the implicit one presented a better stability and a fast convergence. However, the latter demands a computational cost much higher than the explicit, and this is explained by the degree of simplification of the explicit methodology.

For subsequent analysis, it was chosen to work with the meshes that showed the best quality and convergence. Thus, the validation beam was divided in 108160 solid elements and the shear-building, in 79824 elements. Figure 4 shows the behavior of the Validation Beam and Shear-building, respectively, when the impact does not interfere with the structural properties of the elements.



(a) (b)

Figure 4: Displacement response – elastic range: a) Beam e b) Shear-building

A more significant difference between the results of the three methodologies used is observed in the shear-building. This difference can be attributed to the greater complexity of the structure and simplifications used to represent it. In agreement with Chopra [19], the first displacement peak occurs in the time load applied to the beam and after the load for the shear-building.

In plastic analysis of the structures, the impact speed of the block has been increased to 20m/s, and the value of p_0 was estimated similary to the intensity values obtained in an elastic range, having its value equal to 567041

N for the beam and 862052 N for the shear-building. When the beam and shear-building were loading, they reached a maximum tension of 271.88MPa and 338Mpa, respectively. The modelling of the plastic range was performed using the constitutive model of bilinear isotropic hardening, which requires the values of yield stress and tangent modulus as input. The yield stress of the material is 250MPa, while the tangent modulus is 1450MPa, the standard value for structural steel A36.

Figure 5 shows the structures behavior considering the plastic deformation. For this analysis, only the explicit formulation was used due to its low computational cost. The beam and shear-building presented a maximum displacement value of 0.20 m and 0.094 m and the time simulation were 547s and 5595s, respectively. The computational capacity was not able to do simulations with the implicit analysis. It is also observed that the complexity of the structure has a significant impact on the processing time of analysis.

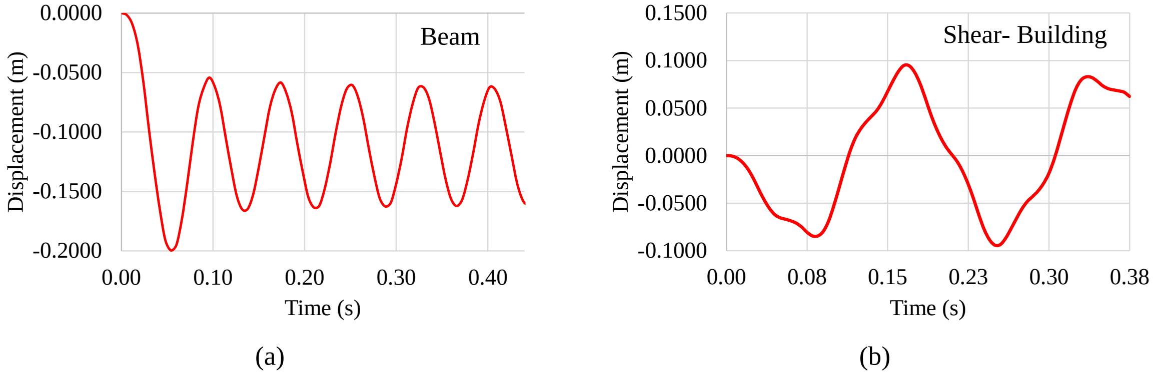


Figure 5: Displacement response considering plastic deformation: a) Beam e b) Shear-building

6 Conclusions

The dynamic problems for large deformations are complex because they cover several variables and the present study observed some expected behaviors. In the elastic range it was possible to confirm that the implicit method demands higher computational cost. In the convergence analysis, it was noticed the stability of the implicit method with the variation of the mesh density. The fast convergence of the explicit method is due to its simplified formulation. Although less precise, the explicit method proved to be more efficient and, therefore, more suitable for modelling more complex problems. Comparing the results of the shear-building with those of the beam, one can estimate the infeasibility of the implicit formulation, with regard to computational cost for more complex problems.

The analytical results for the elastic range were quite consistent with the results of the numerical simulations and was able to validate the entire computational analysis procedure. The approximation of shear-building to a beam model was also shown to be adequate, since the agreement of the results was observed.

In view of the results achieved, plastic deformation analysis was encouraged, where it was observed that the complexity of the structures considerably influences the time of analysis, confirming once again that more robust methodologies such as the implicit method may become unfeasible for the large displacement problems.

Finally, It is important to highlighted that this work is a preliminary study and will be the basis for future developments.

Acknowledgements. The authors greetings FAP-DF (Fundação de Amparo à Pesquisa) and ProIc (Programa de Iniciação Científica) by financial support in 2019-2020.

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