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peek strophic disaster could follow failure aircraft engine turbine unfavorable aluminum problem including aircraft malfunctioning potential engine shutdown even crash aircraft engine fan blade containment could occur detached fb enters fc study employed finite element method ballistic blade penetration fem examine effect utilizing polyether ether ketone peek alternative fb finite element simulation material fc order address issue order investigate effect peek moment inertia methodology aluminum ballistic fb penetration fc thickness 5 4 3 2 mm 255 fem ballistic model developed using abaqus explicit modeling system found working condition none fbs could pierce fc regardless thickness peek might better alternative though fc obviously deformed metal fb decision made conduct additional analytical validation developed fe model moment inertia methodology novel approach employed strong cor relation result fe model analytical answer therefore may said peek better material aluminum making blade casing 1 introduction somewhere world fan blade fb aircraft turbine engine fail every year 1 4 engine fb airplane contained inside fan casing fc failure happens unlikely catastrophic outcome would happen result aircraft fc need able stop damage failed fb aircraft malfunction put life passenger danger death could result impact uncontained failed fb aircraft turbine engine therefore critical continue researching improving field fb containment 1 5 according literature available superior turbine fc structure avoid failed fb penetration obtained corresponding author e mail address vandermerwer1 tut ac za rouxzeta gmail com rouxzeta van der merwe http doi org 10 1016 j heliyon 2024 e24157 received 9 september 2023 received revised form 8 december 2023 accepted 4 january 2024 availableonline8january2024 2405 8440 2024 author published elsevier ltd open access article cc nc nd license http creativecommons org license nc nd 4 0 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 researching behavior various metallic material metal matrix composite additionally study considered way reduce weight aircraft essential cost saving improved flight performance investigation assessment fb confinement researcher solely used metallic material fan blade fbs used therefore result confirmed idea metallic fbs either penetrated fc result dent impact surrounding fbs part inside outside fc 6 containment fb failed rotor hub reportedly one difficult procedure aviation engi neering since operates high speed high energy fb contained fails suffers secondary event damage proper operation numerous engine component fbs containment structure surrounding fan casing fcs bearing bearing support shaft vane externally mounted component becomes compromised 7 failed fb detaches hub contained aircraft malfunction engine shuts immediately cause secondary event damage majority time fb penetrates fc damaging aircraft body structure containment structure rotor compressor internal frame inlet fc rub strip affected various instance fb develops sharp edge malfunction 8 record going back decade shown secondary event brought uncontained engine failure unex pected effect diminishing engine power primary cause majority aviation accident prevent uncontained engine failure numerous effort must made develop dependable efficient containment structure 9 significant study polymer fbs open source literature studying literature hand revealed research done far examine ballistic impact detached polymer fb turbine fc test would also prohibitively expensive hence important perform efficient computer analysis mimic polymer fan blade situation 10 purpose examining numerically ballistic effect detached fb fc damage progression event occur fb break study aim investigate utilization metallic non metallic polymer fb material vestigations done effect changing fc dimension effect aluminum polyether ether ketone peek fbs turbine fc different thickness evaluated study aviation sector may benefit study recommendation alternate fb material fb containment might increase aircraft safety lighten weight 2 methodology methodology entail creating quantitative numerical model determine fb ballistic penetration fc performed abaqus cae 2017 simulating simple model design scenario proprietary reason make future experi mental setup simple impact two different fb material e aluminium peek received taken account calculating kinetic energy detached fb modeling result fc impacted two different fb material done using johnson cook damage approach recently created innovative methodology called moment inertia mi methodology utilized analytically validate finite element method fem model 11 map forward mathe matical modeling numerical modelling analytical validation technique moment inertia methodology study consider following aerospace atmospheric force fatigue failure blade coriolis gyroscopic force force critical consideration blade attached rotor hub scenario considered study vibration rotor casing blade simulating destruction process 2 1 mathematical modeling order investigate ballistic impact released blade engine casing relevant mathematical model used characterize transient dynamic behavior fb includes fb impact velocity impact energy stress engine fig 1 horizontal projectile trajectory 12 2 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 casing failure mode released fb critical velocity plate perforation johnson cook damage model 2 1 1 fb impact velocity study made premise fb trajectory linear small amount distance e 1 mm fb travel fig 1 depicts fb separated moving expected x ignored analysis due fb projectile e 1 mm short distance hitting fc eq 1 3 description newton law used calculate ballistic trajectory impact 13 eqn 1 n represents rotational speed ω angular velocity eq 2 depicts turbine linear velocity initial linear velocity fb taken zero vf final linear velocity rb1 distance hub turbine center outer half fb projectile time defined time take detached fb touch fc x tip clearance distance traveled detached fb launch impact fc π ω n 1 60 v f ω r b1 2 x 3 v f projectile time computed using following value n 32 500 r min rb1 0 075 mm x 1 mm given council scientific industrial research csir 12 outcome numerical simulation modeling start 3 99 x 10 cid 0 6 2πx32500 v x0 075 f 60 255 25m 0 001m 255 25m 3 99x10 cid 0 6 2 1 2 impact energy stress engine casing sensitivity analysis conducted work examined various fb material fc thickness change mass speed separated fb given eq 4 define impact energy 1 k 2mv2 f 4 mass fbs k total kinetic energy prior impact vf previously determined linear impact velocity eq 2 kinetic energy primary factor fragmentation 14 work two different ductile material aluminum peek looked viable fb material highest bending force deflection site impact thus study focus point fig 2 depicts schematic actual fb fc configuration according sharma et al 15 research impact issue shape change dimensional instability factor influence penetration hence focus study bending fig 2 fb fc schematic 12 3 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 axis center axis mi main variable used calculate impact stress deflection strain energy described rela tionship stated mathematically eq 5 represents moment inertia equation 5 along letter b fbs breath h fc plate thickness bh3 5 12 represents moment inertia equation 5 along letter b fbs breath h fc plate thickness eq 6 establishes static stress fc point impact according moon et al 16 denotes impact simulation time f denotes impact force l denotes fc length denotes static stress impact center appropriate fc plate thickness determined using maximum deflection fc contact based eq 7 13 16 maximum stress placed fc impact determined using eq 8 moon et al 16 eq 9 7 used determine much energy fc stored due deformation impacted eq 10 used determine moment force fb impact fc determined eq 11 fbs mass acceleration denoted respectively fl2t σ 8i 6 fl3 7 192ei 2he 0 5 σ max 1 1 lσ 8 m2 u 9 2ei fl 10 8 f 11 2 1 3 failure mode released fb detached fb released specific kinetic energy stress surpasses ultimate tensile strength fb material 14 17 investigation assumed fb material ductile would plug critical impact velocity reached 18 2 1 4 critical velocity plate perforation speed fb pierce fc great force known critical projectile velocity 19 represented mathematically eq 12 vx minimum perforation velocity mp plug mass 0 5 v c2 v f2 v x2 12 p 2 1 5 johnson cook damage model impact research best solved johnson cook j c model benefit able distinguish three essential element stress strain hardening temperature 20 furthermore assessment current issue johnson cook model selected suitable damage model 21 stress threshold material determines completely fail keep withstanding load without leading corresponding rise strain 22 model suitable evaluate fb confinement research shown experimentally viable strain rate 104 cid 0 1 21 analysis strain rate 102 cid 0 1 used within allowed range 21 j c model expressed eq 13 σ e von mi flow stress b c n considered material constant εp equivalent plastic strain given eq 14 ε dimensionless strain rate ε 0 1s1 homologous temperature expressed eq 15 absolute temperature room temperature tm melting temperature material temperature rise plastic work region heat produced plastic work impact zone considered adiabatic stated eq 18 23 j c damage model conditioned damage evolution damage material expressed eq 16 fracture strain εf expressed eq 17 β fraction plastic work converted σ bending stress σ contact stress cid 0 σ e b εp n 1 clin■ 1 cid 0 13 εp ■ 14 ε 0 4 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 cid 0 15 cid 0 δεp 16 ε f cid 0 ε f 1 2ed3σ 1 4lin■ 1 5t 17 β σ 18 σ 2 2 numerical modelling strategy design technique used model impact interaction different material evaluation fb confinement described detail along step taken create finite element analysis fea method fb fc simulated order develop appropriate analytical input file 2 2 1 model development simplify fb model rectangular shape following dimension used 22 mm width 37 mm length 2 mm thickness fig 3 dimension small aircraft engine utilized industry used build fb containment assembly abaqus cae 2017 fea program used construct model 2 2 2 material property peek 1000 aluminum 6082 t651 selected fb material study whereas aluminum 6082 t651 selected fc material 24 experiment material deemed homogeneous isotropic material property peek garcia gonzalez rusinek jankowiak aria 26 aluminum boldyrev shchurov nikonov 25 displayed table 1 4 according et al 27 j c constitutive relation suitable method specific engineering problem especially many fb material different fc thickness table 2 3 display j c constant damage constant peek aluminum respectively assumed high velocity impact fb onto fc adiabatic heat generated plastic work impact location enough time transferred surrounding material table 4 list adiabatic property peek aluminum aerodynamic force thought little effect analysis found aircraft turbine could operate 32 500 foot 9 75 km ground 24 2 2 3 assembly module assembly module controlled formula step various part generated combined single unit assembly module component put together certain location location fb within assembly affect analysis fb thus placed center fc inappropriately positioned fb assembly immediately change simulation result increasing discrepancy numerical analytical result boundary condition interaction including planned loading interaction impacted assembly real aircraft turbine engine design 1 mm gap permitted fb fc consequently fb shifted center fc design clearance 1 mm fc fixed analysis study depicted fig 4 fig 3 segment fb fc geometric form 5 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 table 1 mechanical material property aluminium peek 25 26 property unit aluminium peek elastic modulus e gpa 70 3 6 density ρ kg m3 2700 1304 poisson ratio v 0 33 0 4 kinetic friction coefficient µ 1 4 1 table 2 j c constant aluminium peek 25 26 property unit aluminium peek yield strength mpa 324 1 132 hardening coefficient b mpa 113 8 10 strain hardening exponent n 0 42 1 2 strain rate constant c 0 0074 0 034 softening exponent 1 4 0 7 melting temperature tm k 855 614 table 3 damage constant aluminium peek 25 26 property aluminium peek damage constant d1 cid 0 0 77 0 05 damage constant d2 1 45 1 2 damage constant d3 cid 0 0 47 cid 0 0 254 damage constant d4 0 0 damage constant d5 1 6 1 table 4 adiabatic property aluminium peek 25 26 property unit aluminium peek specific heat cp j kgk 923 2180 inelastic 0 9 0 9 fig 4 assembled model 6 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 2 2 4 step module sequence analysis generated model carried displayed two section step module according abaqus default setup first step defined first step defines relevant beginning condition load interaction boundary condition predefined field second stage developed dynamic explicit phase intended mimic effect fb fc minimum time interval dynamic step set 0 002 since thought appropriate study give enough time determine fb pierce bounce output variable employed inquiry strain energy kinetic energy stress z direction contributed model deformation interaction fb fc influenced factor 28 interaction refers relationship surface e g contact fb fc method capable capturing high impact deformation short time dynamic evaluation explicit contact interaction strategy selected investigation throughout analysis hard contact mechanical behavior tremendous force fb contact fc anticipated fb hit fc friction cause surface creates become heated 2 2 5 mesh generation since mesh generation influence fe model computation time result correctness essential part simulation simulation part processing power needed study since local meshing accelerates computation believed advantageous split component location interest use portion mesh control used define element dimension mesh refinement carried partitioned section place interest fc order obtain accurate result divided area fc seen fig 5 completed model work used dynamic explicit analysis hence suitable mesh needed accurately represent fb impact selection hexahedral element type based improved convergence lower computational cost time increased precision compared tetrahedral el ements 29 following guideline standard provided software three dimensional eight node hexahedral element type c3d8i main element used default hourglass control specified order prevent shear locking could result fake solution 30 table 5 show number node component model possible scenario fb tremendous impact significant deformation associated elemental distortion expected impact zone consequently adaptive meshing selected yield accurate result mesh mesh quality check done evaluate node stability illustrated fig 5 mesh refinement applied partitioned portion 2 2 6 mesh convergence study order shorten calculation time generate finding sufficient precise mesh convergence research carried 31 mesh seed size halved every analysis increase number element convergence achieved table 6 display mesh convergence study 5 mm 4 mm fc thickness table 7 display mesh convergence study fig 5 mesh refinement whole model fb fc 7 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 table 5 number node element model different fc fc thickness mm number node number element 2 5442 5406 3 7612 7668 4 10 584 13 576 5 13 781 10 506 3 mm 2 mm fc thickness reducing seed size resulted finer mesh higher element density mesh convergence analysis presented table 6 led conclusion optimum seed size 1 mm since resulted result impact stress deviation le 10 deflection deviation 5 consequently mesh size 1 mm selected investigation based mesh convergence study shown table 7 determined seed size 1 mm dependable deflection impact percentage error le 10 result 1 mm mesh size selected 2 2 7 boundary condition order imitate fb containment operational restriction model boundary condition set model given displacement rotation boundary condition 28 many restriction entry exit fc essentially cylindrical since impact happens specific location section investigation boundary condition study predicated existence beam like restriction following restriction apply simplified fc fig 6 since impact take place center fc split four equal section expected left right side would fixed manner akin building beam result rotation x z ax well displacement left right side fc equal zero top bottom fc permitted distort result impact load produced fb illustrated fig 6 fc top bottom allowed deform z direction allowed move rotate x direction respectively boundary condition unrestricted assumed fb hub split apart 2 2 8 predefined field preset field dictate kind analysis model conduct aerodynamic force assumed effect fb confinement however adiabatic effect considered objective analysis determine fc deformation feature impacted different fb material 8 velocity z direction fixed 255 obtained using eq 2 jamison snedden turner 24 reported result fb struck fc speed 255 table 8 display case study looked 2 3 definition output 2 3 1 field output field output needed analysis component stress displacement strain contact force response 2 3 2 history output history outcome kinetic energy strain energy plastic dissipation damage dissipation selected study fig 7 provides overview approach utilized numerical model development analysis 2 4 analytical validation technique moment inertia methodology forward map developed analytical validation technique assumption development mi methodology 2 4 1 developed analytical validation technique alluded earlier mi methodology created validate formulated numerical model utilizing newly developed mi approach stress deflection strain energy eight modeling case scenario fc thickness 5 4 3 2 mm struck fbs made aluminum 6082 t651 peek 1000 validated inertia swing baseball bat examined koenig et al 32 research showed swinging bat hit baseball score mi mass bat two table 6 mesh convergence study 5 mm 4 mm fc mesh size mm stress mpa deflection mm percentage error stress percentage error deflection 2 18 23 0 535 7 7 1 20 8 0 548 8 5 0 5 19 0 636 14 5 8 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 table 7 mesh convergence study 3 mm 2 mm fc mesh size mm stress mpa deflection mm percentage difference stress percentage difference deflection 2 218 5 481 30 11 1 160 5 216 5 9 0 5 102 5 419 45 14 fig 6 boundary condition table 8 case scenario description case scenario description 1 5 mm fc aluminium fb 2 5 mm fc peek fb 3 4 mm fc aluminium fb 4 4 mm fc peek fb 5 3 mm fc aluminium fb 6 3 mm fc peek fb 7 2 mm fc aluminium fb 8 2 mm fc peek fb important factor consider sharma et al 15 studied ballistic impact three different metal target projectile thickness ratio 1 0 5 noticed none metal bullet penetrated plate target speed 700 projectile hit plate bulged took different shape mi methodology created using combined ap proaches sharma et al 15 koenig et al 32 study fc fb ratio 2 5 1 2 1 1 5 1 1 1 considered projectile change shape also taken account according experiment sharma et al 15 study sphere projectile diameter rose 10 mm 14 mm impact 2 4 2 assumption development mi methodology following assumption used establish moment inertia methodology projectile mass material property would remain unchanged collision mi would affected altered shape 9 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 fig 7 overview approach utilized numerical model development analysis rectangular projectile width would decrease impact impact casing various increment fb width impact projectile mi would vary increment form change assumed surface projectile make contact target change shape impact zone target would deform shape projectile implying thickness target key factor change mi focus study investigation fc came variety thickness breadth fb mi used mean variable determine deflection maximum stress strain energy point impact fb impact fc linear speed 255 distance considered short e 1 mm modeled straightforward rectangle plate measurement 32 mm 22 mm 2 mm fc square shape 100 mm 100 mm although mass speed remained constant computer model showed fb bulge impact changing shape indicating phenomenon change mi contact fc fc took shape fb point impact shown fig 8 blade shape change breadth height impact change magnitude mi fc eq 5 used calculate fig 8 fb shape impacting fc left fb shape impacting fc right 10 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 mi impact force fb fc proportional width fb since blade shape change analysis assumes breadth factor remaining unchanged 2 4 3 illustration validation simulation using mi methodology investigation impact fb original width taken decreased 22 mm 1 mm 1 mm height variable eq 5 denotes thickness fc ranged 5 mm 2 mm mi m4 various fc thickness width shown table 9 since variable depend mi could estimated mi range determined l 100 mm 0 002 eq 6 used compute stress fc eq 10 yield force f f aluminum fb measured 785 4 n f peek 280 5 n table 10 11 give stress impact fbs made aluminum peek respectively eq 7 calculate deflection fc following impact predicted deflection fc caused impact aluminum peek fc shown table 12 13 respectively table 14 15 show strain energy fc affected aluminum fb peek fb respectively show result calculating strain energy fc impact using eq 8 3 result 3 1 validation simulation using mi methodology simulation result verified mi approach presented analysis done deflection maximum stress strain energy well effect aluminum peek fb impacting aluminum fc fc consideration ranged thickness 5 mm 4 mm 3 mm 2 mm study main focus effect fb fc impact thrown away incident determined damage fc limited dent penetration occurred degree fc deformation revealed recommended fc thickness use final fc design result advice given effort prevent secondary damaging consequence compressed damaged wire sensor could lead aircraft malfunction fb would penetrate fc indicated maximum stress eq 13 used compute maximum stress mi used calculation number element along border fc thickness size component impact zone significant impact outcome relationship simulation mi methodology 3 1 1 stress deflection 8 case investigated result demonstrated sensitivity analysis style 2 case scenario 8 case demonstrated explicitly due paper maximum size simulation 3d visualization result display deflection following impact shown fig 9 12 additionally display maximum stress dissipation fc impacted aluminum peek fb 1 2 m respectively represent case scenario 1 case scenario 2 number table 16 17 calculated using mi methodology table 9 mi m4 different thickness different breadth breadth mm mi m4 different casing thickness 5 mm 4 mm 3 mm 2 mm 22 2 3 10 cid 0 10 1 2 10 cid 0 10 4 9 10 cid 0 11 1 5 10 cid 0 11 21 2 2 10 cid 0 10 1 1 10 cid 0 10 4 7 10 cid 0 11 1 4 10 cid 0 11 20 2 1 10 cid 0 10 1 1 10 cid 0 10 4 7 10 cid 0 11 1 3 10 cid 0 11 19 1 9 10 cid 0 10 1 10 cid 0 10 4 3 10 cid 0 11 1 3 10 cid 0 11 18 1 8 10 cid 0 10 9 6 10 cid 0 11 4 10 cid 0 11 1 2 10 cid 0 11 17 1 7 10 cid 0 10 9 1 10 cid 0 11 3 8 10 cid 0 11 1 1 10 cid 0 11 16 1 6 10 cid 0 10 8 5 10 cid 0 11 3 6 10 cid 0 11 1 10 cid 0 11 15 1 5 10 cid 0 10 8 10 cid 0 11 3 4 10 cid 0 11 1 10 cid 0 11 14 1 4 10 cid 0 10 7 5 10 cid 0 11 3 2 10 cid 0 11 9 4 10 cid 0 12 13 1 3 10 cid 0 10 6 9 10 cid 0 11 3 10 cid 0 11 8 7 10 cid 0 12 12 1 1 10 cid 0 10 6 4 10 cid 0 11 2 7 10 cid 0 11 8 10 cid 0 12 11 1 10 cid 0 10 5 9 10 cid 0 11 2 5 10 cid 0 11 7 3 10 cid 0 12 10 1 10 cid 0 10 5 3 10 cid 0 11 2 3 10 cid 0 11 6 7 10 cid 0 12 9 9 4 10 cid 0 11 4 8 10 cid 0 11 2 10 cid 0 11 6 10 cid 0 12 8 8 10 cid 0 11 4 3 10 cid 0 11 1 8 10 cid 0 11 5 3 10 cid 0 12 7 7 10 cid 0 11 3 7 10 cid 0 11 1 6 10 cid 0 11 4 7 10 cid 0 12 6 6 10 cid 0 11 3 2 10 cid 0 11 4 10 cid 0 11 4 10 cid 0 12 5 5 10 cid 0 11 2 7 10 cid 0 11 1 1 10 cid 0 11 3 3 10 cid 0 12 4 4 10 cid 0 11 2 1 10 cid 0 11 9 4 10 cid 0 12 2 7 10 cid 0 12 3 3 10 cid 0 11 1 6 10 cid 0 11 6 7 10 cid 0 12 2 10 cid 0 12 2 2 10 cid 0 11 1 1 10 cid 0 11 4 5 10 cid 0 12 1 3 10 cid 0 12 1 1 10 cid 0 11 5 3 10 cid 0 12 2 3 10 cid 0 12 6 7 10 cid 0 13 11 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 table 10 stress fc caused aluminium fb impact breadth mm mi m4 different fc thickness 5 mm 4 mm 3 mm 2 mm 22 9 1 17 40 134 21 9 5 18 42 140 20 9 8 18 44 147 19 10 19 46 155 18 12 20 48 164 17 13 22 51 173 16 14 23 55 184 15 15 25 58 196 14 17 26 62 210 13 18 28 67 227 12 20 31 73 245 11 21 33 79 268 10 22 37 87 295 9 25 41 97 327 8 28 46 110 368 7 30 53 120 421 6 30 61 150 491 5 40 74 170 589 4 50 92 220 736 3 60 120 290 982 2 90 180 440 1470 1 200 370 870 2950 table 11 stress fc caused peek fb impact breadth mm mi m4 different fc thickness 5 mm 4 mm 3 mm 2 mm 22 3 6 14 48 21 3 2 6 15 50 20 3 5 7 16 53 19 4 7 16 55 18 4 7 3 17 58 17 4 1 8 18 62 16 4 2 8 19 66 15 4 8 9 21 70 14 5 9 22 75 13 5 10 24 81 12 6 11 26 88 11 6 12 28 96 10 7 15 31 110 9 7 16 35 120 8 8 20 39 130 7 10 20 45 150 6 10 23 52 180 5 11 30 62 210 4 20 30 78 260 3 20 40 100 350 2 30 70 160 530 1 70 100 310 1100 3 2 case scenario 1 case scenario 1 show impact aluminum fb 5 mm thick fc simulated deflection fig 9 1 01 mm dimensional instability shown table 16 occur breadth 5 mm mi 5 2 x 10 cid 0 11 m4 deflection 1 11 mm showed 9 difference percentage analytical result simulated result according table 16 static stress fc 5 2 x 10 cid 0 11 m4 mi 40 mpa maximum stress upon impact 280 mpa calculated using eq 14 static stress value 40 mpa analytically estimated stress 280 mpa maximum stress simulation fig 10 288 7 mpa resulting 3 inaccuracy 12 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 table 12 deflection fc impacted aluminium fb breadth mm mi m4 different fc thickness 5 mm 4 mm 3 mm 2 mm 22 0 255 0 498 1 18 3 98 21 0 267 0 522 1 24 4 17 20 0 281 0 548 1 3 4 38 19 0 295 0 577 1 37 4 61 18 0 312 0 609 1 44 4 87 17 0 33 0 645 1 53 5 16 16 0 351 0 685 1 62 5 48 15 0 374 0 703 1 73 5 84 14 0 401 0 783 1 86 6 26 13 0 432 0 843 2 6 74 12 0 468 0 9137 2 16 7 3 11 0 51 0 996 2 36 7 97 10 0 561 1 1 2 6 8 77 9 0 623 1 22 2 89 9 74 8 0 701 1 37 3 25 11 7 0 801 1 57 3 71 12 5 6 0 935 1 83 4 33 14 6 5 1 12 2 19 5 19 17 5 4 1 4 2 74 6 49 21 9 3 1 87 3 65 8 66 29 1 2 2 8 5 48 13 43 8 1 5 61 11 26 87 7 table 13 deflection fc impacted peek fb breadth mm mi m4 different fc thickness 5 mm 4 mm 3 mm 2 mm 22 0 0911 0 178 0 422 1 42 21 0 0977 0 186 0 442 1 49 20 0 01 0 196 0 464 1 57 19 0 0105 0 206 0 488 1 67 18 0 011 0 217 0 4 1 74 17 0 0111 0 23 0 546 1 84 16 0 0125 0 245 0 58 1 96 15 0 0134 0 261 0 618 2 09 14 0 0143 0 28 0 663 2 24 13 0 0154 0 301 0 714 2 41 12 0 0167 0 326 0 773 2 61 11 0 0182 0 356 0 843 2 85 10 0 02 0 391 0 928 3 13 9 0 0223 0 435 1 03 3 48 8 0 025 0 489 1 16 3 91 7 0 0286 0 559 1 33 4 47 6 0 0334 0 652 1 55 5 22 5 0 0401 0 783 1 86 6 26 4 0 0501 0 978 2 32 7 83 3 0 0668 1 3 3 09 10 4 2 1 1 96 4 64 15 7 1 2 3 9 9 28 31 3 3 3 case scenario 2 case 2 show impact peek fb 5 mm thick fc fig 11 show simulation deflection 0 41 mm table 17 demonstrates breadth 5 mm dimensional instability occurs determines mi 5 2 x 10 cid 0 11 m4 deflection 0 401 mm giving error margin 2 simulation analytical result similarly maximum stress 148 mpa calculated using static stress 13 mpa found table 17 impact simulation highest stress 137 mpa 7 higher theoretically predicted stress see fig 12 decrease tension seen approached support end explained force resistance fc impact location rather insignificant 3 3 1 strain energy graph graphical detail simulation analytical strain energy case scenario 1 2 shown fig 13 14 13 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 table 14 strain energy fc impacted aluminium fb breadth mm mi m4 different fc thickness 5 mm 4 mm 3 mm 2 mm 22 1 53 2 99 2 1 2 39 21 1 61 3 14 2 43 2 51 20 1 69 3 29 2 81 2 63 19 1 77 3 47 8 22 2 77 18 1 87 3 66 8 67 2 93 17 1 98 3 87 9 18 3 1 16 2 11 4 12 9 76 3 29 15 2 25 4 39 10 4 3 51 14 2 41 4 7 11 2 3 76 13 2 59 5 07 12 4 09 12 2 81 5 49 13 4 39 11 3 07 5 99 14 4 79 10 3 37 6 59 15 6 5 27 9 3 75 7 32 17 3 5 85 8 4 22 8 23 19 5 6 59 7 4 82 9 41 22 3 7 53 6 5 62 11 26 8 78 5 6 74 13 2 31 2 10 5 4 8 43 16 5 39 13 2 3 11 3 22 52 17 6 2 16 9 32 9 78 1 26 3 1 33 1 69 156 52 2 table 15 strain energy fc impacted peek fb breadth mm mi m4 different fc thickness 5 mm 4 mm 3 mm 2 mm 22 0 345 0 697 1 65 0 557 21 0 375 0 73 1 73 0 584 20 0 392 0 766 1 82 0 613 19 0 431 0 806 1 91 0 645 18 0 436 0 851 2 02 0 681 17 0 461 0 901 2 14 0 721 16 0 49 0 958 2 27 0 766 15 0 523 1 02 2 42 0 871 14 0 56 1 09 2 59 0 876 13 0 603 1 18 2 79 0 94 12 0 654 1 28 3 03 1 02 11 0 713 1 39 3 3 1 11 10 0 785 1 53 3 63 1 23 9 0 872 1 75 4 04 1 36 8 0 981 1 93 4 54 1 53 7 1 12 2 19 5 19 1 75 6 1 31 2 55 6 05 2 04 5 1 57 3 06 7 26 2 45 4 1 96 3 83 9 08 3 06 3 7 85 5 11 12 1 4 09 2 35 7 7 66 18 6 13 1 37 4 15 1 36 3 12 3 reducing breadth fc thickness reflects height mi methodology study shown numerical model assessed following section methodology respectively graph show flow dynamic penetration effect time simulation analytical calculation case scenario 1 dynamic impact effect becoming stable case scenario 2 dynamic impact effect becoming unstable due polymer bounce effect impact point impact strain energy highest time energy decrease due impact force higher peek fb fc impact aluminum fb store energy 3 3 2 kinetic energy kinetic energy behavior peek aluminum fb shown fig 15 according image peek fb lower pitch kinetic energy aluminum fb therefore obvious fc suffered deformation result aluminum fb kinetic energy pitch peek aluminum fbs persisted 0 3 m stabilizing 14 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 fig 9 simulated deflection case scenario 1 fig 10 maximum stress simulation case scenario 1 fig 11 simulated deflection case scenario 2 3 3 3 sensitivity result deflection maximum stress strain energy 8 case scenario examined study used basis sensitivity analysis fig 16 show order increase plastic deformation various case scenario table 18 show 15 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 fig 12 maximum stress simulation case scenario 2 table 16 mi methodology case scenario 1 breadth mm moment inertia m4 deflection mm static stress mpa 22 2 3 10 cid 0 10 0 255 9 1 21 2 2 10 cid 0 10 0 267 9 5 20 2 1 10 cid 0 10 0 281 9 8 19 1 9 10 cid 0 10 0 295 10 18 1 8 10 cid 0 10 0 312 12 17 1 7 10 cid 0 10 0 33 13 16 1 6 10 cid 0 10 0 351 14 15 1 5

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longer stabilize penetration effect showed le fc deflection fb would deform fc also determined kinetic energy fbs 4 discussion finding 4 1 discussion number element fc border mesh size impact zone significantly affected simulation outcome achieve good correlation found thinner fc plate dimension needed coarse mesh size impact zone fewer element side edge whereas thicker fc plate dimension needed finer mesh size impact zone element side edge fundamentally thickness fc decides whether fb impact enter fc 16 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 table 17 mi methodology case scenario 2 breadth mm moment inertia m4 deflection mm static stress mpa 22 2 3 10 cid 0 10 0 0911 3 21 2 2 10 cid 0 10 0 0977 3 2 20 2 1 10 cid 0 10 0 1 3 5 19 1 9 10 cid 0 10 0 105 4 18 1 8 10 cid 0 10 0 11 4 17 1 7 10 cid 0 10 0 111 4 1 16 1 6 10 cid 0 10 0 125 4 2 15 1 5 10 cid 0 10 0 134 4 8 14 1 4 10 cid 0 10 0 143 5 13 1 3 10 cid 0 10 0 154 5 12 1 1 10 cid 0 10 0 167 6 11 1 10 cid 0 10 0 182 6 10 1 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damage sensor cable close fc impact significantly influenced kinetic friction projectile fc result none fb pierced fc showed sign friction impact resistance instead collision merely caused fc swell case 2 4 6 modest deflection 5 mm 4 mm 3 mm fcs due peek fb impact three case found eligible blade containment since three deflection slight deflection case 8 2 mm fc struck peek fb roughly twice thick fc preventing fb penetrating fc however decided suitable blade confinement since would cause additional damage aircraft engine case 1 3 impact aluminum fb caused greater damage 5 mm 4 mm fcs despite fact deflection le thickness fcs suggests fcs would confine fb without causing additional damage however case 5 7 involved fcs thickness 3 mm 2 mm respectively aluminium fb severely damaged fcs result extremely high deflection subjected suggests taking account 3 mm 18 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 table 19 maximum stress sensitivity 8 case scenario c maximum stress mpa c fc 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peek aluminum fbs affected varied thickness aluminum fcs numerical simulation aluminium fb struck fcs fcs underwent significant plastic deformation penetration occurred simulation impacted fcs undergo appreciable plastic deformation relation peek fb following obser vations several case provided case 1 2 include 5 mm casing struck aluminium peek fbs

respectively result mi methodology consistent minor deflection seen fc impact fbs fbs appropriate situation none managed breach 5 mm fc additionally deflection case substantially smaller actual fc thickness deflection peek aluminum fbs respectively 0 41 mm 1 01 mm finding clear peek fb better suited due contribution lowering aircraft overall weight improving fuel efficiency resulting cost reduction peek blade harm case severely aluminium blade according simulation stress finding impact blade regarding case 3 4 4 mm fc struck aforementioned fbs deflected 2 7 mm aluminium fb 0 578 mm peek fb neither fbs managed enter fc cable sensor may compressed fc deflection brought aluminum fb could lead sensor gradually failing wire connecting engine control system malfunctioning could lead aircraft failure case 5 6 3 mm fcs aluminum fb impact deflection 4 45 mm penetration attached sensor would suffer immediate damage even penetration since impact fb fc may create sharp edge could damage aircraft body structure hand peek fb impact fc resulted modest 0 56 mm deflection result case 7 8 showed 2 mm fc struck aluminum peek fbs deflected 9 13 mm 4 7 mm respectively instance neither blade broke fc sensor cable would suffer severe damage since impact deflection fbs far greater thickness casing demonstrated post yield deformation 2 mm fc occurred outside scope current investigation described 2 mm fc employed according judgment drawn case observation mi methodology finding consistent deflection fcs validate mi methodology stress simulation analysis various casing thickness performed stress deflection percentage error larger 10 might wise conduct experiment verify finding projectile target bend collide yet mass material characteristic unaltered shape alteration impact mi plastic defor mation proposed mi methodology accurately validated generated numerical model good correlation eight simulated deflection maximum stress method suggested moment inertia approach take account deformation occurs projectile target impact modifies mi study literature demonstrated impact shape two colliding body change result fc fb moment inertia 19 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 changed investigation four various thickness casing strain energy exhibited dynamic behavior according examination fc strain energy graph single plateau followed slow decline stable region according olsson donadon falzon 33 impactor react energetically differently projectile differing mass impact peek aluminum fbs investigation showed tiny mass projectile enough time deflect behave transversely impactor despite sharing property strain energy graph stabilized different value result shown dynamic effect fcs peek fb unstable take time stabilize time deformation occurs indicated plateau strain energy steadily drop stabilizes leading penetration event 255 velocity strain energy graph produced numerical model produced mi methodology demonstrated pattern strong correlation crucial note point finding showed high energy aluminum peek fbs 0 3 m m comparing kinetic energy finding two type fbs plateau seen graph aluminum fb however larger peek fb speed raised aluminum fb material quality would cause distortion would seriously damage fc enter fc even speed increased peek blade le likely penetrate since kinetic energy roughly one fourth aluminum fb instead might cause blade shatter fc deflect numerical model unable account incidence occurred experiment according sharma et al 34 discussed noticeable error discrepancy experimental numerical assessment mi methodology study unable account temperature related incident happened numerical model may concluded error difference numerical model methodology 4 2 finding 1 penetration seen case regardless fb material fc thickness nonetheless amount deformation decreased fc thickness increased 2 strain energy maximum stress deflection sensitivity analysis table displayed deformation pattern 3 excessive plasticity present case 8 7 5 3 sequence 4 case 2 1 4 6 order given deform within elastic zone 5 outcome showed model plasticity behavior predicted johnson cook effective solving fb containment issue 6 proposed mi methodology accurately validated constructed numerical model deflection maximum stress eight simulated case closely correlated 5 conclusion new methodology mi approach developed account projectile ability instantly change shape simulation model mi methodology high correlation prior research ballistic test experiment proved expensive hence mi methodology shown practical affordable way validate numerical model finding led following mi case influenced fb shape influence resistant deflection correlation simulation conducted using abaqus explicit 2017 mi methodology mi methodology appropriate ballistic collision based finding lead concluded peek utilized make fbs material dependability potential reduce risk non containment problem addition peek material appropriate 2 mm fb 5 mm 4 mm fc another benefit manufacturing peek fb requires two day compared seven day aluminum fb order rank different range choose best fc would case 2 1 4 3 6 5 7 using mi methodology additional research impact various projectile shape conducted data availability statement data associated study deposited tshwane university technology library pretoria campus additional information additional information available paper credit authorship contribution statement shade rouxzeta van der merwe writing review editing writing original draft visualization validation supervision software resource project administration methodology investigation funding acquisition formal analysis data curation conceptualization writing review editing writing original draft visualization validation supervision software resource 20 rouxzeta van der merwe et al h e l n 1 0 2024 e24157 project administration methodology investigation funding acquisition formal analysis data curation conceptualization dawood ahmed desai writing original draft visualization 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