Transient response of delaminated torsion stiff composite conical shell panel subjected to low velocity oblique impact

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Outline

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- Why composite
- Why low velocity oblique impact
- Present model
- Analysis method
- Results & Discussions
- Conclusions

Why composite

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- **Improved tailored properties of materials**
  - High strength and stiffness
  - High corrosion and wear resistance
  - High thermal and acoustic insulation
  - High thermal conductivity
  - Prolonged fatigue life cycle

- **Customerization in utility of material**
  - Attractiveness
  - Surface finish
  - Low maintenance

- **Weight sensitive and cost-effective**
  - High strength to weight ratio
  - High stiffness to weight ratio
  - Low utility cost in long-run

Why composite

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- **Application oriented**

  a) **Aerospace**

  Turbo-machines' impellers, fan blades, aircraft wings, space shuttle

  b) **Automobile / Marine**

  Propellers, composite superstructure

  c) **Civil / Construction**

  Roof structures, housing cells

  d) **Others**

  i) Electrical & Electronics: - Insulator, armor, antennas

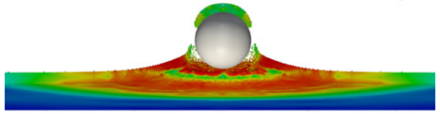
  ii) Bio-medical: - Dental implants, osteosynthesis plates

  ii) Transport: Trailers, wagons, interior panels

  iii) Sports: Skis, bicycle

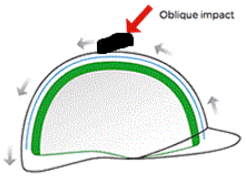
  iv) Miscellaneous: Helmet

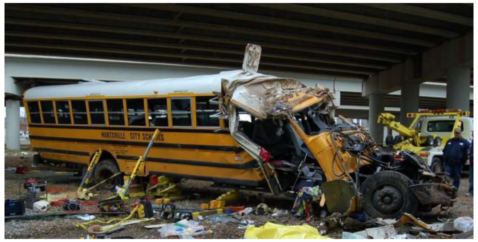
Why low velocity oblique impact

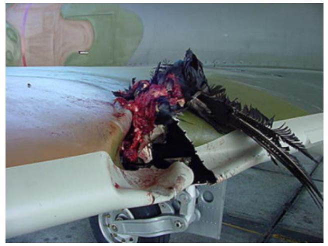


In real-life, oblique impact mostly occurs due to shock applied in short time period when two or more bodies collide

- High velocity impacts are, no doubt, dangerous but Low velocity impacts can be equally dangerous.
- Low velocity impacts can cause onset of delamination, fiber breakage or matrix crack, all insidious failures, that can't be caught by mere external inspection with eyes.
- Critically depends on relative velocity of bodies to one another.







Applications of oblique impact:

- Practically, impacts are hardly in normal direction i.e. perpendicular to the impact surface. They are mostly oblique. e.g. Bird-hit problem of aircraft.
- Any foreign object colliding with the helmet of a rider riding bike.
- Any hailstones impacting on the roof of a house.
- The Runway debris impacting the aircraft wings and fuselage of the aircraft.
- The collision of two vehicles whose drivers' efforts of steering away to avoid collision.
- Any tool drop during manufacturing, storage and transportation of composites.

Delamination and impact

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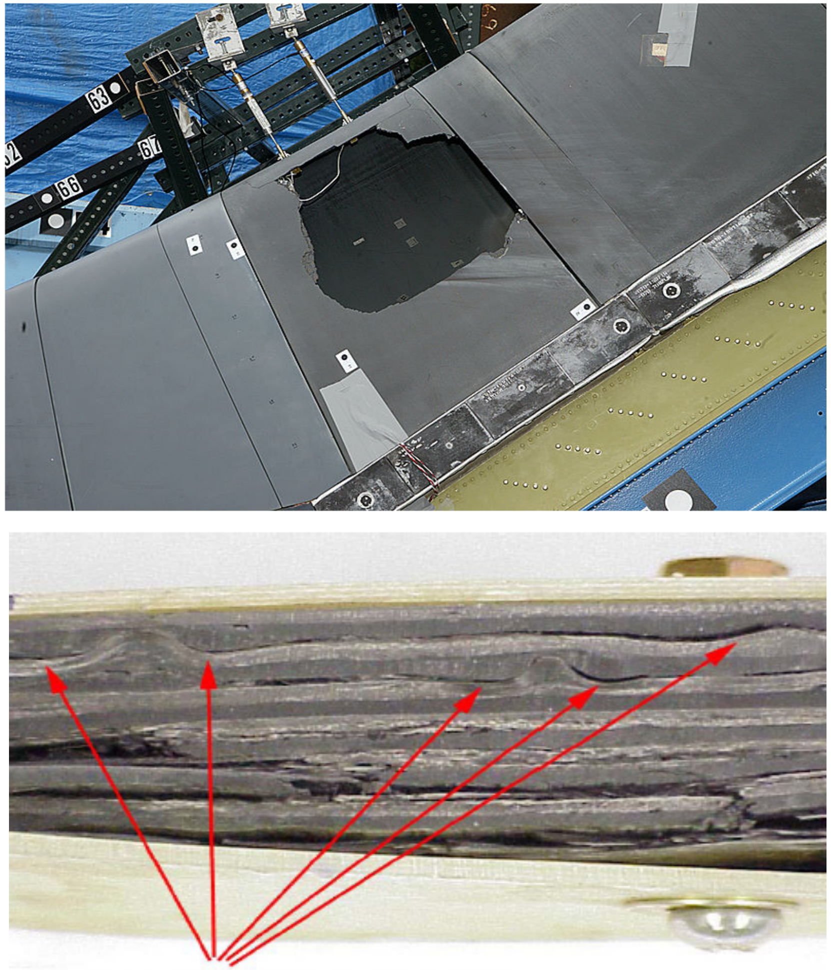


DELAMINATIONS ASSOCIATED WITH WAVES

Consequence of Misalignment in Large, Composite Structure

Fig. Damages due to delamination and impact

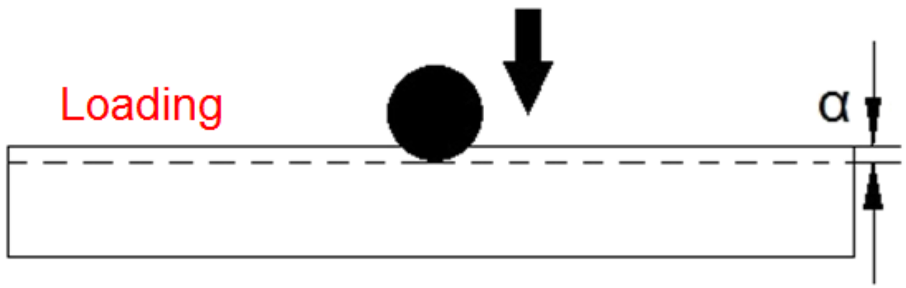
- Delamination is the most common mode of failure for the composite laminates and hence the most feared.

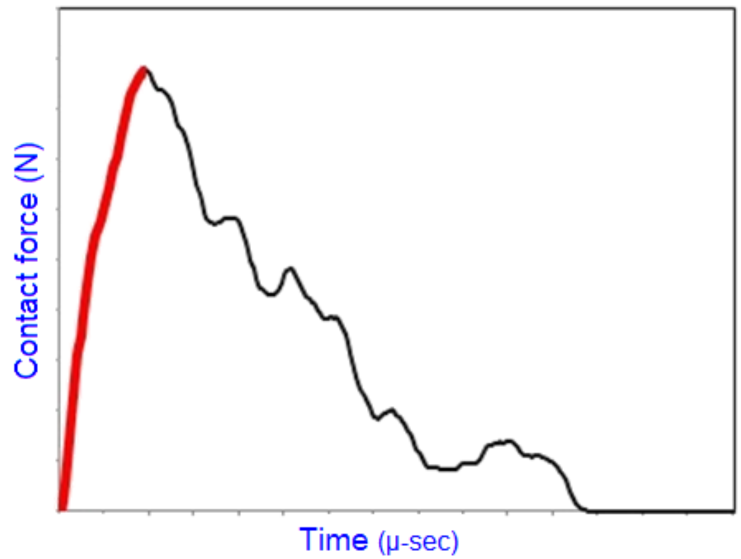
- In spite of the whole list of advantages that the composite have on offer, delamination or inter-laminar debonding of the constituent laminae cause degradation of strength and can promote instability.

- The fear of delamination can further be compounded by low velocity impact causing severe damage leading to failure.

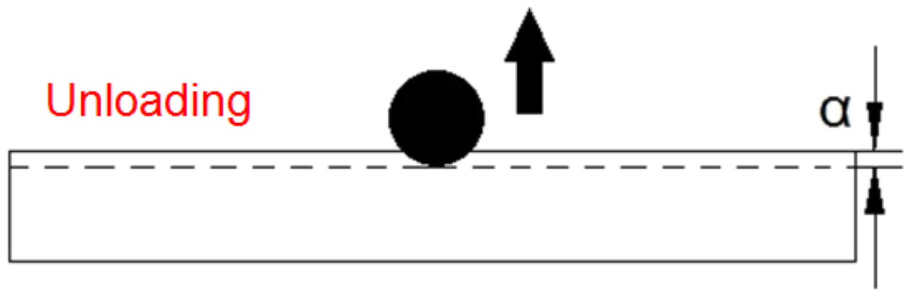
Source: www.wikipedia.com

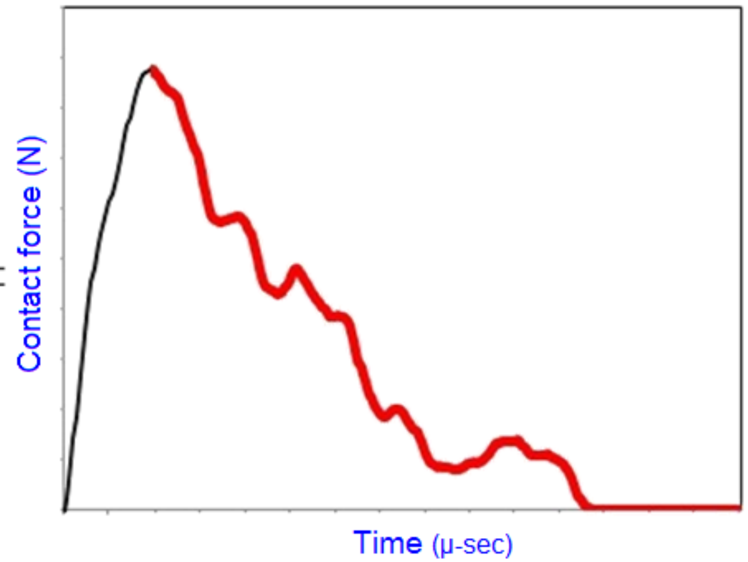
Contact force





α = Local indentation i.e., change in distance between centre of the impactor and the mid-surface of target shell





Some existing works

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- Regarding delamination model, two notable works are
  a) Finite element modelling of laminated plates studied by *Gim (1994) [1]*
  b) Finite element treatment of the delaminated composite cantilever beam and plates by *Krawczuk (1997) [2]* for free vibration analyses.

- The impact response of initially stressed composite plates received attention in the investigations by *Sun and Chen (1985) [3]*

- Transient response of delaminated composite rotating shallow shells subjected to low velocity impact studied by *Karmakar and Kishimoto (2006) [4]*

- Limited number of investigations have been carried out for laminated composite cantilever conical shells subjected to low velocity oblique impact.

[1] Gim C.K., Plate Finite element modelling of laminated plates, Composite Structures, 52, 157-168, 1994.
[2] Krawczuk M., Ostachowicz W., Zak A., Dynamics of cracked composite material structures, Computational Mechanics, 20, 79-83, 1997.
[3] Sun C.T., Chen J.K., On the impact of initially stressed composite laminates, Composite Materials, 19 (1985) 490–504.
[4] Karmakar A., Kishimoto K., Transient dynamic response of delaminated composite rotating shallow shells subjected to impact, Shock and Vibration, 13, 619–628, 2006.

Theoretical formulation

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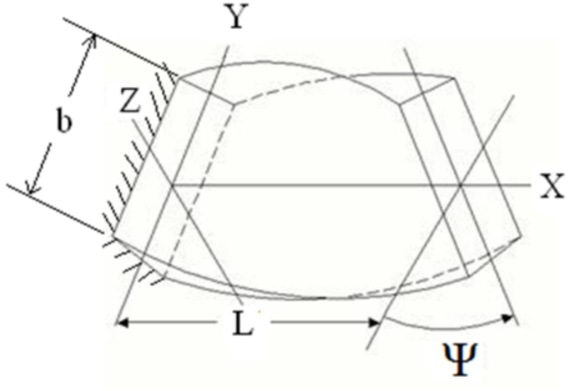

Fig. Pretwisted cantilever Shell panel

where,
R_x, R_y=radius of curvature in x- and y-direction,
δ=displacement, [M]=mass matrix,
[K]=stiffness matrix, {F}=Force vector,
k= contact stiffness, F_c=contact force,
F_m=maximum contact force,
m_i=mass of impactor, α=local indentation,
α_m=maximum indentation during loading,
α_o=permanent indentation in loading-unloading cycle

- A shallow shell is characterized by its middle surface, defined as

$$z = -\frac{1}{2}\left[\frac{x^2}{R_x} + 2\frac{xy}{R_{xy}} + \frac{y^2}{R_y}\right]$$

- The radius of twist (R_{xy}), length (L) of the shell and twist angle (Ψ) are related by the expression [1]

$$\tan\psi = -\frac{L}{R_{xy}}$$

- Dynamic equilibrium eqn. by Lagrange's eqn.[2],

$$[M]\{\ddot{\delta}\} + [K]\{\delta\} = \{F\}$$

For the impact problem

$$\{F\} = \{0\ 0\ 0 \ldots F_C \ldots 0\ 0\ 0\}^T$$

- Equation of motion of the rigid impactor:

$$m_i\ \ddot{w}_i + F_C = 0$$

- Contact laws [3]:

$$F_C = k\,\alpha^{1.5},\quad 0 \le \alpha \le \alpha_m \qquad \text{(for loading)}$$

$$F_c = F_m\left[\frac{\alpha-\alpha_o}{\alpha_m-\alpha_o}\right]^{5/2} \quad and \quad F_c = F_m\left[\frac{\alpha-\alpha_o}{\alpha_m-\alpha_o}\right]^{3/2}$$

(for unloading) (for reloading)

[1] Liew K.M., Lim C.M., Ong L.S., Vibration of pretwisted cantilever shallow conical shells, I. J. Solids Structures, 31(18), 2463-74, 1994.
[2] Karmakar A., Sinha P.K., Failure analysis of laminated composite pretwisted rotating plates, JRPC, 20(14-15), 1326-1357, 2001.
[3] Sun C.T., Chen J.K., On the impact of initially stressed composite laminates, Composite Materials, 19 (1985) 490–504.

Multipoint constraints

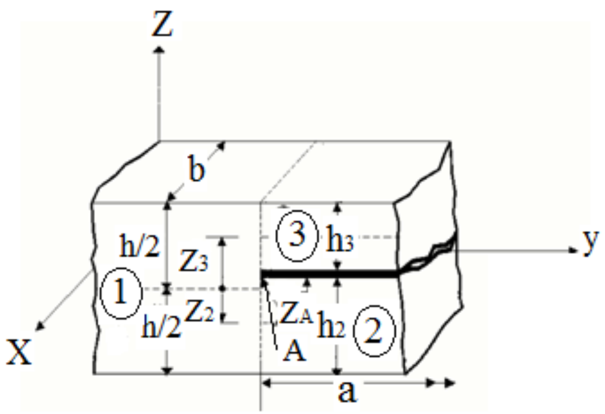

Fig. Delamination crack tip

- The nodal displacements at crack tip expressed as **

$$u_i = u'_j - (z - z'_j)\,\theta_{xi} \qquad v_i = v'_j - (z - z'_j)\,\theta_{yi} \qquad w_j = w'_j \quad (\text{where, } j = 2, 3)$$

- Transverse displacements and rotations at common node

$$w_1 = w_2 = w_3 = w$$
$$\theta_{x1} = \theta_{x2} = \theta_{x3} = \theta_x$$
$$\theta_{y1} = \theta_{y2} = \theta_{y3} = \theta_y$$

In-plane displacements of all three elements at crack tip are equal and related as,

$$u'_2 = u'_1 - z'_2\,\theta_x \qquad u'_3 = u'_1 - z'_3\,\theta_x$$
$$v'_2 = v'_1 - z'_2\,\theta_y \qquad v'_3 = v'_1 - z'_3\,\theta_y$$

- Mid-plane strains between elements 2 and 3 are related as, $\{\varepsilon'\}_j = \{\varepsilon'\}_1 + z'_j\,\{k'\}$

where, $\{\varepsilon'\}$ and $\{k'\}$ are the strain vector and the curvature vector, respectively

- Force and moment resultants are:

$$\{N\}_j = [A]_j\,\{\varepsilon'\}_1 + (z'_j\,[A]_j + [B]_j)\,\{k'\}$$
$$\{M\}_j = [B]_j\,\{\varepsilon'\}_1 + (z'_j\,[B]_j + [D]_j)\,\{k'\}$$

- At delamination front:

$$\{N\} = \{N\}_1 = \{N\}_2 + \{N\}_3$$
$$\{M\} = \{M\}_1 = \{M\}_2 + \{M\}_3 + z'_2\,\{N\}_2 + z'_3\,\{N\}_3$$
$$\{Q\} = \{Q\}_1 = \{Q\}_2 + \{Q\}_3$$

** Gim C.K., Plate Finite Element Modeling of Laminated Plates, *Computers & Structures*, 52(1), 157-168, 1994.

Newmark's time integration

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- In present analysis, equation of motion of the rigid impactor expressed in the iteration form at each time step [1]

$$[\bar{K}]\{\Delta\}_{t+\Delta t}^{i+1} = \frac{\Delta t^2}{4}\{F\}_{t+\Delta t}^{i} + [M]\{b\}_i$$

where

$$[\bar{K}] = \frac{\Delta t^2}{4}[K] + [M]$$

$$\{b_i\} = \{\Delta\}_t + \Delta t\{\dot{\Delta}\}_t + \frac{\Delta t^2}{4}\{\ddot{\Delta}\}_t$$

- Neglecting the contribution of plate displacements along global x and y directions, the indentation α is given as [2]

$$\alpha(t) = w_i(t)\,\text{Cos}\,\zeta_i - w_p(x_c, y_c, t)\,\text{Cos}\,\psi$$

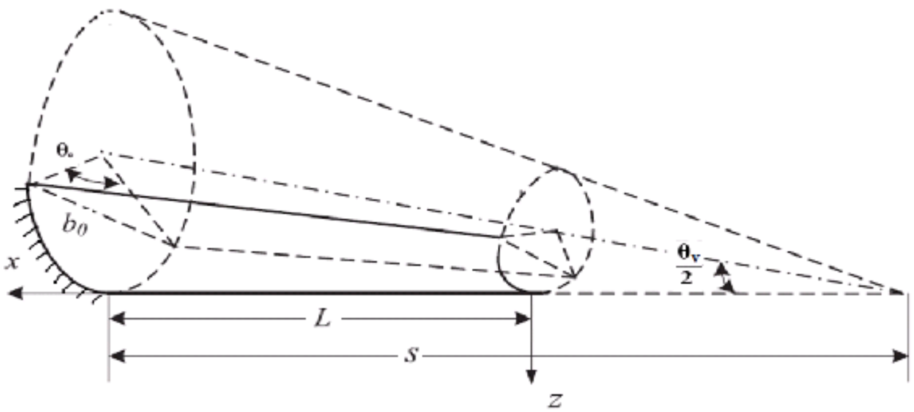
where, ζ_i =oblique impact angle, ψ =twist angle, w_i and w_p are displacement of impactor and target plate displacement along global z direction

- The components of force at impact point in global directions are given by

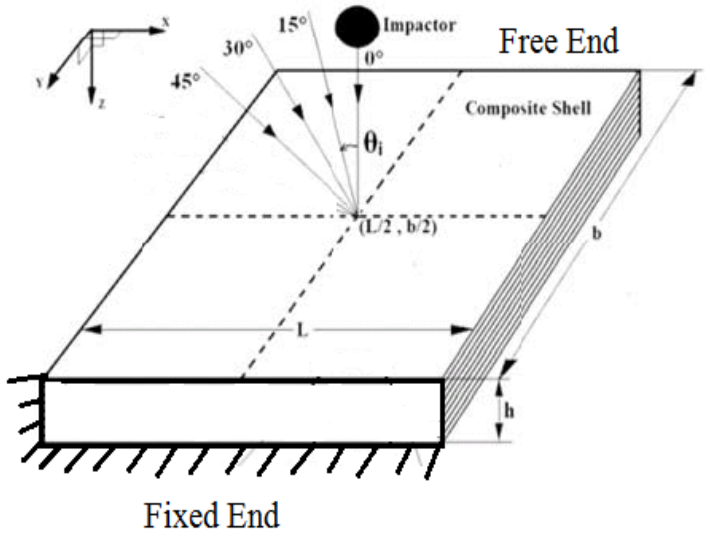
$$F_{ix} = 0, \quad F_{iy} = F_C \sin\psi \quad \text{and} \quad F_{iz} = F_C \cos\psi$$

[1] Bathe K.J., Finite Element Procedures in Engineering Analysis, New Delhi: PHI; 1990.
[2] Karmakar A., Sinha P.K., Finite element transient dynamic analysis of laminated composite pretwisted rotating plates subjected to impact, Int. J. of Crashworthiness, 3(4), 379–391, 1998.

Present model

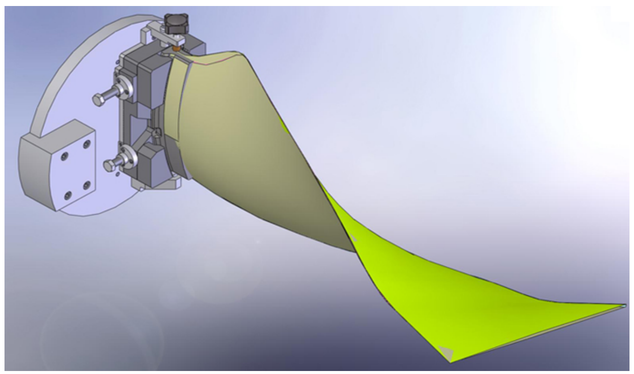


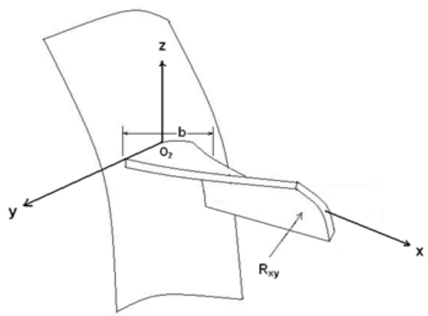
a) Untwisted conical shell model



b) Twisted plate

Fig. Geometry of cantilever shallow conical shell panel





Conical shell geometry

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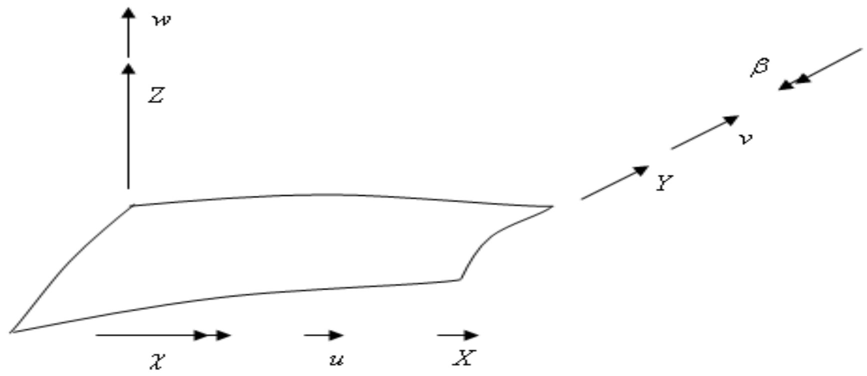


Fig. Conical shell element with degrees of freedom

- Non-dimensional coordinate system given by

$$\xi = \frac{x}{L} \quad and \quad \eta = \frac{y}{b_o}$$

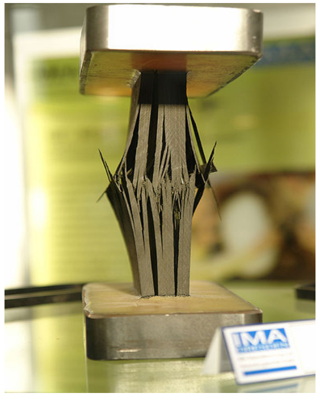
(where b_o=reference width)

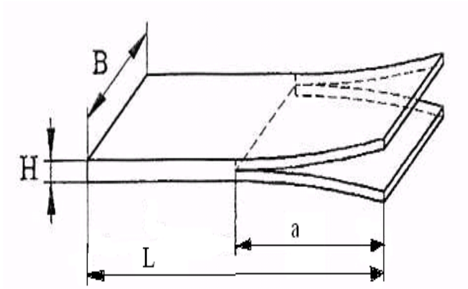
- The varying radius of curvature $R_y(\xi,\eta) = \frac{\beta_o}{f(\xi,\eta)}$

- The function expressed from the geometry of conical shell given by

$$f(\xi,\eta) = \tan(\theta_v/2)\frac{s}{R_y(\xi,\eta)}$$

Scope of present study





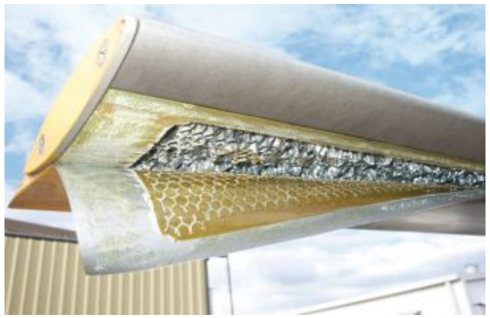


Fig. Delamination

Source: www.wikipedia.com

- Pretwisted conical shells with low aspect ratio can be idealized as turbo-machinery blades.
- Delamination and oblique impact can degrade the strength and promote instability.
- Severe cascading effect of damage caused due to:
  a) Poor through-the-thickness strength
  b) Susceptibility to high strain rate loading under low velocity impact by foreign objects.
- Present analyses aimed to study on transient response of pretwisted **torsion-stiff** composite conical shell panel subjected to **low velocity oblique impact**

Low velocity oblique impact and delamination may cause severe structural instability

Validation (Special case)

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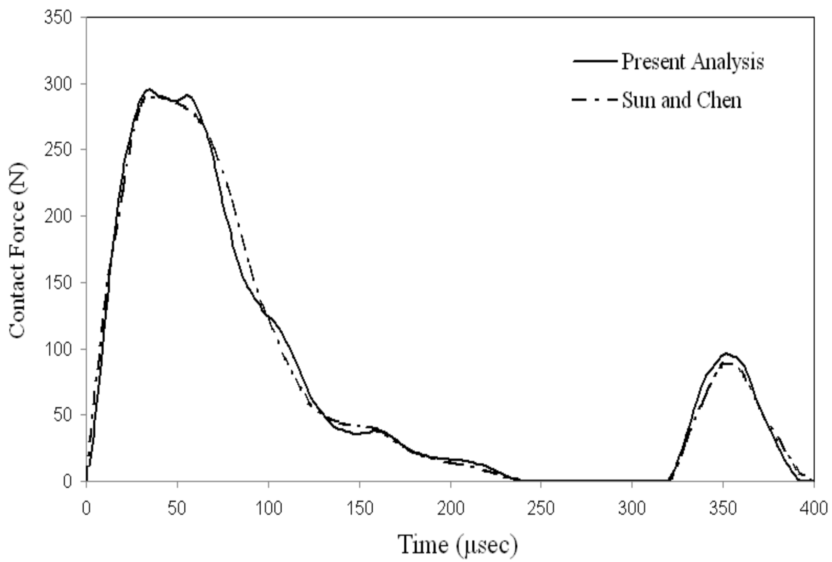
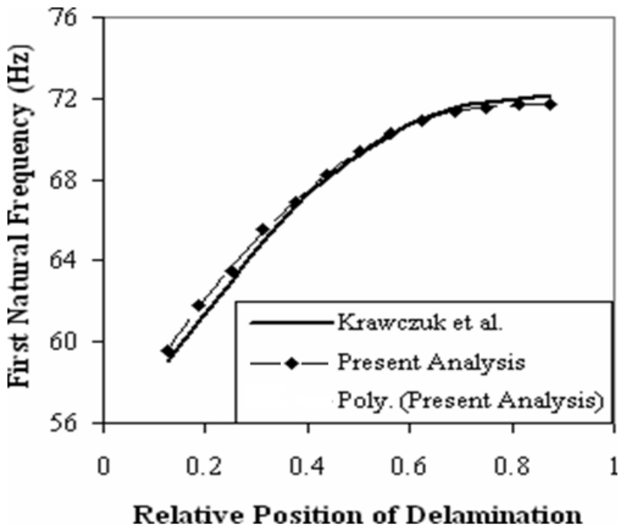
(a) Contact force with respect to time for centrally impacted cross-ply ($[0/90/0/90/0]_S$) composite plate under simply supported boundary condition, considering laminate dimension 20 cm x 20 cm x 0.269 cm, contact stiffness coefficient (k)=0.805×10^9 $N/m^{1.5}$, mass density of impactor=7.96 x 10^{-5} $N\text{-}sec^2/cm^4$, time step=1.0 μ-sec, E_1=120 GPa, E_2=7.9GPa, E_i=210 Gpa, $G_{12}=G_{23}=G_{13}$=5.5 GPa, ρ=1580 kg/m^3, $v_i=v_{12}$=0.3, velocity of impactor=3 m/s

(b) Influence of the relative position of delamination on the first natural frequency of the composite cantilever beam



(a)



(b)

a) Sun C.T., Chen J.K., On the impact of initially stressed composite laminates, *Composite Materials,* Vol. 19, p.490–504, 1985.
b) Krawczuk M., Ostachowicz W., Zak A., Dynamics of Cracked Composite Material Structures, J. Computational Mechanics, Vol. 20, pp. 79-83, 1997.

Laminate configuration

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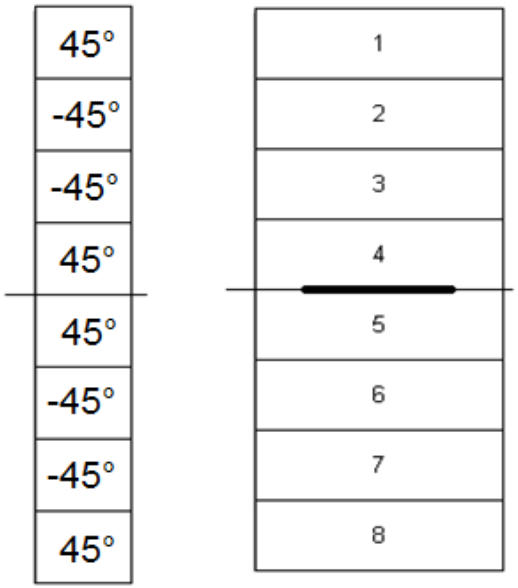
Torsion Stiff (45°/ -45°/ -45°/ 45°)s

Considering eight noded isoparametric quadratic plate bending element with 5 dof for graphite-epoxy composite conical shells with n=8, h=0.005 m, v=0.3, a/L=0.33, s/h=1000, L/s=0.7, θ_o=45°, θ_v =20°

Material properties (Graphite-Epoxy)**: E_1=138.0 GPa, E_2=8.96GPa, G_{12}=7.1GPa, G_{13}=7.1 GPa, G_{23}=2.84 GPa, v=0.3



Where,

n=number of layers

h=thickness of laminate

a= crack length,

L/s=aspect ratio

θ_o=base subtended angle of conical shell panel

θ_v =vertex angle of conical shell panel

Fig. Laminate Configuration

** M. S. Qatu and A. W. Leissa, Natural frequencies for cantilevered doubly-curved laminated composite shallow shells, *Composite Structures*, 17, pp. 227-255, 1991.

Effect of oblique impact and twist angles

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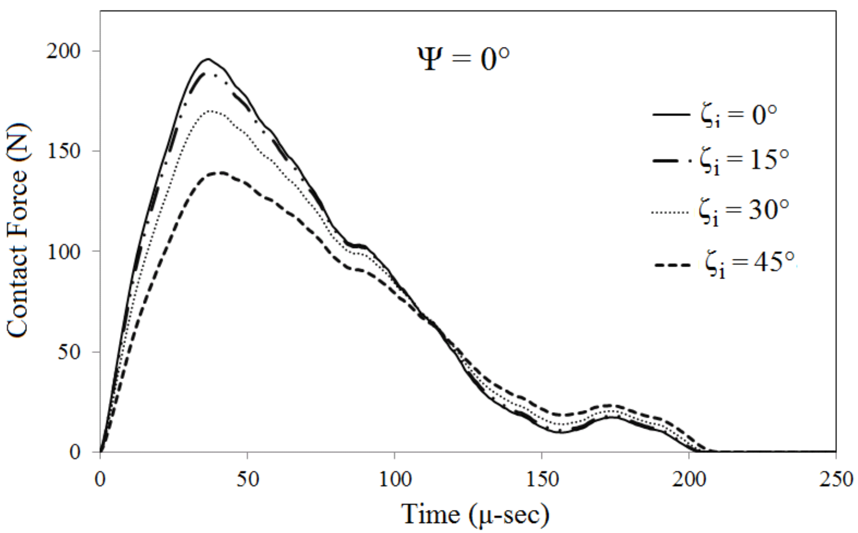
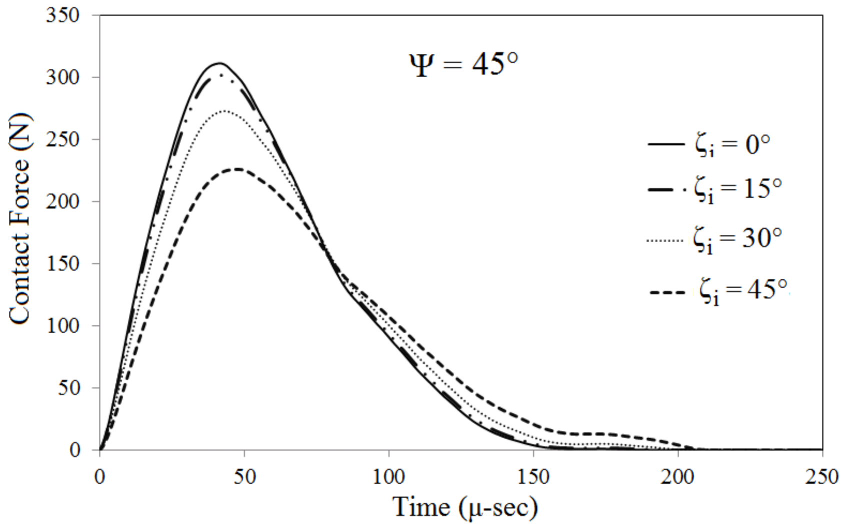
n=8, h=0.005 m, Ω =0.0, a/L=0.33, s/h=1000, L/s=0.7, θ_o=45°, θ_v =20°



Untwisted



Twisted

- Peak Contact Force (PCF) decreases with increase of oblique impact angle

- $PCF_{twisted} > PCF_{untwisted}$

Effect of oblique impact and twist angles

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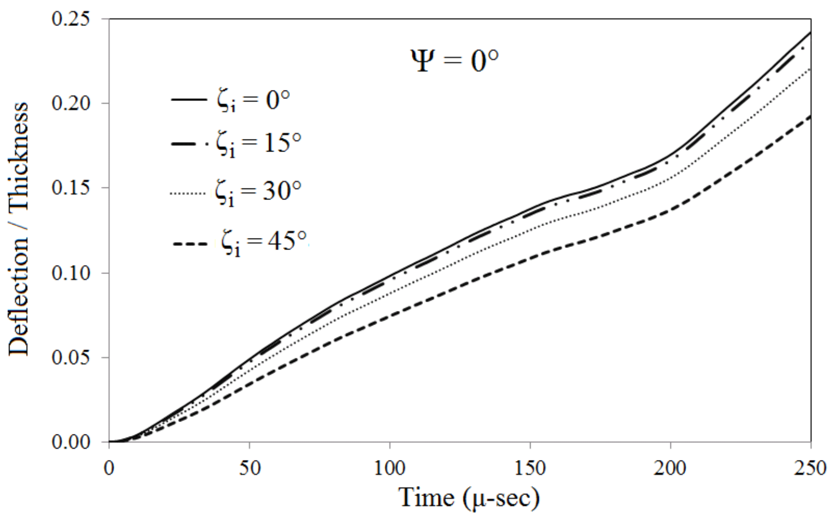
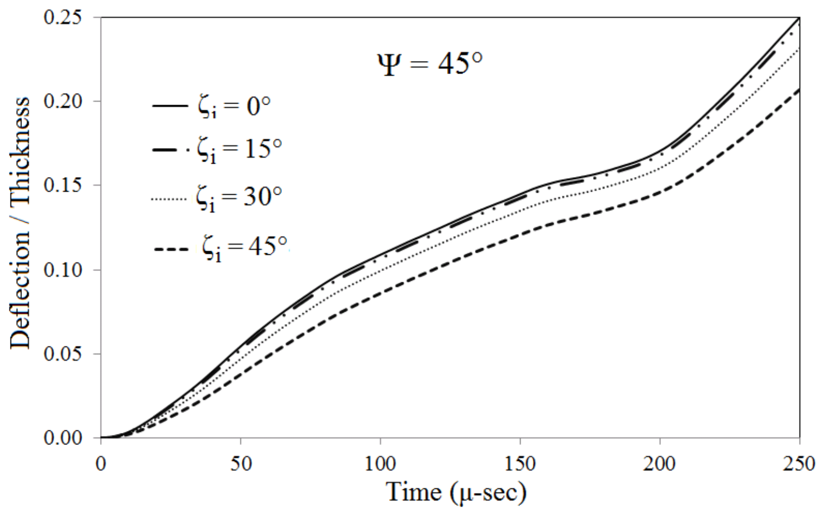
n=8, h=0.005 m, Ω =0.0, a/L=0.33, s/h=1000, L/s=0.7, θ_o=45°, θ_v=20°



Untwisted



Twisted

- Deflection/Thickness (D/T) decreases with increase of oblique impact angle

- $(D/T)_{twisted} > (D/T)_{untwisted}$

Effect of oblique impact and twist angles

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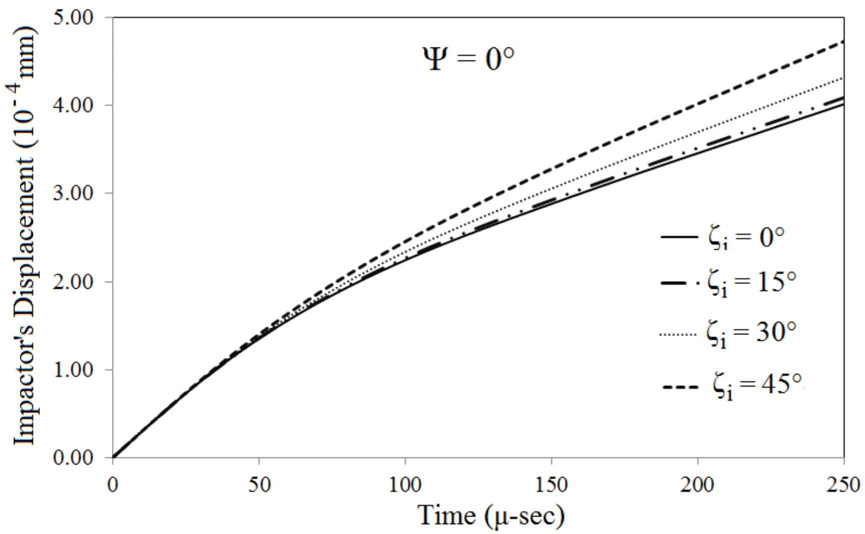
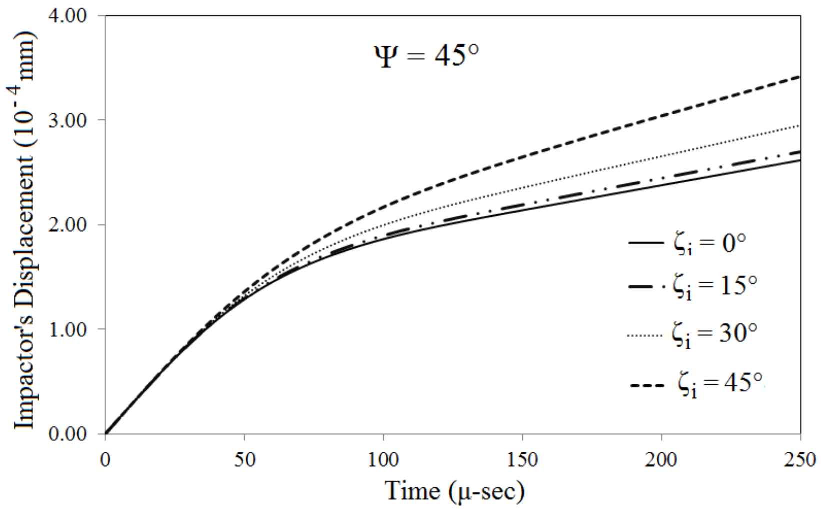
n=8, h=0.005 m, Ω =0.0, a/L=0.33, s/h=1000, L/s=0.7, θ_o=45°, θ_v =20°



Untwisted



Twisted

- ❖ Impactor's Displacement (ID) increases with increase of oblique impact angle
- ❖ $(ID)_{twisted}$ < $(ID)_{untwisted}$

Effect of oblique impact and twist angles

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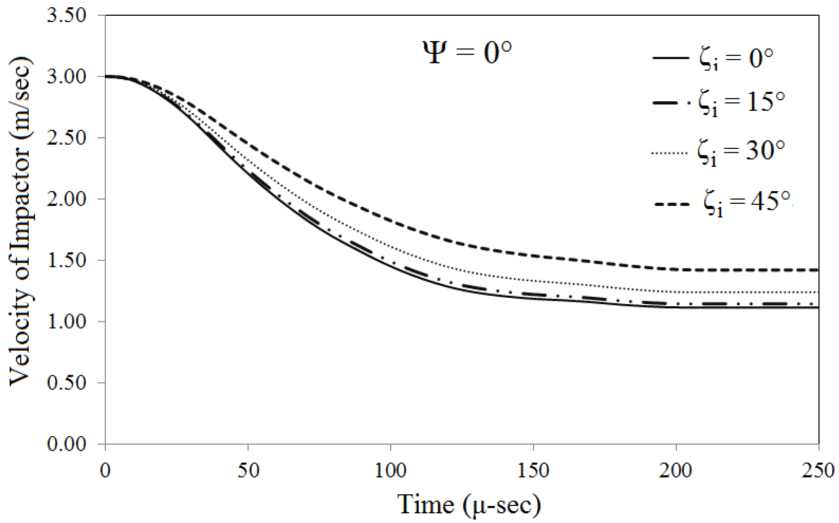
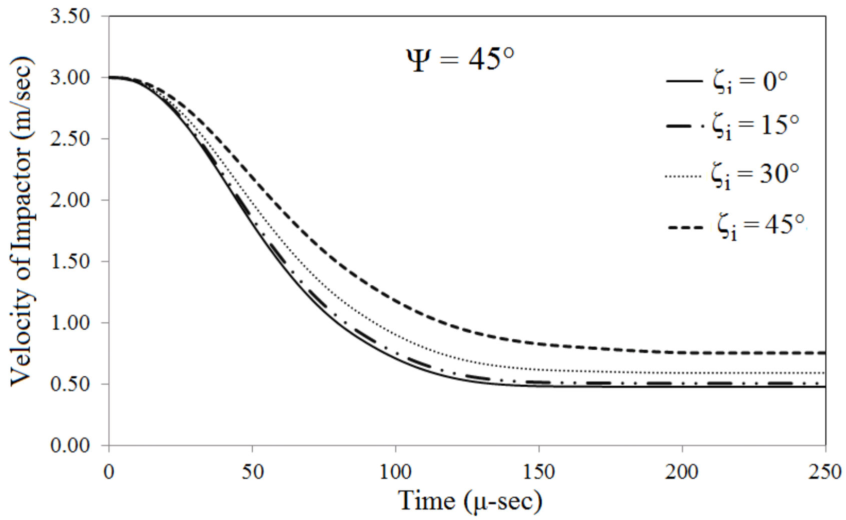
n=8, h=0.005 m, Ω =0.0, a/L=0.33, s/h=1000, L/s=0.7, θ_o=45°,θv =20°



Untwisted



Twisted

❖ Velocity Of Impactor (VOI) increases with increase of oblique impact angle

❖ $(VOI)_{twisted}$ < $(VOI)_{untwisted}$

Conclusions

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- ❑ An approach for investigation of the effect of oblique impact on delaminated composite conical shell panel is presented.

- ❑ The developed finite element code is validated with results from open literature both in respect of impact and delamination model.

Summary of numerical results

- Peak value of the contact force increases with the rise of twist angle
- Peak value of the contact force of untwisted case is found lower than that of the twisted one.
- Peak value of the contact force decreases with the increase of the oblique impact angle, irrespective of the twist angle.
- The deflection/thickness of the target shell is found to reduce with the increase of the oblique impact angle.
- The impactor's displacement and velocity of the impactor are found to increase with the increase of the oblique impact angle.