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Impact Response of Laminated Composite Simply-Supported Stiffened Conoidal Shell With Cut-Out

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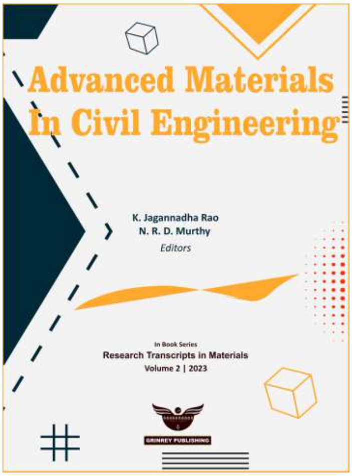

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Abstract

Laminated composite has become popular in the weight sensitive branches of engineering. In recent times it is widely used in civil engineering as roofing entity. It has advantages like low specific weight, high specific strength, weathering resistance and can be tailored as per the user. Despite these advantages low transverse shear capacity under impact loading compelled researchers to conduct further research for its successful implementation industrial sectors. Impact, which is likely to occur in cyclone prone zones and aircraft bases where wind borne debris causes the same. Impact causes delamination, cracks in epoxy medium or tearing of fibers which remains suppressed under lamina and causes eventual failures. Conoidal shells used as roofing entity is often provided with cut-outs for accommodation of utilities. Concentration of stresses in discontinuous edges may cause unacceptable deformation and stress concentration. Stiffeners become unavoidable in certain cases to lower the stress generated around cut-outs. Incorporation of proper contact law is important for impact analysis. Literature survey reveals that conoidal shell is an interesting roofing entity and needs to be studied for its confident application. Present study is an effort to investigate the impact behaviour of such conoidal shell roof.

1. Introduction

Due to its inherent benefits over other conventional materials like steel, composite has gained popularity among weight sensitive engineering branches. It has several advantages like low specific weight, high specific strength, weathering resistance and it can be tailored as per the need of the user. To build roofing structures, civil engineers have also used this material. Singly ruled, anticlastic, non-developable conoidal shell designs can be employed to fill in huge column-free spaces since they are aesthetically pleasing and structurally rigid. Despite these benefits, consumers are now quite concerned about the limited transverse shear capability under impact pressure. Impact can easily cause permanent deformations in graphite/epoxy composites, even at very modest velocities. To limit the overall amount of deformation induced, stiffeners have become necessary in a number of different spots on the shells. To limit the overall amount of deformation induced, stiffeners have become necessary in a number of different spots on the shells. Classical contact law of Hertz [1] found to be insufficient for laminated composite. Four decades ago, static properties of conoids were studied by various approaches by Hadid [2]. Unstiffened isotropic conoids' static properties under regular fixities, were examined by Brebbia and Hadid [3]. Static contact law proposed by Tan and Sun [4] for composite laminates and various-sized spherical indenters which considers the permanent indentation. Unstiffened isotropic conoids' static properties were further examined by Choi [5]. Sun and Chen [6] reported impact response of pre-twisted laminated composite plate under the impact load. Authors like Dey et al. [7] and Das and Bandyopadhyay [8] made substantial contributions, experimentally and theoretically, in this area. According to review articles written by Sinha and Mukhopadhyay [9], Chakravorty and Bandyopadhyay [10], and Qatu [11,12], study of dynamic properties of conoids was not recorded in any major way until 1993. These authors studied free vibration properties of conoids using finite element. Sengupta et al. [13] studied the progressive failure of cylindrical shell roof. Bakshi and Chakravorty [14] reported the geometrically nonlinear analysis of conoidal shell. Neogi et al. [15] studied the frictional response oblique impact of hyper shell roof.

According to literature review researchers have shown interest in conoidal shells because they are structurally appealing, and they have conducted analyses for a variety of static loads. However, the response due to impact loading remained untouched in case of stiffened conoidal shell with opening. This paper aims to conduct a detailed numerical study on impact induced behavior conoidal shell roof with openings and stiffeners for simply supported boundary conditions. Geometry of conoidal shell is illustrated in Fig. 1.

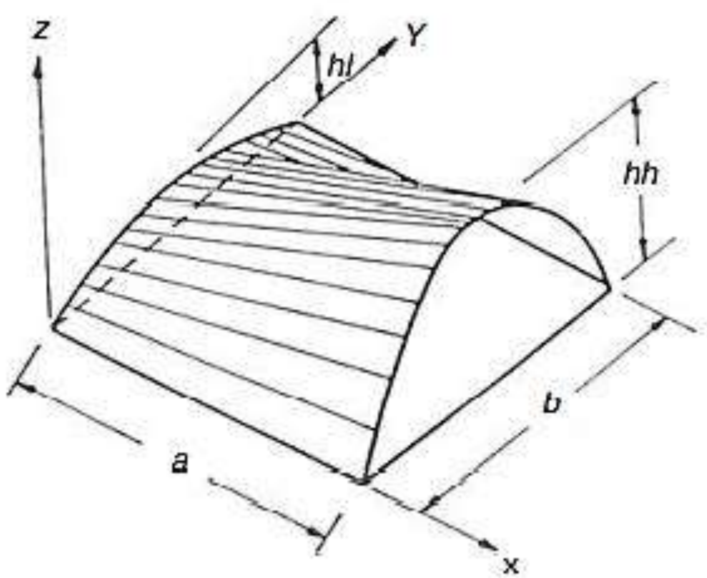

Fig. 1. Conoidal Shell

2. Numerical Examples

The solutions to benchmark problems that were previously addressed by Qatu and Leissa [13] on non-dimensional frequencies for twisted plates are used to verify the correctness of the current approach as shown in Table 1. To verify the formulation of impact, a problem previously solved by Sun and Chen [6] is taken up as shown in Fig. 2.

Table 1. Non-dimensional natural frequencies ($\tilde{\omega}$) of twisted plates [ϴ/-ϴ/ϴ]

Twist Angle	ϴ deg.	0º	15º	30º	45º	60º	75º	90º
ϴ = 15º	Qatu and Lessia [11]	1.00	0.93	0.74	0.53	0.35	0.27	0.26
	Current Formulation	0.98	0.92	0.77	0.51	0.33	0.28	0.26
ϴ = 30º	Qatu and Lessia [11]	0.96	0.89	0.72	0.52	0.34	0.26	0.24
	Current Formulation	0.95	0.87	0.71	0.53	0.33	0.25	0.23

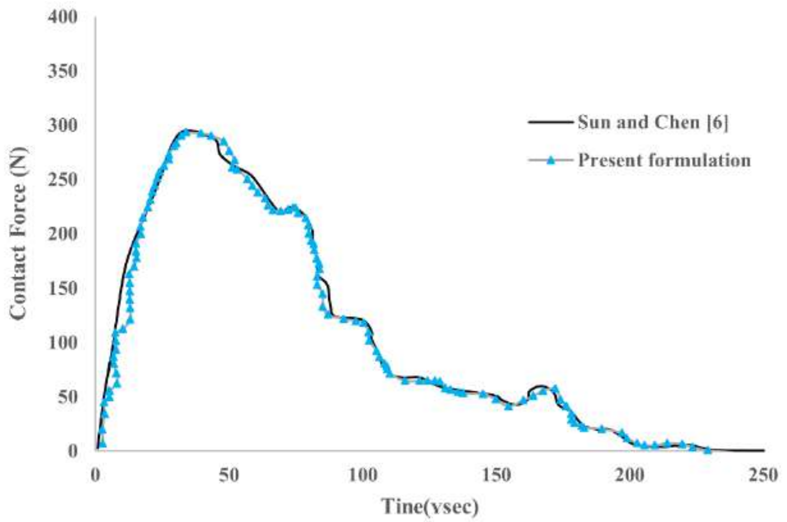

Fig. 2. Contact force history of plate

(i) Fixities: Simply-supported (SS)
(ii) Ply-angle: 0º/90º(CP)
(iii) Velocity in m/s: 1,3,5,10
(iv) shell geometry: a=b; a/h = 100; a/hh = 5; hl/hh = 0.25 a/t= 100

(v) stiffener geometry: t/tt = 1
(vi) Properties of materials: E_{11}=120GPa, E_{22}=7.9Gpa, $G_{12}=G_{23}=G_{13}$ = 5.5GPa, v_{12} =0.30, ρ = 1.58x 10^{-5} N-sec^2/cm^4
(vii) Details of indenter: Diameter = d; d/a = 0.06; density = 7.96x10^{-5} N-sec^2 /cm^4

Finite element engine Ansys 2022 R1 is used for the current formulation.

Five cases are considered in the study as shown in Fig. 3.
Case I - Only conoidal shell with cut-out (without stiffener)
Case II – Conoidal shell with stiffeners around the cut-out
Case III – Conoidal shell with stiffeners at middle of the shell along X-direction in presence of cut-out
Case IV- Conoidal shell with stiffeners at middle of the shell along Y-direction in presence of cut-out
Case V- Conoidal shell with stiffeners around the cut-out, in middle and along X and Y-directions.

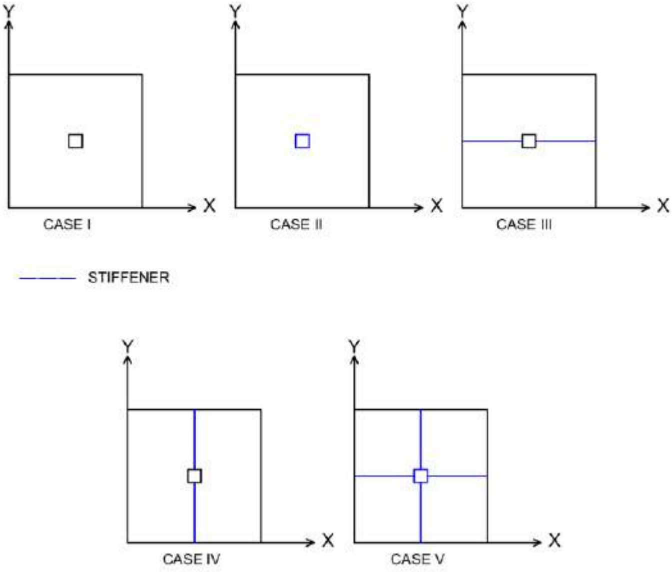

Fig. 3. Different geometries of conoidal shells

3. Results and Discussions

Results obtained in Table-1 demonstrate that the non-dimensional fundamental frequency of twisted plates solved by current numerical formulation agrees to those stated by Qatu and Leissa [13]. This agreement verifies that current code correctly incorporates stiffness and mass matrix formulation. Fig.2 shows time history of impact force on composite plate under low velocity impact reported by Sun and Chen [6]. Again, excellent agreement between the data is seen, confirming accuracy of the impact formulation. Results of impact response are shown in Fig. 4 to Fig. 33 and Table 2. The research of time step convergence led to development of all impact force, stress, strain, and displacements findings that are shown in graphical or tabular form. It's noteworthy to note that the contact force increases as expected with increasing indenter velocity. The lower velocities display a greater null region before the collision due to lack of interaction as the indenter is dropped from a constant distance. A concentrated pressure is supplied at site of impact to provide a central displacement equal to the greatest dynamic displacement in order to calculate equivalent static load (ESL) for that indenter velocity. When maximal dynamic displacements are divided by the centre displacement under such a load, the result is the dynamic magnification factor (DMF). Maximum impact force, maximum dynamic deformation, and equivalent static load (ESL) are almost linearly related to indenter velocity. However, the relationship between the indenter velocity and the dynamic magnification factor (DMF) is logarithmic, and the DMF is a decreasing function of velocity. The total deformation, maximum principal stress, strain has also increased with the increase of velocity of the indenter. Stiffeners has successfully diminished the deformation of the shell. Conoidal shell with stiffeners around the cut-out as well as along X and Y-direction has shown best results under the impact loading. Conoidal shell with stiffeners along Y-direction in presence of cut-out is seems to be more optimized in economical aspect.

Table 2. Maximum Contact Force, deformation, principal stress, principal strain, ESL and DMF

Case No.	Velocity (m/s)	Maximum Contact Force (N)	Maximum deformation (mm)	Maximum principal stress (MPa)	Maximum principal strain	ESL (N)	DMF
I	0	0	0	0	0	0	0
	1	1480.3	6.4435	5.0108	0.0002476	7889.999	2.81
	3	4318.4	8.5328	10.253	0.0006889	19929.416	2.07
	5	6718.23	10.096	30.44	0.0029594	23775.815	1.97
	10	13298.17	14.53	76.225	0.0060861	39229.601	1.57
II	0	0	0	0	0	0	0
	1	1503.7	6.4036	4.2238	0.000236	8014.721	2.82
	3	4484.1	8.2171	10.533	0.000662	20694.12	2.11
	5	7473.8	10.095	31.676	0.002904	26449.77	1.96
	10	14933	14.116	77.998	0.005967	44052.35	1.53
III	0	0	0	0	0	0	0
	1	1342.2	6.9366	7.8296	0.000394	7153.926	2.81
	3	4607.1	9.5179	21.853	0.001062	21261.766	2.07
	5	7219.3	10.074	29.205	0.003049	25549.102	1.95
	10	15591	14.314	63.452	0.006413	45993.45	1.53
IV	0	0	0	0	0	0	0
	1	2067.5	6.2166	7.6088	0.000512	11019.77	2.81
	3	6201.1	8.0015	22.035	0.001523	28620.2	2.09
	5	10338	9.9546	23.777	0.002852	36596.00	1.95
	10	20665	13.55	63.594	0.006162	81684.62	1.57
V	0	0	0	0	0	0	0
	1	4037.2	5.3928	11.166	0.00063	21518.276	2.89
	3	11832	7.4199	49.421	0.00256	54604.68	2.06
	5	19720	8.9682	24.969	0.00299	69789.08	1.93
	10	39454	13.199	69.859	0.00575	116389.3	1.54

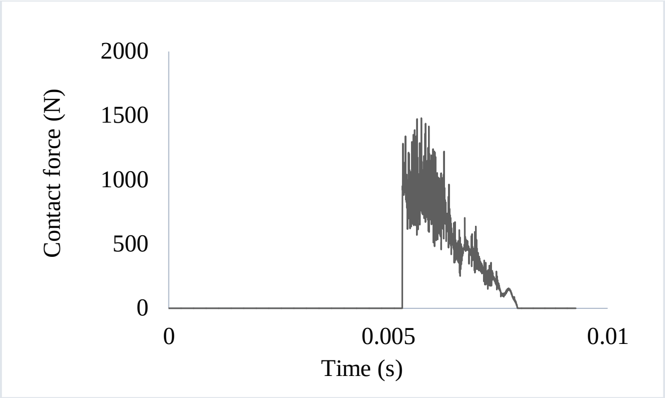

Fig. 4. Contact force vs Time (1m/s; Case I)

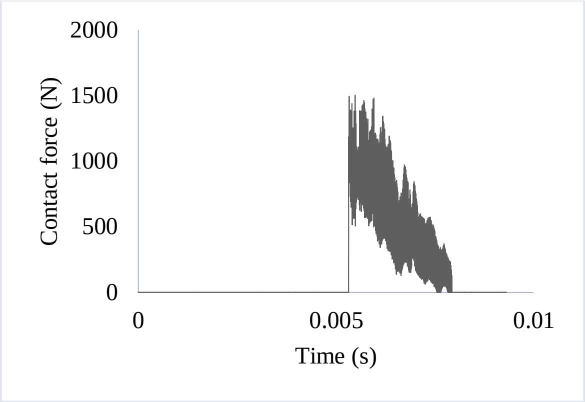

Fig. 5. *Contact force vs Time (1m/s; Case II)*

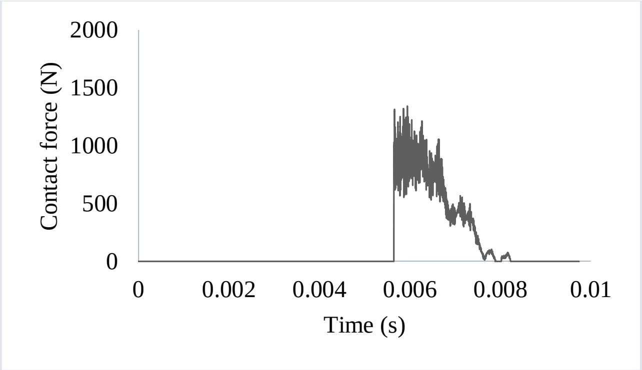

Fig. 6. Contact force vs Time (1m/s; Case III)

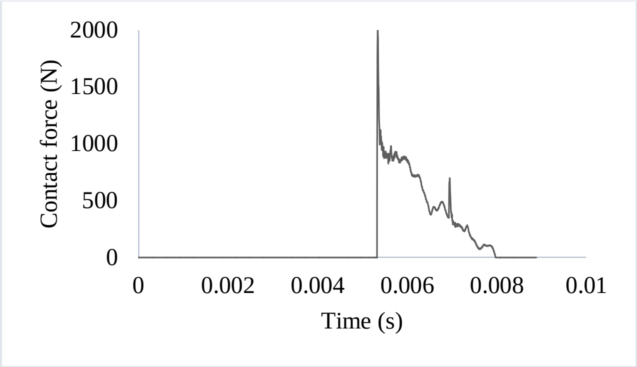

Fig. 7.*Contact force vs Time (1m/s; Case IV)*

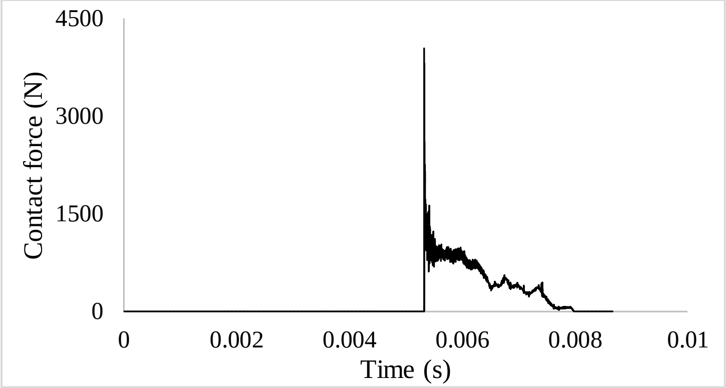

Fig. 8. Contact force vs Time (1m/s; Case V)

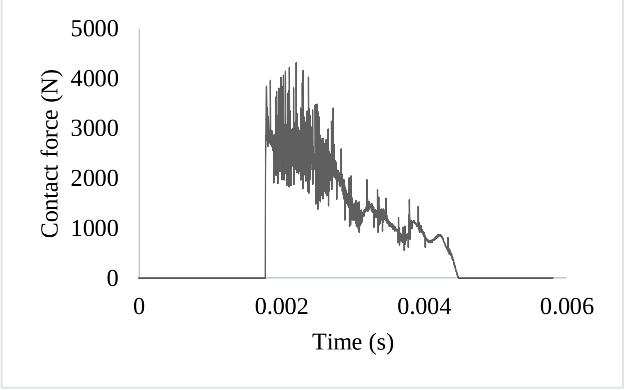

Fig. 9. *Contact force vs Time (3m/s; Case I)*

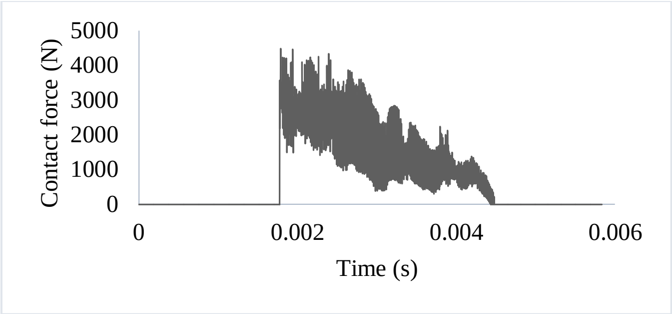

Fig. 10. Contact force vs Time (3m/s; Case II)

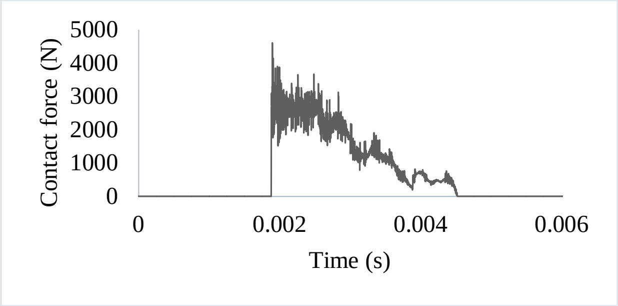

Fig. 11. *Contact force vs Time (3m/s; Case III)*

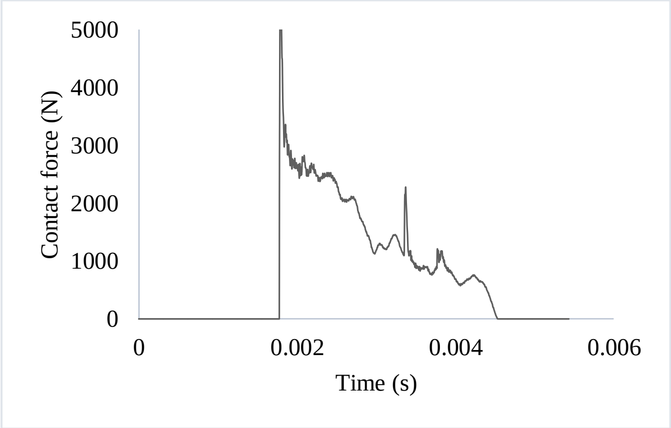

Fig. 12. Contact force vs Time (3m/s; Case IV)

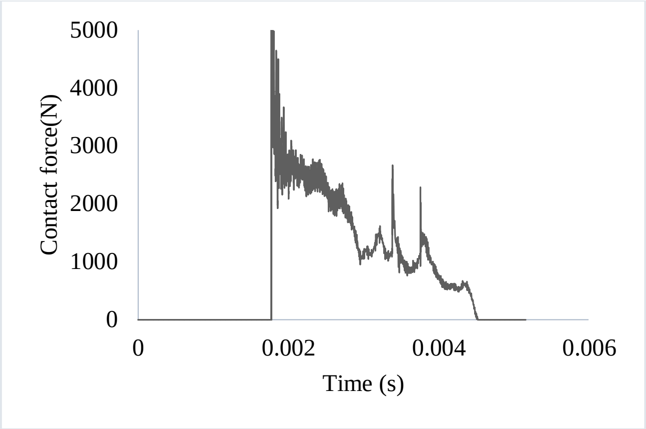

Fig. 13. *Contact force vs Time (3m/s; Case V)*

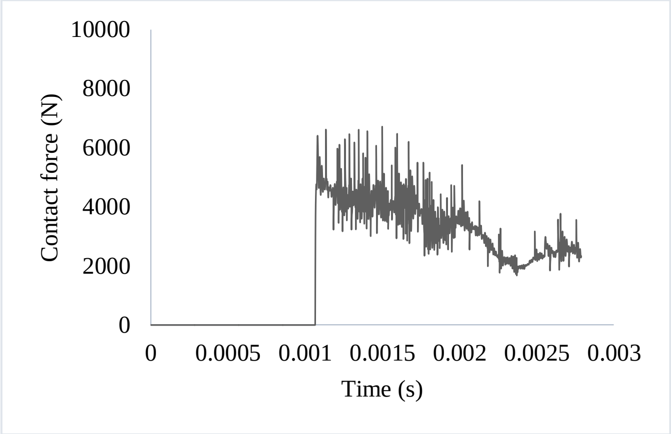

Fig. 14. Contact force vs Time (5m/s; Case I)

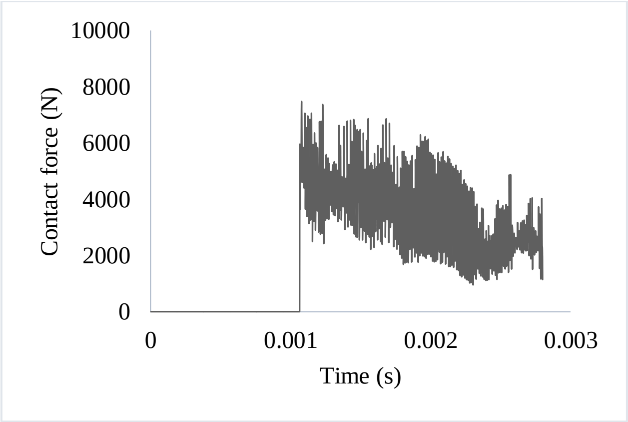

Fig. 15. *Contact force vs Time (5m/s; Case II)*

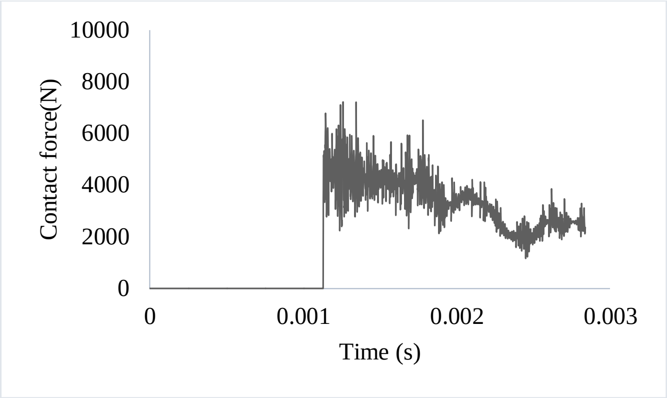

Fig. 16. Contact force vs Time (5m/s; Case III)

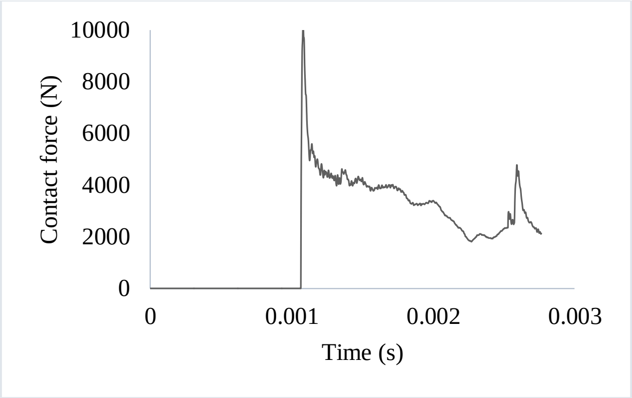

Fig. 17. *Contact force vs Time (5m/s; Case IV)*

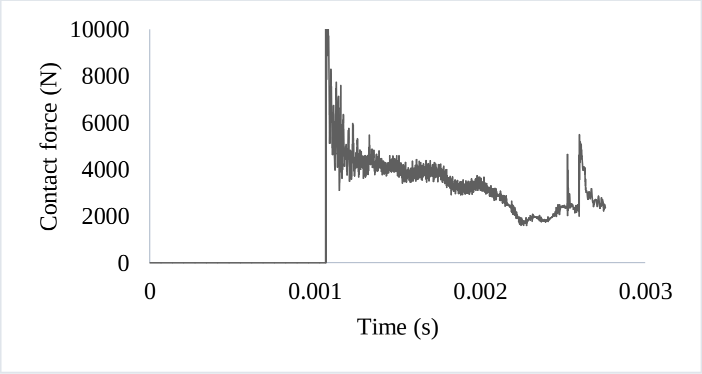

Fig. 18. Contact force vs Time (5m/s; Case V)

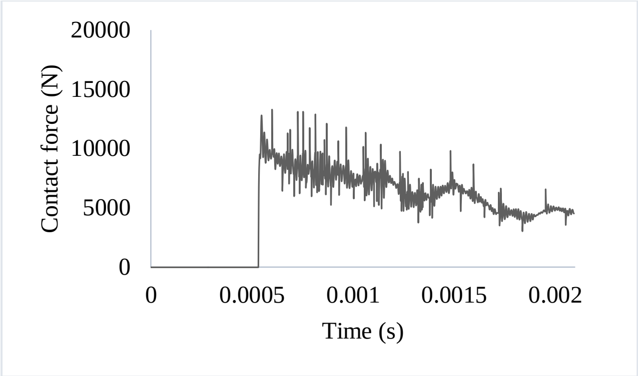

Fig. 19. Contact force vs Time (10m/s; Case I)

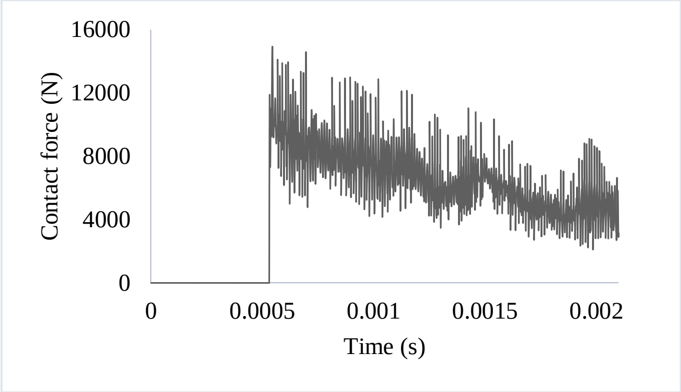

Fig. 20. Contact force vs Time (10m/s; Case II)

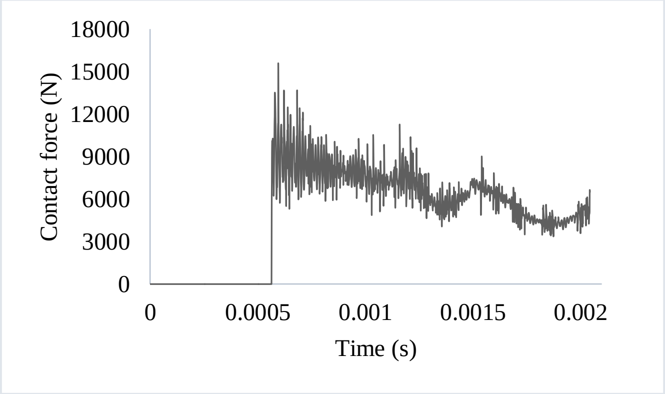

Fig. 21. *Contact force vs Time (10m/s; Case III)*

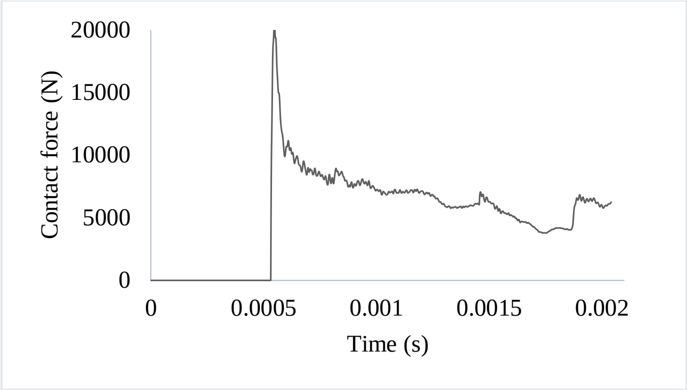

Fig. 22. Contact force vs Time (10m/s; Case IV)

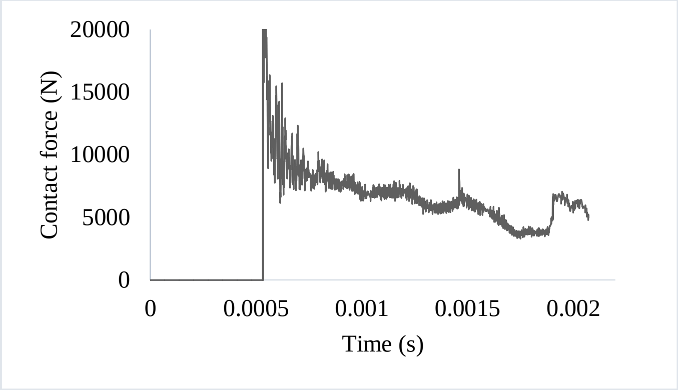

Fig. 23. *Contact force vs Time (10m/s; Case V)*

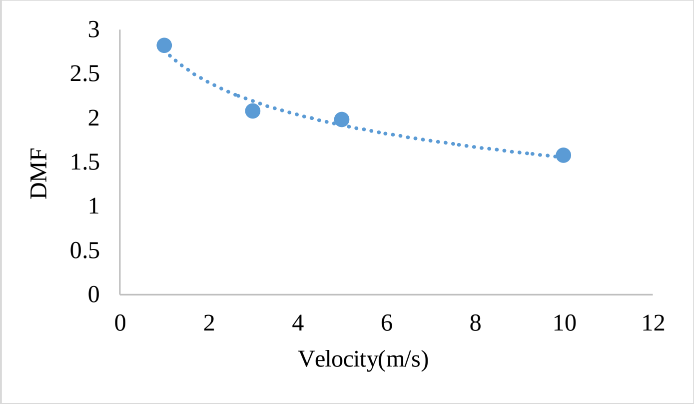

Fig. 24. DMF vs Velocity (Case I)

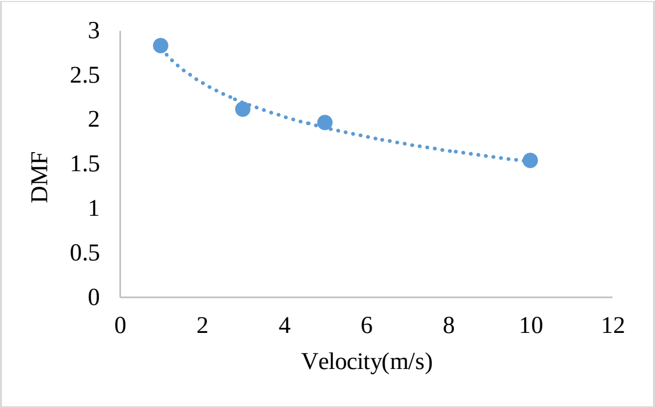

***Fig. 25.** DMF vs Velocity (Case II)*

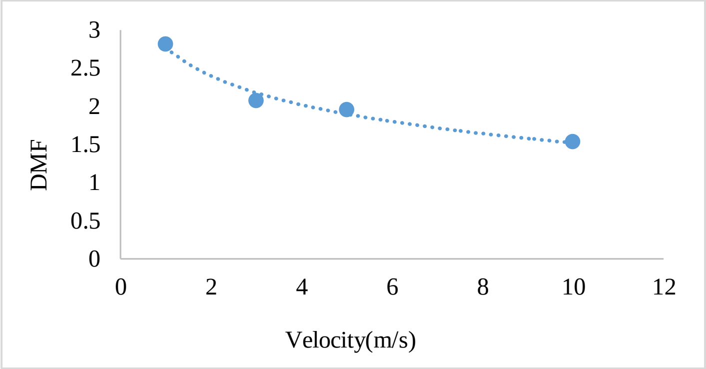

Fig. 26. DMF vs Velocity (Case III)

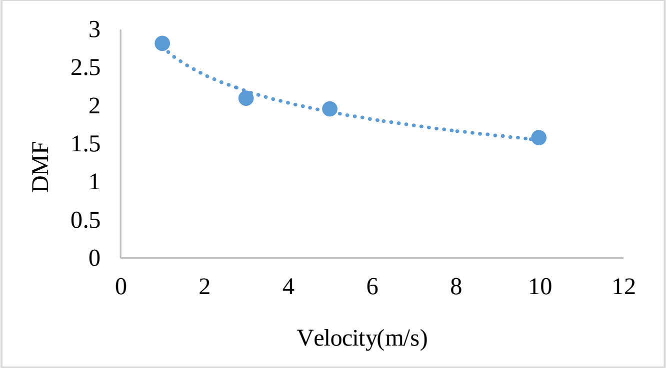

Fig. 27. DMF vs Velocity (Case IV)

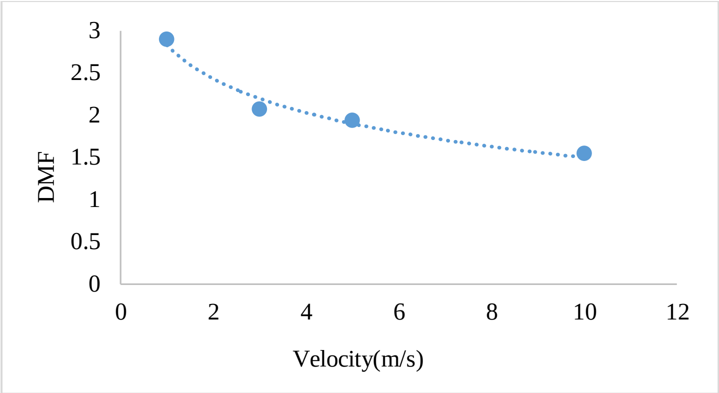

Fig. 28. DMF vs Velocity (Case V)

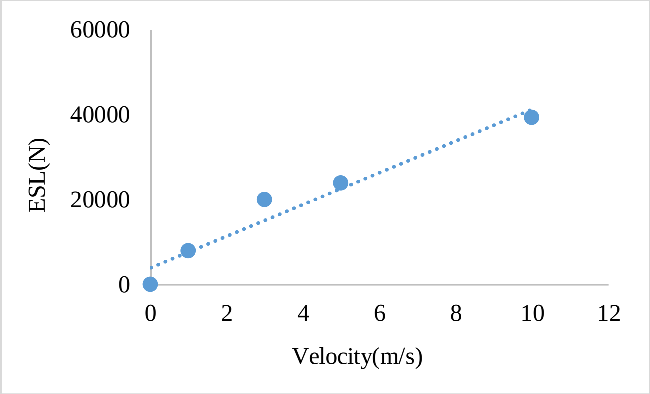

Fig. 29. *ESL vs Velocity (Case I)*

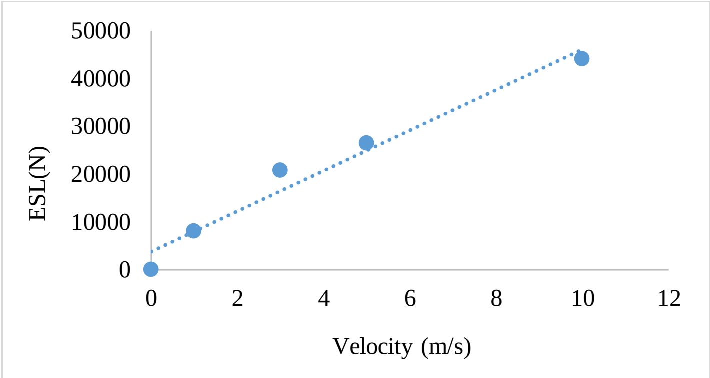

Fig. 30. ESL vs Velocity (Case II)

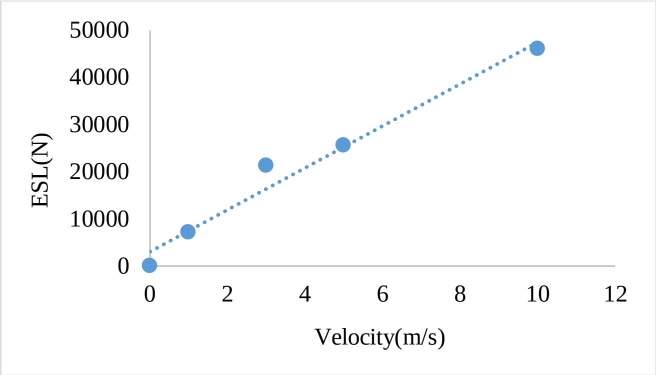

Fig. 31. *ESL vs Velocity (Case III)*

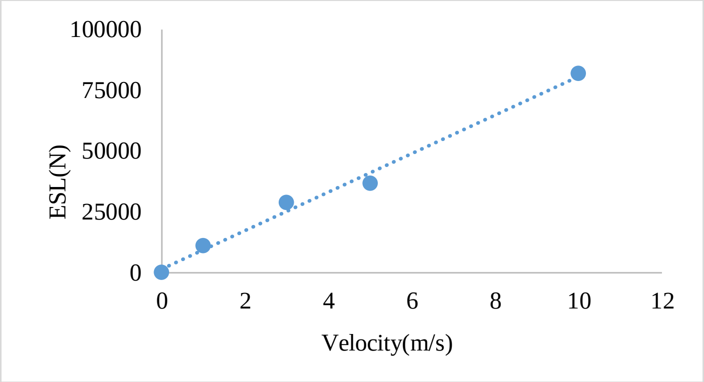

Fig. 32. ESL vs Velocity (Case IV)

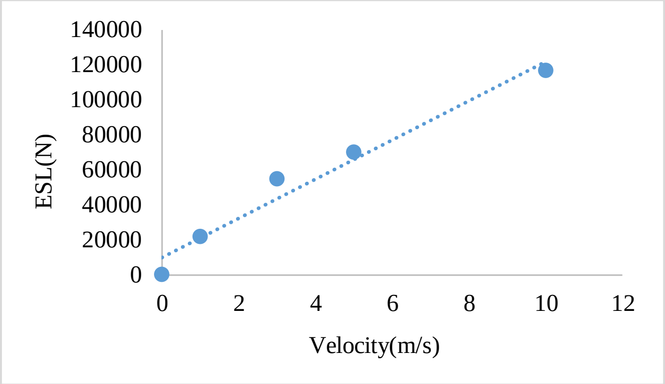

Fig. 33. *ESL vs Velocity (Case V)*

4. Conclusion

1. The accurate inclusion of impact formulation is established by close agreement between findings achieved by current process and those found in this chapter.
2. With the increase of velocity maximum deformation, maximum principal stress, maximum principal strain and contact force are also increasing.
3. Case-V exhibits the best result under impact loading whereas considering the economical aspect Case-IV is found to be more optimized.
4. Maximum impact force and equivalent static load (ESL) variations with indenter velocity follow a nearly undeviating relationship.
5. The indenter velocity and dynamic magnification factor (DMF) exhibit logarithmic relationship, and DMF is decreasing velocity function.

Nomenclature

a, b	:	span of shell
E_{11}, E_{22}	:	elastic moduli
G_{12}, G_{13}, G_{23}	:	shear moduli
h	:	thickness of the shell
hl, hh	:	rise of the shell
d	:	diameter of indenter
t	:	thickness of shell
tt	:	thickness of stiffener
v_{12}	:	Poisson's ratio
ρ	:	density

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