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B I L T E N

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Nakladnik
HRVATSKA AKADEMIJA ZNANOSTI I UMJETNOSTI

Za nakladnika
Akademik Dario Vretenar, glavni tajnik

Glavni i odgovorni urednik
Akademik Sven Lončarić

Tehnička urednica
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RAZRED ZA TEHNIČKE ZNANOSTI
10000 Zagreb, Trg Nikole Šubića Zrinskog 11

Elektroničko izdanje
Učestalost izlaženja: dva puta godišnje

Znanstveni skup

SUVREMENE METODE U PROJEKTIRANJU I ANALIZI INŽENJERSKIH KONSTRUKCIJA

Razred za tehničke znanosti
Hrvatsko društvo za mehaniku

Organizacijski odbor:
Ivo Senjanović, Sven Lončarić, Ignac Lovrek,
Nikola Vladimir, Marko Čanađija

Zagreb, 20. listopada 2023.

PREDGOVOR

U skladu s poslanjem Hrvatske akademije znanosti i umjetnosti, Razred za tehničke znanosti od svog osnutka 1997. godine, samostalno ili u suradnji s drugim institucijama, organizira pozvana predavanja eminentnih znanstvenika s područja tehničkih znanosti, okrugle stolove o aktualnim temama i znanstvene skupove u cilju upoznavanja šire javnosti o znanstvenim postignućima, razmjeni iskustava te unapređenju i primjeni suvremenih znanja i tehnologija u Hrvatskoj. Popis svih održanih znanstvenih skupova, okruglih stolova i predstavljanja knjiga može se naći u monografiji: 25 godina Razreda za tehničke znanosti Hrvatske akademije znanosti i umjetnosti 1997.-2022., Zagreb, 2022.

Slijedom navedenih stremljenja 20. listopada 2023. godine održan je znanstveni skup Suvremene metode u projektiranju i analizi inženjerskih konstrukcija, u organizaciji Razreda za tehničke znanosti i Hrvatskog društva za mehaniku. Sa šest predavanja istaknutih znanstvenika iz zemlje i inozemstva obuhvaćene su tri osnovne numeričke metode, koje su danas u širokoj primjeni za projektiranje i analizu konstrukcija, u gotovo svim granama tehnike: Metoda konačnih elemenata, Računalna dinamika fluida i Spregnuta metoda za simultanu analizu hidrodinamičkih opterećenja i odziva konstrukcije (Metoda hidroelastične analize). Skup je otvorio akademik Ignac Lovrek, tajnik Razreda za tehničke znanosti. Predavanjima u dva bloka predsjedavali su prof. dr.sc. Marko Čanađija, predsjednik Hrvatskog društva za mehaniku i prof. emer. dr. sc. Jurica Sorić. Na kraju se učesnicima skupa obratio akademik Ivo Senjanović u ime Organizacijskog odbora.

U nastavku je prikazan uvod u aktualne numeričke metode te prezentacije održanih predavanja s pripadajućim sažecima i kratkim biografijama predavača. Svrha ovako koncipiranog Biltena Razreda za tehničke znanosti je ostaviti pisani trag o održanim znanstvenim skupovima, kao podsjetnik na razvoj i popularizaciju znanosti u određenom vremenskom razdoblju.

Akademik Ivo Senjanović

SADRŽAJ

DOI 10.21857/9xn31cw7ky

Ivo Senjanović, Nikola Vladimir

UVOD U NUMERIČKE METODE ZA PROJEKTIRANJE I ANALIZU INŽENJERSKIH KONSTRUKCIJA

Numeričke metode za rješavanje matematičkih problema počele su se razvijati još u 19. stoljeću kada je bila poznata metoda konačnih razlika. Primjena numeričkih metoda u inženjerstvu uslijedila je sredinom 20. stoljeća razvojem elektroničkih računala. Od tada postojeće metode se unapređuju za obradu na elektroničkim računalima i razvijaju se nove metode potpuno orijentirane na velike mogućnosti računala. U organizacijskom smislu numerička simulacija se provodi kroz tri programa: predprocesor, procesor i postprocesor. Predprocesor je računalni program za generiranje proračunskog modela, procesor je program koji numerički rješava željeni matematički model sa zadanim početnim i rubnim uvjetima, dok je postprocesor program koji je u principu opće namjene a služi za vizualizaciju rezultata proračuna, odnosno za izračunavanje pojedinih integralnih veličina. Za ubrzanje rješenja vrlo složenih problema danas se koriste računala s paralelnim procesorima.

U projektiranju i analizi inženjerskih konstrukcija danas su u najširoj upotrebi tri metode:

1. Metoda konačnih elemenata (Finite Element Method, FEM)

Ova metoda se primjenjuje za statičku i dinamičku, linearnu i nelinearnu analizu konstrukcija. Konstrukcija se modelira pomoću velikog broja malih konačnih elemenata konstantnih značajki. Na osnovi diferencijalnih jednadžbi koje opisuju određenu fizikalnu pojavu, formiraju se potencijalna i kinetička energija konačnog elementa. Iz uvjeta minimuma ukupne energije dobiva se matrična jednadžba, koja povezuje sile i pomake u čvorovima konačnog elementa. Konačni elementi konstrukcije spajaju se zadovoljavanjem ravnoteže čvornih sila i kompatibilnosti pomaka čvorova. Na konturi konstrukcije zadovoljavaju se rubni uvjeti, koji se mogu odnositi na sile ili pomake. Na ovaj način formira se matrična jednadžba čitave konstrukcije u kojoj figuriraju matrica krutosti, matrica masa, matrica prigušenja i vektor opterećenja. Ovom metodom rješavaju se problemi raspodjele naprezanja u konstrukcijama za zadano vanjsko opterećenje ili uslijed širenja topline, problemi stabilnosti konstrukcije, širenja buke u okruženju konstrukcije, te vibracija pobuđenih periodičkom ili općom uzbudom. U slučaju periodičke uzbude problem se rješava u frekventnoj domeni, a kada je opća uzbuda rješavanje je u vremenskoj domeni.

Razvoj računala omogućio je modeliranje konstrukcija na mikrorazini i na nanorazini (razini atoma), pri čemu se primjenjuju višerazinski algoritmi. To omogućuje razvoj novih materijala, što spada u područje znanosti o materijalima (material science). Na taj način moguće je primjenom metode konačnih elemenata, kombinacijom različitih konstituenata na mikrorazini, numerički simulirati novu heterogenu strukturu materijala koja će pridonijeti povećanju pouzdanosti i sigurnosti inženjerskih konstrukcija. Osim toga, razmatra se razvoj oštećenja na atomističkoj i na mikrorazini, što omogućuje procjenu vijeka trajanja konstrukcija. Danas se metoda konačnih elemenata primjenjuje u kombinaciji s tzv. **strojnim učenjem (machine learning)** koje se temelji na **neuronskim mrežama** i **umjetnoj inteligenciji.**

2. Računalna dinamika fluida (Computational Fluid Dynamics, CFD)

Računalna dinamika fluida je grana znanosti koja se, uz primjenu elektroničkih računala, bavi kvantitativnim određivanjem veličina koje opisuju gibanje fluida (tekućina ili plin), rješavanjem matematičkih jednadžbi kojima su definirani zakoni očuvanja mase, količine gibanja i energije. Metode računalne dinamike fluida podrazumijevaju višu razinu fizikalne idealizacije u odnosu na opis gibanja fluida potencijalnom teorijom, kojima je moguće u obzir uzeti fenomene poput viskoznosti i stlačivosti fluida kao i temperaturne gradijente, a problem se svodi na numeričko rješavanje Navier-Stokesovih (parcijalnih diferencijalnih) jednadžbi, za što su izrazito važne računalne performanse. Svaka numerička simulacija uključuje definiciju problema i izbor matematičkog modela, njegovo rješavanje i analizu rješenja. Pod numeričkim rješavanjem problema podrazumijeva se diskretizacija prostora (izrada geometrijske mreže), diskretizacija jednadžbi (numerička shema – metoda konačnih volumena, metoda konačnih elemenata, metoda konačnih razlika i sl.), te samo njihovo rješavanje. Rezultat diskretizacije parcijalne diferencijalne jednadžbe na zadanoj geometrijskoj mreži je sustav algebarskih jednadžbi (ako je polazna diferencijalna jednadžba linearna dobije se sustav linearnih algebarskih jednadžbi, inače nelinearnih). Nelinearni sustav jednadžbi rješava se iterativnim postupkom koji u sebi sadrži rješavanje sustava linearnih algebarskih jednadžbi.

CFD nalazi vrlo široku primjenu u svim granama inženjerstva,od strojarstva, brodogradnje i pomorske tehnike, preko građevinarstva do kemijskog inženjerstva. CFD se najčešće primjenjuje u interakciji s čvrstim tijelima, odnosno njihovu opstrujavanju. Simulira se opstrujavanje fluida oko šasije automobila, zrakoplova, brodova i drugih inženjerskih konstrukcija. Stoga CFD nalazi veliku primjenu u automobilskoj i zrakoplovnoj industriji. Radi se o univerzalnoj metodi, koja se može primijeniti i na druga područja kao što je meteorologija, što uključuje prognoziranje vremena. U novije vrijeme primjena CFD-a se proširuje i na biološko inženjerstvo.

3. Spregnuta metoda za simultanu analizu hidrodinamičkih opterećenja i odziva konstrukcije (Coupled method for simultaneous analysis of hydrodynamic loads and structural responses)

Ova metoda, poznatija kao metoda hidroelastične analize, primjenjuje se u strukturnoj analizi brodskih i pomorskih konstrukcija. Karakteristika konvencionalnih brodova je njihova velika krutost, pa se čvrstoća takvih brodova računa u dva koraka. Prvo se odredi valno opterećenje za gibanje broda na valovima kao krutog tijela (oscilacije). Zatim se tako određeno opterećenje narine na 3D model konačnih elemenata brodske konstrukcije.

Veliki suvremeni brodovi su vrlo elastični, kao što su na primjer brodovi za prijevoz kontejnera zbog širokih palubnih otvora. Deformacije broda uslijed plovidbe na valovima utječu na hidrodinamičko opterećenje. Stoga je problem opterećenja i odziva konstrukcije spregnut i treba ga rješavati kao jedinstvenu zadaću. Najprije se odrede prirodni oblici vibracija broda izvan vode metodom konačnih elemenata, te matrica krutosti i matrica masa. Ukupni odziv brodske konstrukcije sastoji se od pomaka broda kao krutog tijela i elastičnih prirodnih oblika vibracija. Za svaki pomak i oblik vibriranja određuje se matrica masa okolne tekućine, matrica viskoznog prigušenja i matrica povratne krutosti uslijed promjene urona oplakane površine broda. Za određivanje ovih parametara koristi se klasična numerička hidrodinamika za potencijalno strujanje tekućine oko tijela, tj. pretpostavlja se da je tekućina nestlačiva i da nema rotacija. Dodatno određuje se još valna uzbuda pri čemu se uzima u obzir brzina plovidbe broda i smjer nailaska valova u odnosu na brod. Zbrajanjem parametara brodske konstrukcije i parametara okolne tekućine dobiva se matrična jednadžba s valnom uzbudom. Problem se rješava računalom pomoću posebno razvijenih programa za ovu svrhu.

Područje primjene numeričkih metoda

Ove tri metode nalaze široku primjenu u gotovo svim granama tehnike pri projektiranju inženjerskih konstrukcija za njihovu strukturnu analizu i simulaciju dinamičkog odziva za zadanu vanjsku uzbudu.

Građevinarstvo
Objekti: neboderi, hale, mostovi, vijadukti, brane, nuklearna postrojenja i dr.
Opterećenje: gravitacijsko, hidrostatičko, vjetrovno, potresno.

Strojarstvo
Objekti: motori, turbine, generatori, reaktori, automobili, kamioni, lokomotive, dizalice, komponente hidrocentrala, termocentrala i nuklearnih centrala, komponente čeličana i dr.
Opterećenje: gravitacijsko, vjetrovno, eksplozivno, sudarno, potresno.

Brodogradnja
Objekti: sve vrste brodova (putnički, teretni, ratni): kruzeri, tankeri, brodovi za ukapljeni plin, kontejnerski brodovi, krstarice, razarači, nosači aviona, podmornice i dr.
Opterećenje: gravitacijsko, valno, eksplozivno, sudarno.

Morska tehnologija
Objekti: plutajuće i fiksne platforme za eksploataciju nafte i plina, podmorske nastambe, podmorski naftovodi i plinovodi, sidreni sustavi i dr.
Opterećenje: gravitacijsko, hidrostatičko, valno, potresno, sudarno.

Zrakoplovstvo i raketna tehnika
Objekti: sve vrste civilnih i ratnih zrakoplova, helikopteri, rakete i dr.
Opterećenje: gravitacijsko, uzgonsko, vjetrovno, eksplozivno.

Elektrotehnika
Objekti: elektromotori, generatori, transformatori, dalekovodi.
Opterećenje: uslijed kvara u sinkronizaciji, uslijed kratkog spoja, potres.

Rudarstvo
Objekti: oprema rudnika, naftnih i plinskih polja, bušeći tornjevi, naftovodi, plinovodi i dr.
Opterećenje: gravitacijsko, sile bušenja, potres.

Medicina
Matematičko modeliranje tkiva i simulacija operacijskih zahvata: krvne žile, kosti, zubi i dr.

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Prezentacija predavanja

KRATKI OSVRT NA ORGANIZACIJU I RAD HRVATSKOG DRUŠTVA ZA MEHANIKU

Prof. dr. sc. Marko Čanađija
Predsjednik HDM


HRVATSKA AKADEMIJA ZNANOSTI I UMJETNOSTI – RAZRED ZA TEHNIČKE ZNANOSTI
Suvremene metode u projektiranju i analizi inženjerskih konstrukcija
Zagreb, 20. listopada 2023.
HDM
HRVATSKO DRUŠTVO ZA MEHANIKU
ZAGREB – OSIJEK – RIJEKA – SL. BROD – SPLIT
MARKO ČANAĐIJA
Hrvatsko društvo za mehaniku

HDM – kratka povijest

- Preteča HDM-a je hrvatska podružnica Jugoslavenskog društva za mehaniku, osnovana 1954. godine u Zagrebu.
- 18.4.1969. osnivačka skupština Društva za mehaniku SR Hrvatske, koje se 29.9. registrira kao udruženje građana, 1987. mijenja ime u Društvo za mehaniku Hrvatske.
- 1991. sa raspadom SFRJ raskidaju se veze s JDM; ime se mijenja u Hrvatsko društvo za mehaniku (HDM).

HDM – Osnovne informacije

- Sjedište u Zagrebu, podružnice: Osijek, Rijeka, Slavonski Brod i Split, te hrvatska podružnica European Structural Integrity Society
- Oko 120 članova sa 5 sveučilišta
- Mehanika čvrstih tijela i mehanika fluida
- Organizacija predavanja, ljetnih škola te promocija mehanike
- Organizacija kongresa
- Više sadašnjih i bivših članova HDM-a su i članovi HAZU (redoviti, suradnici, počasni).

HDM – domaća i međunarodna članstva

HIS

CISM motus est vita

IUTAM

ceacm Central European Association for Computational Mechanics

iacm

Međunarodni kongres ICCSM

- Svake treće godine
- 100-150 predavača
- 11. kongres: Vodice, 30.9.-3.10.2025.

Danubia-Adria Symposium

- Zajedno sa 12 partnerskih zemalja organizira godišnji kongres

  Danubia-Adria Symposium on Advances in Experimental Mechanics

- Do danas održano 37 kongresa

DANUBIA
ADRIA

Austrian Society of Experimental Strain Analysis (ASESA)
Croatian Society of Mechanics (HDM)
Czech Society for Mechanics (CSM)
German Society of Experimental Structural Analysis (GESA)
Greek Society of Experimental Mechanics of Materials (GSEMM)
Hungarian Scientific Society of Mechanical Engineering (GTE)
Italian Association for Stress Analysis (AIAS)
Polish Committee for Mechanics of the Polish Academy of Sciences (KMPAN)
Romanian Association of Stress Analysis and Materials Testing (ARTENS)
Serbian Society of Mechanics (SSM)
Slovak Society of Mechanics (SSM)
Slovenian Society of Experimental Mechanics (SSEM)

Susreti HDM-a

- Naglasak na mlađim članovima HDM-a
- Godišnji skup, 12x
- Na hrvatskom jeziku, samo za članove

Predavanja na 6. susretu HDM, Rijeka, 29. - 30. svibnja 2014.

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Prezentacija predavanja

NAPREDNE NUMERIČKE METODE U PRORAČUNU KONSTRUKCIJA, DOSADAŠNJI RAZVOJ I NOVI IZAZOVI

Prof. emer. dr. sc. Jurica Sorić
Fakultet strojarstva i brodogradnje Sveučilišta u Zagrebu

Jurica Sorić

NAPREDNE NUMERIČKE METODE U PRORAČUNU KONSTRUKCIJA, DOSADAŠNJI RAZVOJ I NOVI IZAZOVI

Sažetak predavanja

Prikazat će se napredne numeričke metode koje se primjenjuju u proračunu inženjerskih konstrukcija, a najveća pozornost posvetit će se metodi konačnih elemenata (MKE). MKE se temelji na fizičkoj diskretizaciji, pri čemu se kontinuum s beskonačno stupnjeva slobode zamjenjuje s diskretnim modelom međusobno povezanih elemenata s konačnim brojem stupnjeva slobode. Rješavanje inženjerskih problema svodi se na rješavanje sustava algebarskih jednadžbi s velikim brojem nepoznatih veličina u diskretnim točkama, što je vezano za primjenu računala. Prikazat će se primjena MKE na različite inženjerske konstrukcije. Osim linearnih problema, dat će se kratki osvrt na složenije nelinearne formulacije koje obuhvaćaju probleme čvrstoće, stabilnosti i elastoplastičnosti. Posebna pozornost usmjerit će se na greške koje se javljaju pri analizi konstrukcija. Pored osnovnih formulacija konačnih elemenata, dat će se prikaz tzv. elemenata višega reda koji se temelje na nelokalnoj teoriji kontinuuma, a primjenjuju se pri rješavanju problema oštećenja. Razmatrat će se oštećenje u krtim i duktilnim homogenim i heterogenim materijalima. Za modeliranje nastanka pukotina, prikazat će se metoda faznih polja. Pri modeliranju konstrukcija iz heterogenih materijala primjenjuje se višerazinski postupak, gdje se na mikrorazini na reprezentativnom volumnom elementu provodi proces homogenizacije za izračunavanje varijabli na makrorazini. Pri računalnoj homogenizaciji moguće je primijeniti postupak klasteriranja pri čemu se diskretizacija konačnim elementima zamjenjuje s diskretizacijom tzv. klasterima, potpodručjima za koje su varijable stanja konstantne, što značajno pridonosi smanjenju vremena računanja. Kao alternativa numeričkim metodama temeljenim na fizičkoj diskretizaciji, za analizu konstrukcija koriste se i bezmrežne metode, gdje je mreža konačnih elemenata zamijenjena samo diskretizacijskim točkama (čvorovima) koji nisu povezani u elemente, a njima su pridružene nepoznate varijable stanja. Osim tradicionalnih računalnih postupaka, za rješavanje problema deformiranja inženjerskih konstruk-

cija razmatrat će se primjena metode umjetne inteligencije, koja se temelji na neuronskim mrežama. Prikazat će se „Feedforward neural network", Recurrent neural network" i „Physics-informed neural network". Dat će se kratki osvrt na budući razvoj numeričkih metoda.

O predavaču

Jurica Sorić je professor emeritus na Fakultetu strojarstva i brodogradnje Sveučilišta u Zagrebu. Na istom fakultetu je doktorirao 1989. Za docenta je izabran 1990., za izvanrednog profesora 1995., za redovitog profesora 2000., a za redovitog profesora u trajnom zvanju 2005. Umirovljen je 2020., a za počasno zvanje professor emeritus izabran je 2021. Bio je voditelj Katedre za mehaniku i čvrstoću. Kao gostujući istraživač i gostujući profesor, u više je navrata boravio na inozemnim sveučilištima. Kao stipendist DAAD-a (Deutscher Akademisher Austauschdienst) i zaklade Alexander von Humboldt provodio je istraživanja na Sveučilištu Ruhr u Bochumu. Boravio je na Tehničkom sveučilištu u Beču i na Sveučilištu Karlsruhe. Za istraživanja na University of California, Irvine, SAD, dodijeljena mu je stipendija zaklade Fulbright. U okviru zajedničkih projekata boravio je i provodio istraživanja na Tehničkom sveučilištu u Darmstadtu i na Sveučilištu u Hannoveru. Njegova znanstvena djelatnost odnosi se na razvoj numeričkih algoritama u metodi konačnih elemenata za linearnu i nelinearnu analizu čvrstoće i stabilnosti ljuskastih konstrukcija, te na razvoj bezmrežnih metoda. Objavio je 290 znanstvenih radova (po CROSBI profilu), od kojih su 72 u znanstvenim časopisima. Dobio je međunarodne nagrade CEACM Prof. Mang Award, 2023. i ICCES Distinguished Fellow, SAD, 2015. Domaće nagrade su Velika medalja Fakulteta strojarstva i brodogradnje Sveučilišta u Zagrebu, 2019.; Nagrada Sveučilišta u Zagrebu Fran Bošnjaković, 2018.; Nagrada Hrvatske akademije znanosti i umjetnosti, 2005.; Nagrada Josip Juraj Strossmayer, 2004.; te Državna nagrada za znanost, 2000. Član je Uređivačkog odbora časopisa CMES: Computer Modeling in Engineering & Sciences i Transactions of FAMENA. Bio je član organizacijskog ili znanstvenog odbora više od 50 međunarodnih konferencija. Recenzent je više od 50 radova u međunarodnim časopisima. Član je Znanstvenog vijeća Međunarodnog centra za mehaničke znanosti, CISM Udine, Znanstvenog odbora CEACM-a, predsjednik od 2005. do 2008., Općeg vijeća IACM-a. Od domaćih znanstvenih udruga, član je Izvršnog odbora Hrvatskog društva za mehaniku, predsjednik od 2007. do 2009. Član je suradnik Hrvatske akademije znanosti i umjetnosti (HAZU), a redoviti je član Akademije tehničkih znanosti Hrvatske.

Napredne numeričke metode u proračunu konstrukcija, dosadašnji razvoj i novi izazovi

Jurica Sorić

Laboratorij za numeričku mehaniku
Katedra za mehaniku i čvrstoću Fakulteta strojarstva i brodogradnje
Sveučilište u Zagrebu

Zagreb, HAZU, 20. listopada 2023.

Laboratory of Numerical Mechanics   University of Zagreb

Sadržaj

- Pregled inženjerskih konstrukcija. Oštećenja konstrukcija i numeričko modeliranje
- O metodi konačnih elemenata. Formulacije i kratki povijesni pregled
- Modeliranje oštećenja u heterogenim materijalima. Višerazinski postupci
- Modeliranje rasta pukotine metodom faznih polja
- Modeliranje deformiranja bioloških tkiva. Primjena MKE u medicini
- Primjena neuronskih mreža u mehanici čvrstih tijela

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Pregled inženjerskih konstrukcija. Oštećenja konstrukcija i numeričko modeliranje

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Bilt. Razreda teh. znan., god. 17: br. 1 (2024), str. 9-171

Gubitak stabilnosti tankostjenih spremnika

W. Wagner, CISM Udine 2008

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Gubitak stabilnosti tankostjenih spremnika

Oštećenje silosa uslijed oluje, Ivankovo, Slavonija 2023

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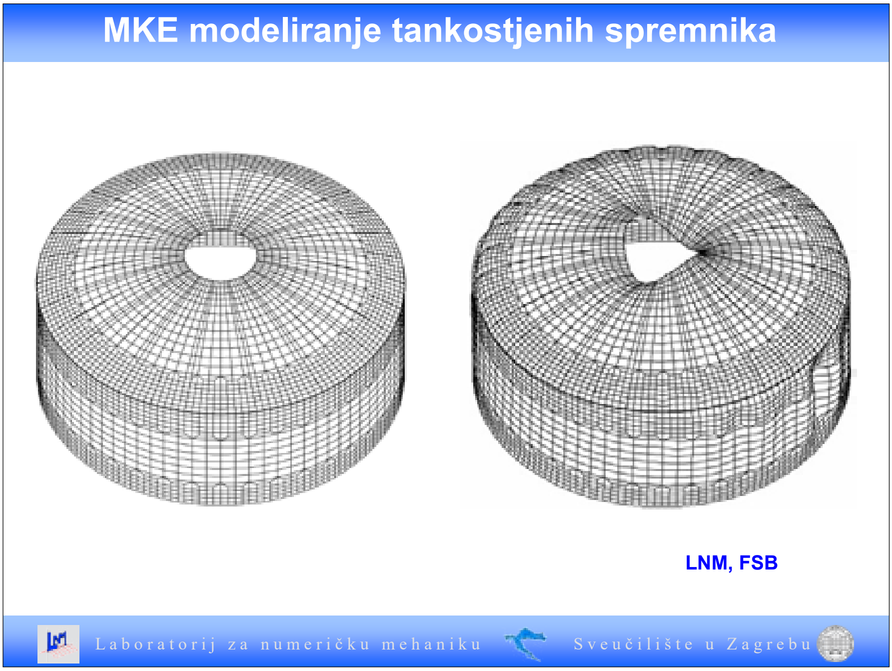
MKE modeliranje tankostjenih spremnika
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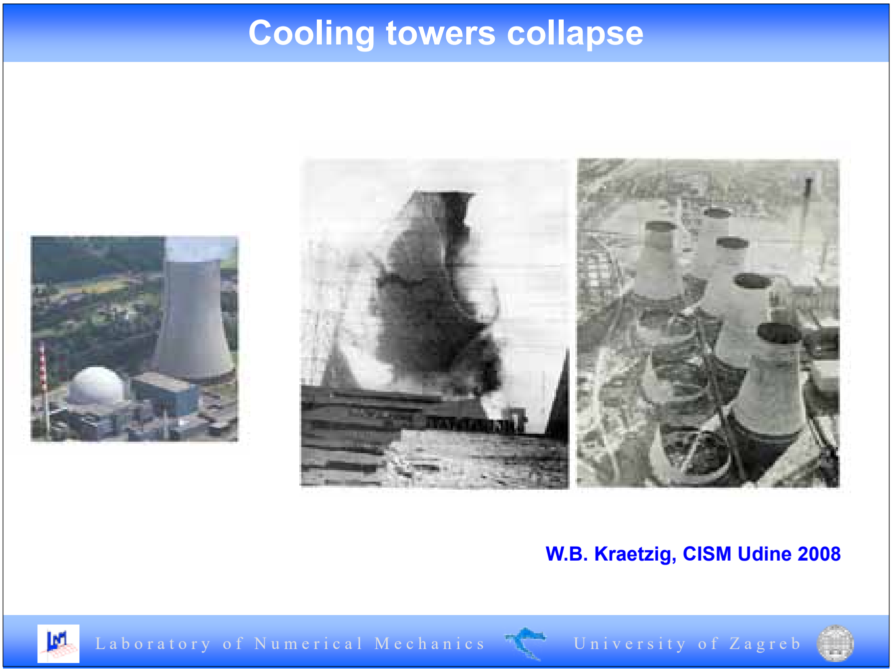
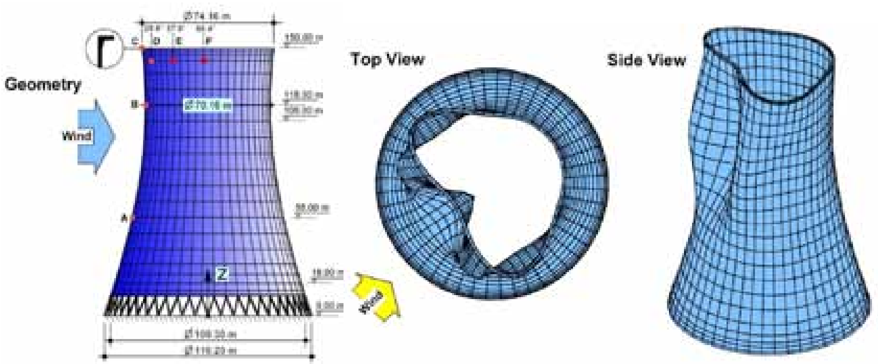

Cooling towers collapse
W.B. Kraetzig, CISM Udine 2008
Laboratory of Numerical Mechanics
University of Zagreb

FE modeling of cooling tower



W.B. Kraetzig, CISM Udine 2008

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Bridge collapse

Minneapolis bridge collapse 2007, https://en.wikipedia.org/wiki/I-35W_Mississippi_River_bridge

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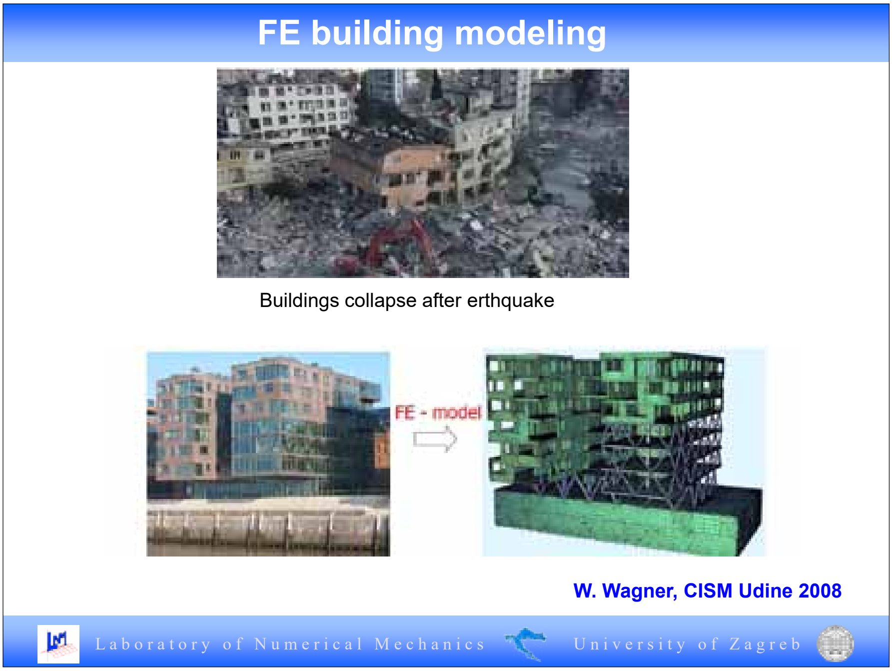
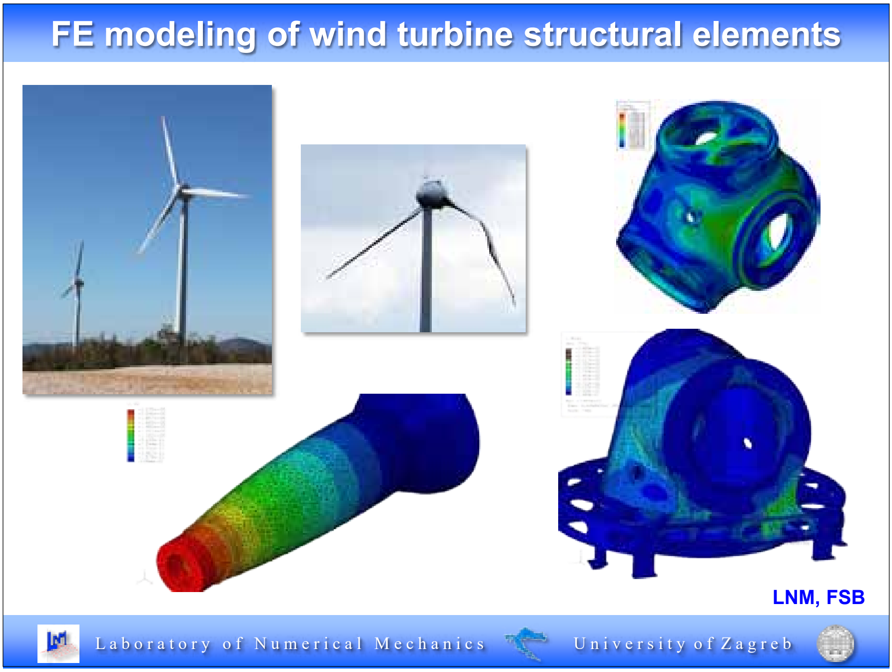
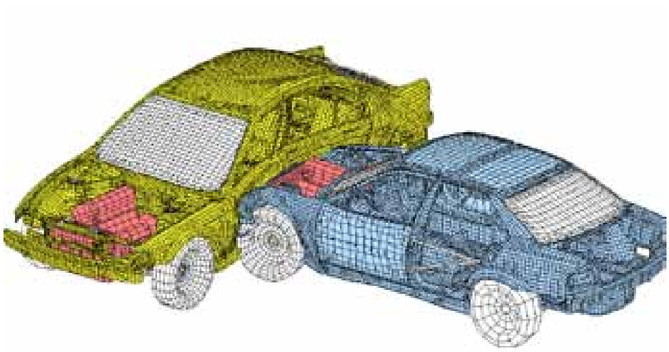

FE building modeling
Buildings collapse after erthquake
FE - model
W. Wagner, CISM Udine 2008
Laboratory of Numerical Mechanics
University of Zagreb


FE modeling of wind turbine structural elements
LNM, FSB
Laboratory of Numerical Mechanics
University of Zagreb

FE car crash modeling



google.com

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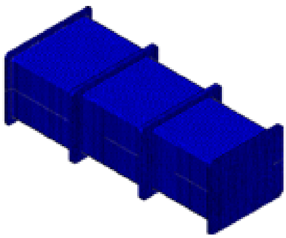
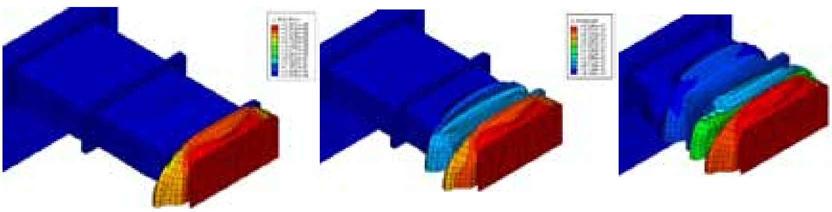
FE modeling of energy absorber

Real crash test of energy absorber





Deformation process of energy absorber

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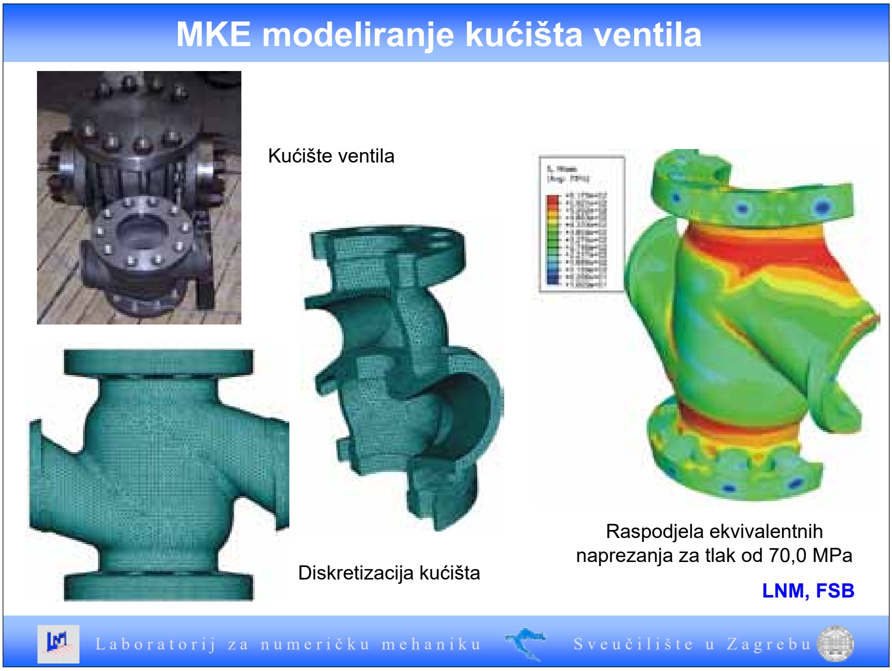
MKE modeliranje kućišta ventila
Kućište ventila
Diskretizacija kućišta
Raspodjela ekvivalentnih naprezanja za tlak od 70,0 MPa
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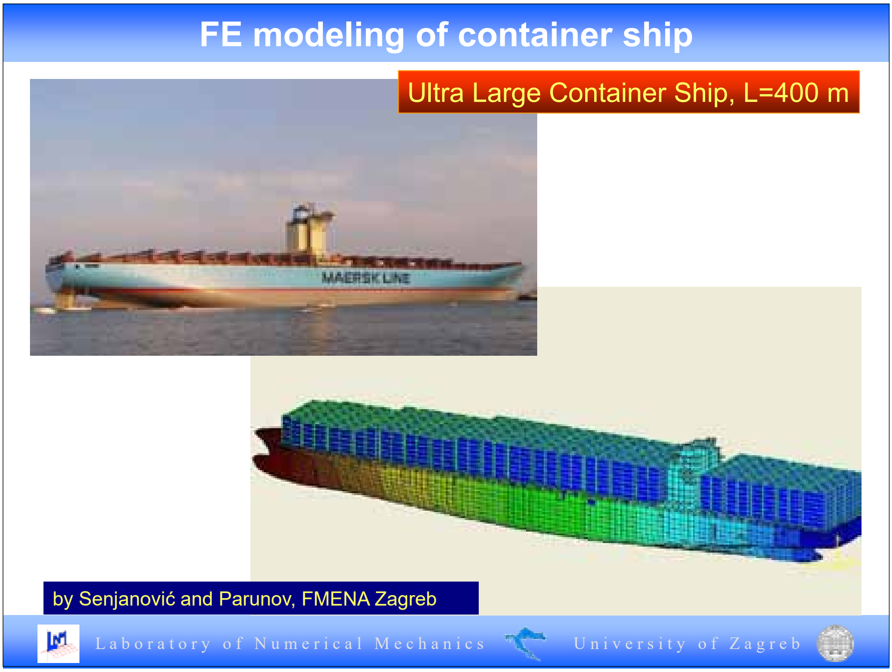
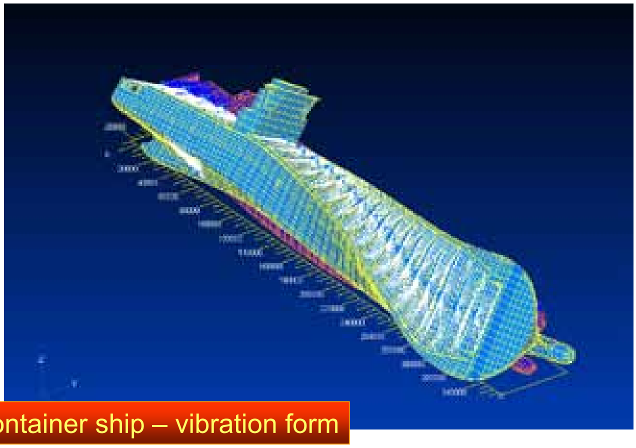

FE modeling of container ship
Ultra Large Container Ship, L=400 m
MAERSK LINE
by Senjanović and Parunov, FMENA Zagreb
Laboratory of Numerical Mechanics
University of Zagreb

FE modeling of container ship



Container ship – vibration form

Ref.: I. Senjanović, S. Tomašević, N. Vladimir: An advanced theory of thin-walled girders with application to ship vibrations, Thin-Walled Structures 2008.

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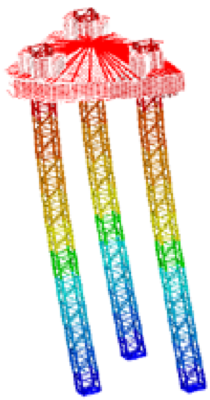
MKE model platforme Labin



V. Čorić, I. Čatipović, FSB

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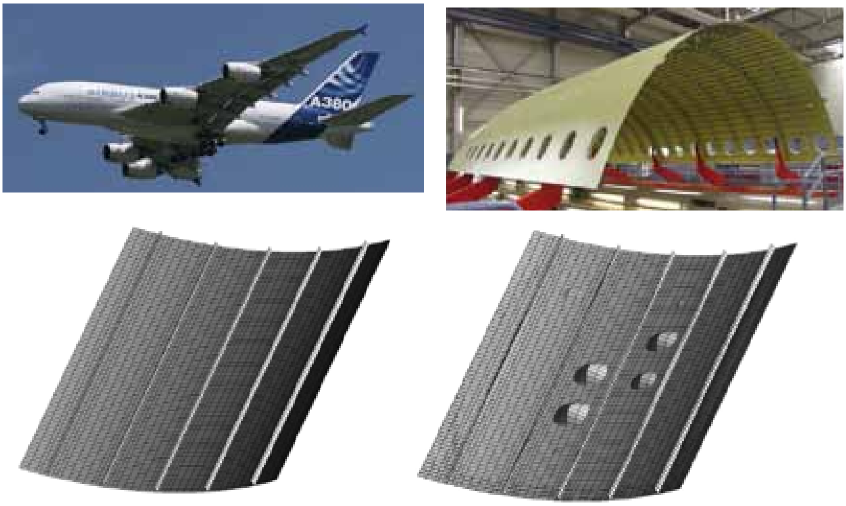
FE modeling in aviation



W. Wagner, CISM Udine 2008

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O metodi konačnih elemenata. Formulacije i kratki povijesni pregled

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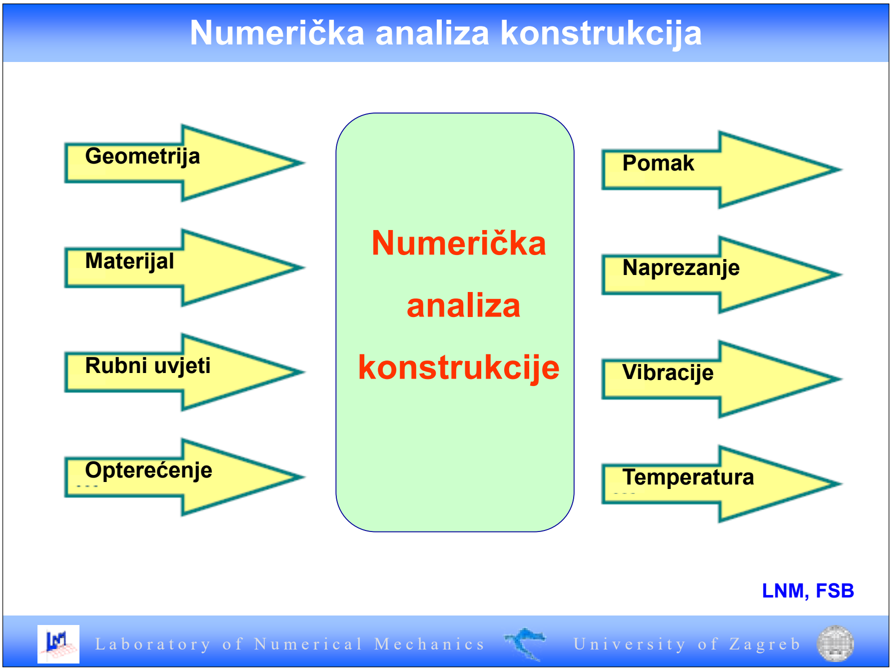
Numerička analiza konstrukcija
Geometrija
Materijal
Rubni uvjeti
Opterećenje
Numerička analiza konstrukcije
Pomak
Naprezanje
Vibracije
Temperatura
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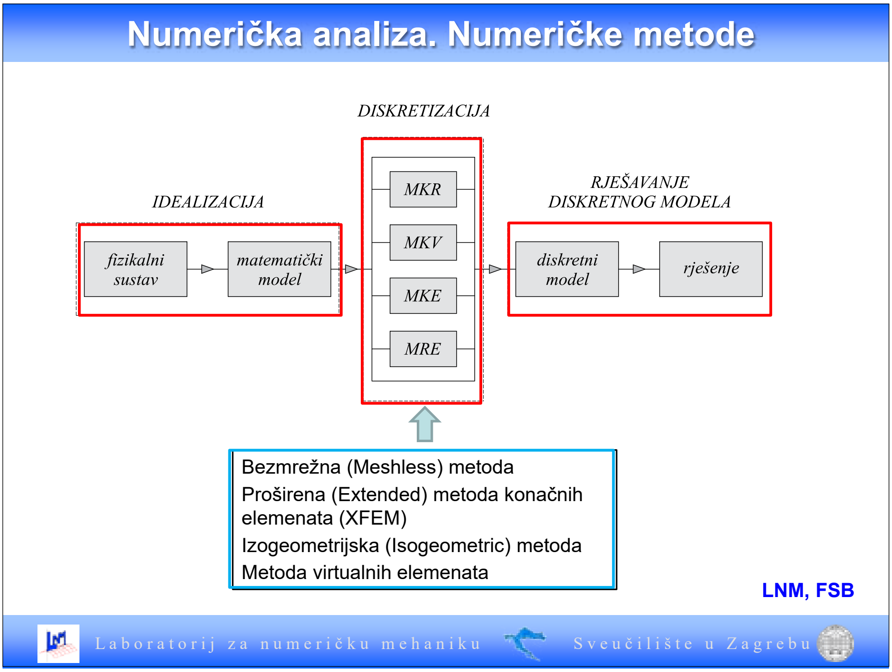
Numerička analiza. Numeričke metode
DISKRETIZACIJA
IDEALIZACIJA
fizikalni sustav
matematički model
MKR
MKV
MKE
MRE
RJEŠAVANJE DISKRETNOG MODELA
diskretni model
rješenje
Bezmrežna (Meshless) metoda
Proširena (Extended) metoda konačnih elemenata (XFEM)
Izogeometrijska (Isogeometric) metoda
Metoda virtualnih elemenata
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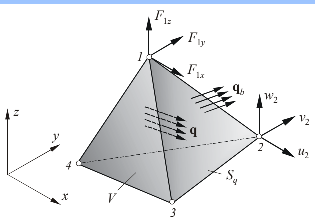
Osnovne analize konačnih elemenata



- Statička analiza:

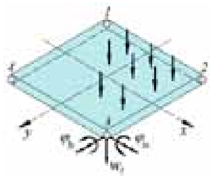
$$\mathbf{K}\,\mathbf{V} = \mathbf{R}$$

gdje je: $\mathbf{K}$ - matrica krutosti proračunskog modela,
$\mathbf{V}$ - vektor stupnjeva slobode,
$\mathbf{R}$ - vektor koji opisuje opterećenje.

- Dinamička analiza:

$$\mathbf{M}\ddot{\mathbf{V}} + \mathbf{C}\dot{\mathbf{V}} + \mathbf{K}\mathbf{V} = \mathbf{R}(t)$$

gdje je: $\mathbf{M}$ - matrica masa,
$\mathbf{C}$ - matrica prigušenja.



- Analiza prijenosa topline:

$$\mathbf{K}_T\mathbf{T} = \mathbf{Q}$$

gdje je: $\mathbf{K}_T$ - matrica (provodljivosti) konduktivnosti,
$\mathbf{T}$ - vektor čvornih temperatura,
$\mathbf{Q}$ - vektor toplinskih opterećenja.

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History of FEM

Ref.: Eighty Years of the Finite Element Method: Birth, Evolution, and Future.

Authors:
Wing Kam Liu, Northwestern University
Shaofan Li, UC Berkeley
Harold S. Park, Boston University

Archives of Computational Methods in Engineering (2022) 29:4431–4453.

The development of the finite element method (FEM) has been divided into four time periods:

1. **(1941–1965) The Birth of the Finite Element Method**
2. **(1966–1991) The Golden Age of the Finite Element Method**
3. **(1992–2017) Broad Industrial Applications and Materials Modeling**
4. **Present and Future**

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History of FEM

(1941–1965) The Birth of the Finite Element Method

A. Hernnikhoff, 1941- the earliest form of a mesh discretization.
R. Courant , 1943 - primitive form of the finite element method based.
on the Rayleigh–Ritz approach.
R. Clough, 1960 - introduced the name of Finite Element Method.

Pioneers of the Finite Element Method (The Three Musketeers):
J. Argyris, R.W.Clough, O.C. Zienkiewicz

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History of FEM

(1966–1991) The Golden Age of the Finite Element Method

- Mathematical foundation of FEM, convergence conditions.
- FEM to simulate dynamic behaviour of structures.
- Application to fluid mechanics, fluid–structure interaction.
- Computational plasticity, geometrically nonlinear formulation.
- Plastic-damage theory based FEM formulation.
- FEM analysis in computational contact mechanics.

Nenad Bićanić, 1945 – 2016
Corresponding member of the Croatian Academy of Sciences and Arts (HAZU)
Ph.D., University of Wales, Swansea,1978, under the supervision of O.C. Zienkiewicz

FEM application in Naval Architecture:

Vedran Žanić
Ivo Senjanović

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History of FEM

(1992–2017) Broad Industrial Applications and Materials Modeling

- Validation and verification procedures of FEM.
- Modeling of material fracture and damage problems.
- Development od eXtended finite element (X-FEM).
- Phase-field finite element method to solve growth and crack propagation problem.
- Development of isogeometric FEM.
- Multiscale methods and comutational homogenization of heterogeneous materials.
- Modeling of biological material responses. Application in medicine.
- Development of virtual element method.

Present and Future

- Development of machine learning based finite element methods.
- Construction of the finite element shape functions using deep neural networks.
- The use of deep neural network to learn the material behaviour.
- Physics-Informed Neural Networks (PINNs) to solve engineering problems.
- Reduced order machine learning FE modeling with a purpose of accelerating simulations of engineering problems.

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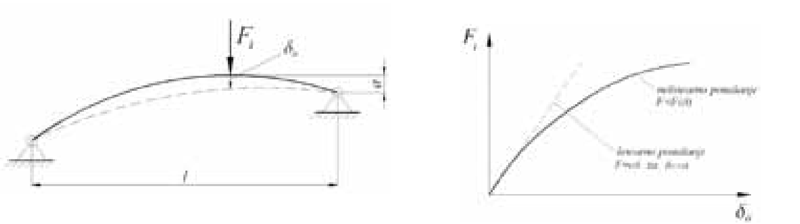
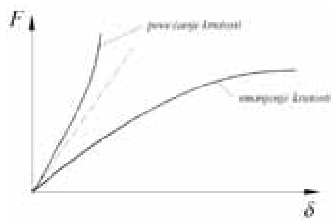
Nelinearna analiza konstrukcija

Primjer nelinearnog ponašanja konstrukcije





Različiti nelinearni odzivi konstrukcija

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Inkrementalna formulacija jednadžbe konačnih elemenata

Diskretizacija

$$\bar{\mathbf{u}} = \mathbf{N}\bar{\mathbf{v}}, \quad \Delta\bar{\mathbf{u}} = \mathbf{N}\Delta\bar{\mathbf{v}}$$

$$\boldsymbol{\varepsilon} = f(\bar{\mathbf{v}}, \Delta\bar{\mathbf{v}})$$

$\Downarrow$

Inkrementalni princip virtualnih pomaka

$\Downarrow$

Diskretizirani inkrementalni princip virtualnih pomaka

$\Downarrow$

$$\left[\mathbf{k}_{eu}(\bar{\mathbf{v}}) + \mathbf{k}_{\sigma}(\bar{\mathbf{v}})\right]\Delta\bar{\mathbf{v}} = \mathbf{F}_e - \mathbf{F}_i(\bar{\mathbf{v}}) \quad \Rightarrow \quad \mathbf{K}_T(\bar{\mathbf{V}})\Delta\bar{\mathbf{V}} = \mathbf{R} - \mathbf{R}_I(\bar{\mathbf{V}})$$

elastična matrica krutosti

matrica početnih naprezanja ili geometrijska matrica krutosti

vektor unutarnjih sila

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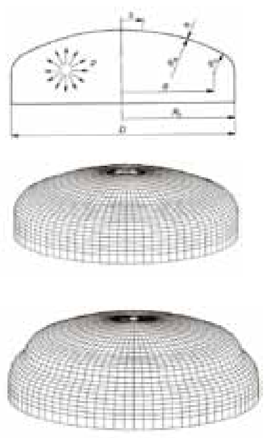
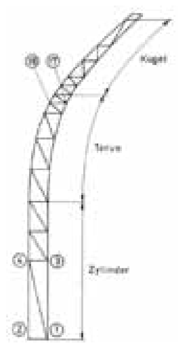
Geometrijska nelinearnost podnice tlačne posude

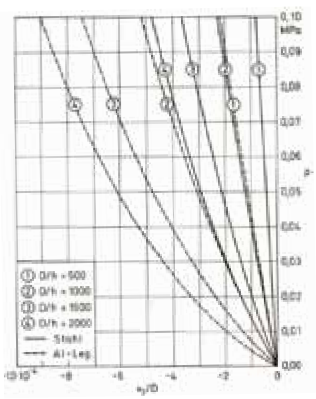


Deformirani oblik

Proračunski model



[J. Sorić, *Stahlbau* 1990.]



Međusobna ovisnost unutarnjeg tlaka i normalnog pomaka u čvoru 17 za čelik i aluminijsku leguru (R_s / D =1, R_t / D = 0,1)

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Analiza elastične stabilnosti

Klasični (linearni) problem stabilnosti. Problem vlastitih vrijednosti

$$(\mathbf{K}_e + \lambda_k \mathbf{K}_\sigma)\overset{e}{\mathbf{V}} = 0$$

gdje je:

$\mathbf{K}_e$ - elastična matrica krutosti

$\mathbf{K}_\sigma$ - matrica početnih naprezanja (geometrijska matrica krutosti)

λ_k - vlastita vrijednost

$\overset{e}{\mathbf{V}}$ - vlastiti vektor $\Rightarrow$ oblik gubitka stabilnosti

Kritično opterećenje:

$$\mathbf{F}_k = \lambda_k \mathbf{F}_0$$

gdje je:

$\mathbf{F}_0$ - zadano referentno opterećenje

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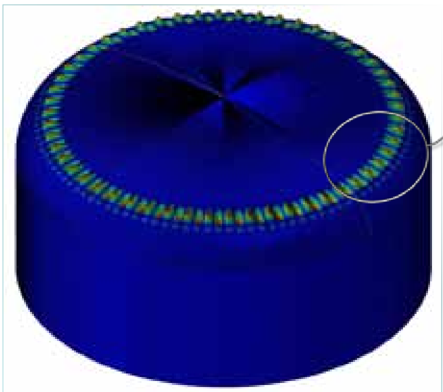
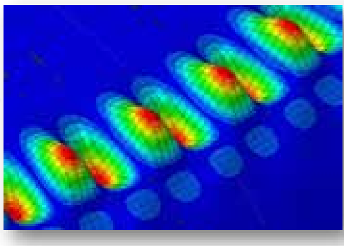
Analiza elastične stabilnosti podnice tlačne posude





Oblik gubitka stabilnosti

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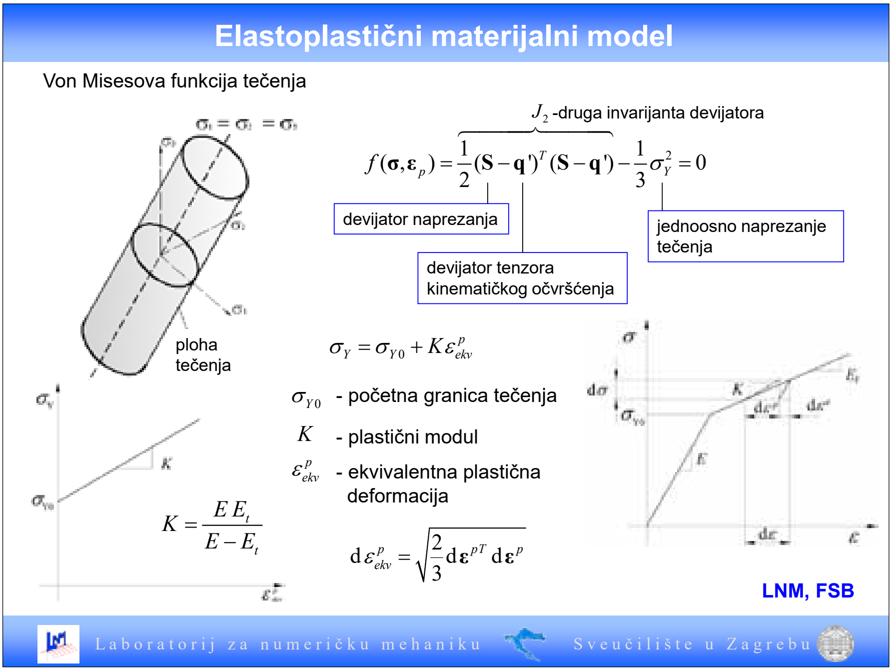
Elastoplastični materijalni model
Von Misesova funkcija tečenja
J_2 -druga invarijanta devijatora
$f(\boldsymbol{\sigma},\boldsymbol{\varepsilon}_p)=\frac{1}{2}(\mathbf{S}-\mathbf{q}')^T(\mathbf{S}-\mathbf{q}')-\frac{1}{3}\sigma_Y^2=0$
devijator naprezanja
devijator tenzora kinematičkog očvršćenja
jednoosno naprezanje tečenja
ploha tečenja
$\sigma_Y=\sigma_{Y0}+K\varepsilon_{ekv}^p$
σ_{Y0} - početna granica tečenja
K - plastični modul
ε_{ekv}^p - ekvivalentna plastična deformacija
$K=\frac{E\,E_t}{E-E_t}$
$\mathrm{d}\varepsilon_{ekv}^p=\sqrt{\frac{2}{3}\mathrm{d}\boldsymbol{\varepsilon}^{pT}\,\mathrm{d}\boldsymbol{\varepsilon}^p}$
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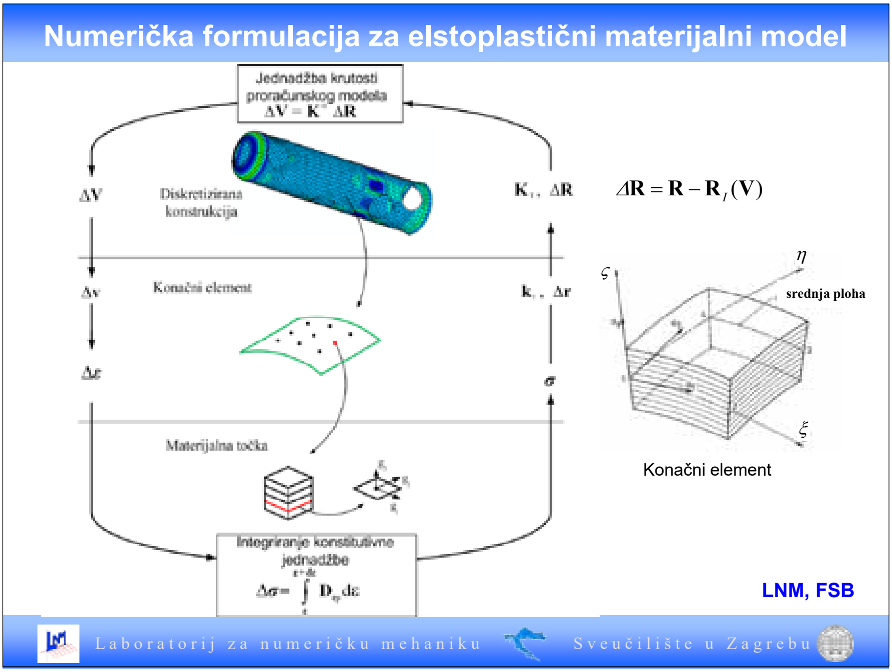
Numerička formulacija za elstoplastični materijalni model
Jednadžba krutosti proračunskog modela
Diskretizirana konstrukcija
Konačni element
Materijalna točka
Integriranje konstitutivne jednadžbe
$\Delta\mathbf{R}=\mathbf{R}-\mathbf{R}_I(\mathbf{V})$
srednja ploha
Konačni element
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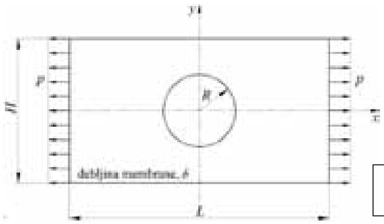
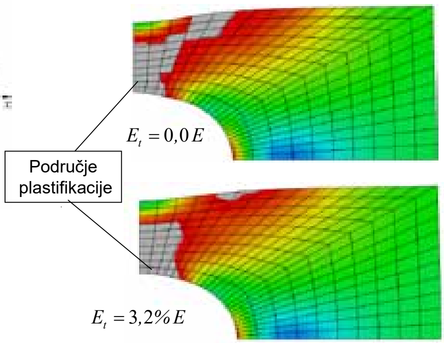
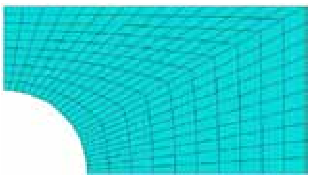
Elastoplastični proračun osno opterećene tanke ploče s otvorom



$p = 121{,}5$ $R = 5$ $\sigma_{Y0} = 243$
$H = 20$ $L = 36$ $E = 70 \cdot 10^3$
$\delta = 1$ $\nu = 0{,}2$



Područja plastifikacije za različiti E_t



Proračunski model

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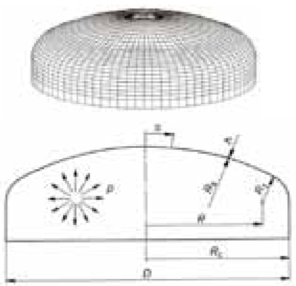
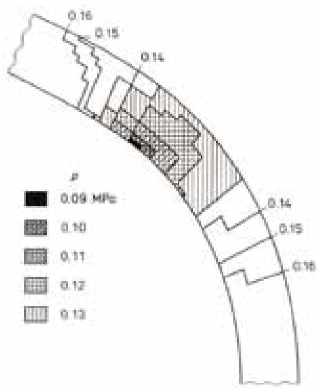
Elastoplastična analiza tankostjene podnice





$D / h = 1000$
$R_s / D = 1$
$R_t / D = 0{,}1$
$h = 3$
$E = 207$ GPa
$\nu = 0{,}3$
$\sigma_Y = 207$ MPa

[Sorić, Thin Walled Structures, 1995]

Raspodjela područja plastifikacije za različite razine unutarnjeg tlaka za elastičan idealno plastičan materijal pri geometrijski nelinearnoj analizi

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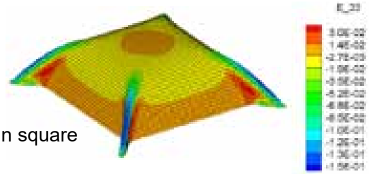
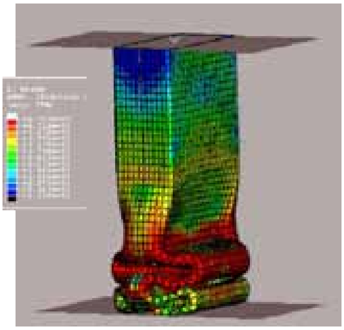
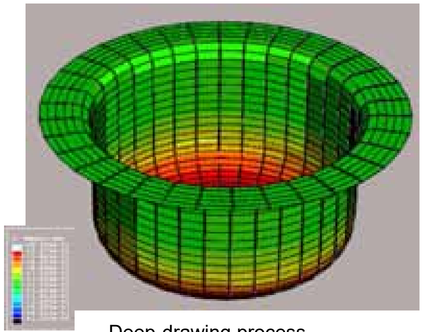
Modeling of large strain elastoplastic material responses



Highly deformed thin square plate



Crash simulation of square column



Deep-drawing process

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Modeliranje oštećenja u heterogenim materijalima. Višerazinski postupci

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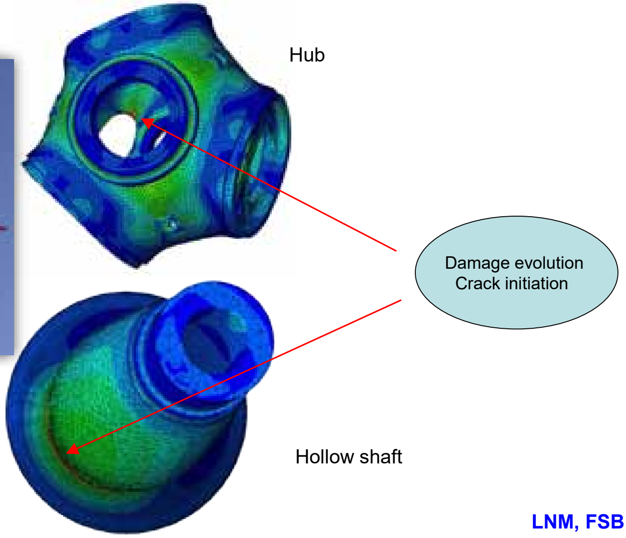
Damage evolution in structural components



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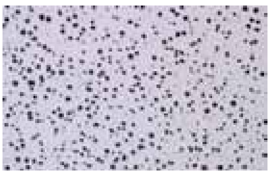
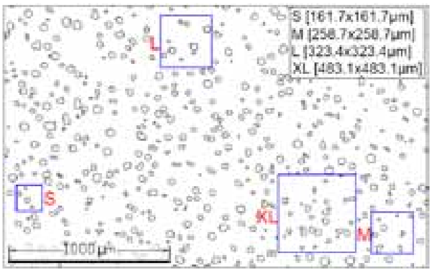
Heterogenity of engineering materials

Nodular cast iron



Metallographic image of EN-GJS-400-18-LT microstructure (Inmould)



Selection of samples (statistical RVEs) satisfying the global average graphite nodules content

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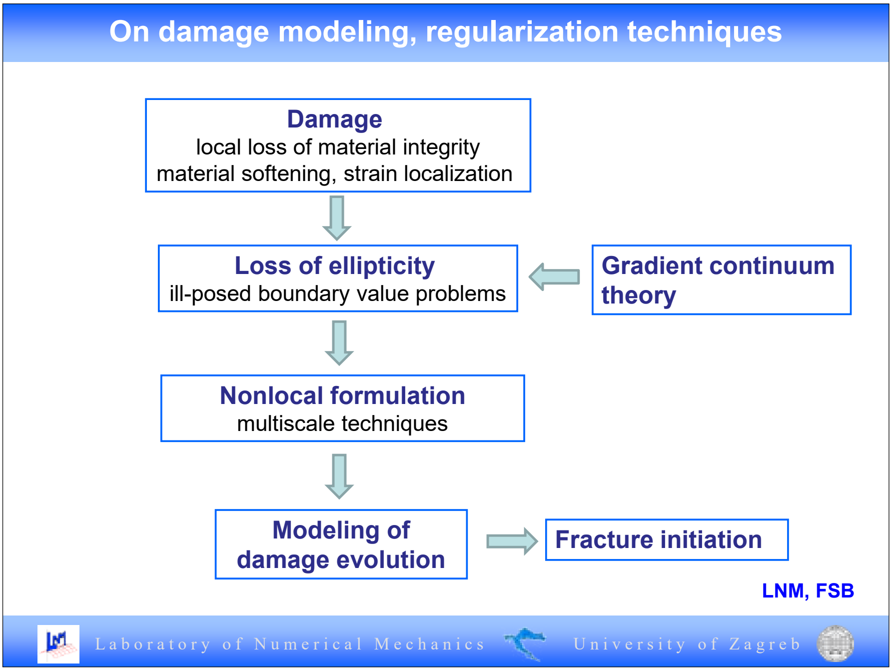
On damage modeling, regularization techniques
Damage
local loss of material integrity
material softening, strain localization
Loss of ellipticity
ill-posed boundary value problems
Gradient continuum theory
Nonlocal formulation
multiscale techniques
Modeling of damage evolution
Fracture initiation
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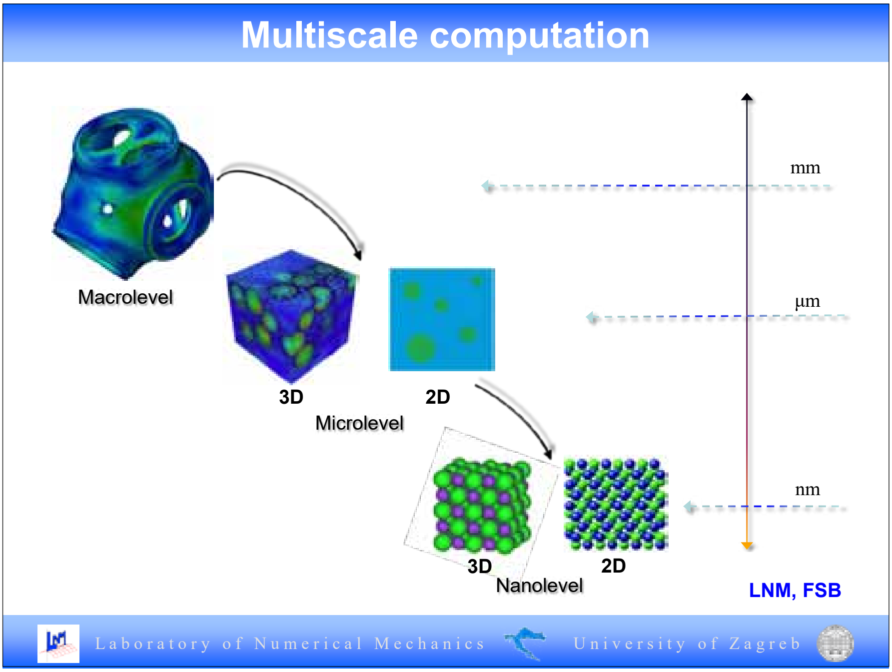
Multiscale computation
mm
μm
nm
Macrolevel
3D
2D
Microlevel
3D
2D
Nanolevel
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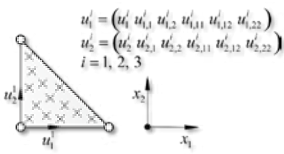
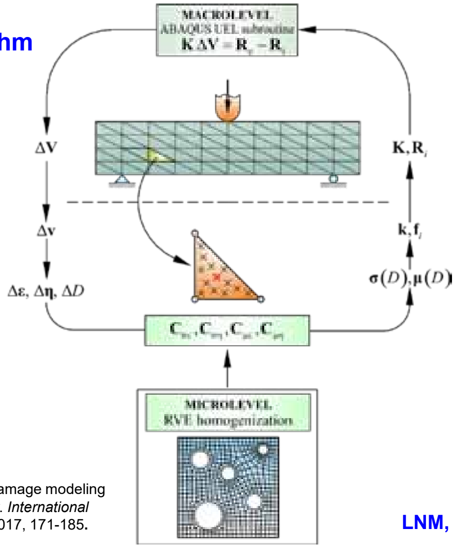
Quasi-brittle damage, computation scheme

Scheme of damage algorithm



$$\Delta\boldsymbol{\sigma} = \Delta\left[(1-D)\left(\mathbf{C}_{\sigma\varepsilon}\boldsymbol{\varepsilon} + \mathbf{C}_{\sigma\eta}\boldsymbol{\eta}\right)\right]$$
$$\Delta\boldsymbol{\mu} = \Delta\left[(1-D)\left(\mathbf{C}_{\mu\varepsilon}\boldsymbol{\varepsilon} + \mathbf{C}_{\mu\eta}\boldsymbol{\eta}\right)\right]$$



Ref.: F. Putar, J. Sorić, T. Lesičar, Z. Tonković: Damage modeling employing strain gradient continuum theory. *International Journal of Solids and Structures*, Vol 120, 2017, 171-185.

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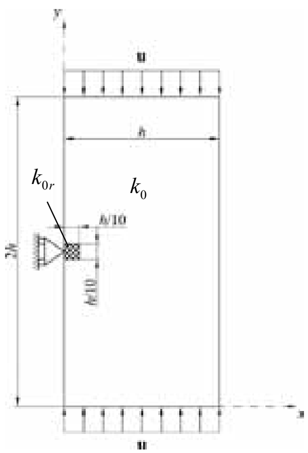
Quasi-brittle damage, shear band problem



Linear-elastic material:

$E = 2\times10^4\ \mathrm{N/mm^2},\ \nu = 0.2$

Modified von Mises equivalent strain:

$$\varepsilon_{eqv} = \frac{1}{1+\nu}\sqrt{-3J_2},\ J_2 = \frac{1}{6}I_1^2 - \frac{1}{2}\varepsilon_{ij}\varepsilon_{ij},\ I_1 = \varepsilon_{kk}$$

Exponential softening:

$$D = 1 - \frac{k_0}{\varepsilon_{eqv}}\left(1-\alpha+\alpha e^{\beta\left(k_0-\varepsilon_{eqv}\right)}\right)$$

$k_0 = 10^{-4},\ k_{0r} = 5^{-5},\ \alpha = 0.99,\ \beta = 300$

Imposed displacement:

$u = 0.08$ mm

Ref.: A. Simone, H. Askes, L.J. Sluys, Incorrect initiation and propagation of failure in non-local and gradient-enhanced media, International Journal of Solids and Structures, 41 (2004) 351-363.

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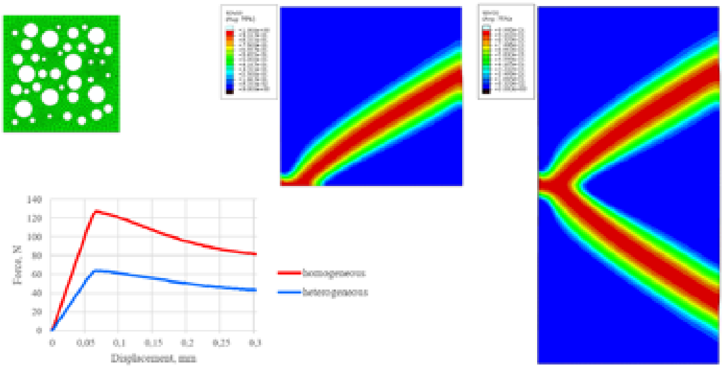
Quasi-brittle damage, shear band problem

Comparison of homogeneous and heterogeneous material damage responses



Force-displacement curves and damage evolutions for internal length scale *l* = 2 mm

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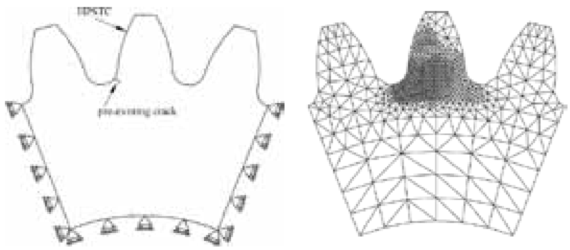
Quasi-brittle damage, gear tooth problem

Gear tooth pre-existing crack

Teeth number: *z* = 25 Module: *m* = 2 mm Pressure angle: α = 20° Tooth profile: ISO 53-A



Geometry, boundary conditions and finite element discretization of the gear model
with the pre-existing crack loaded in the highest point of single tooth contact (HPSTC)

- Linear-elastic material: $E = 2.1 \times 10^5$ N/mm^2, $\nu = 0.3$
- Von Mises equivalent strain: $k = 10$
- Exponential softening: $\kappa_0 = 0.002$, $\alpha = 0.99$, $\beta = 200$

Ref: Vučković, K., 2009. Fatigue crack initiation in the tooth root of thin-rimmed gears. Ph.D. thesis. University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Croatia.

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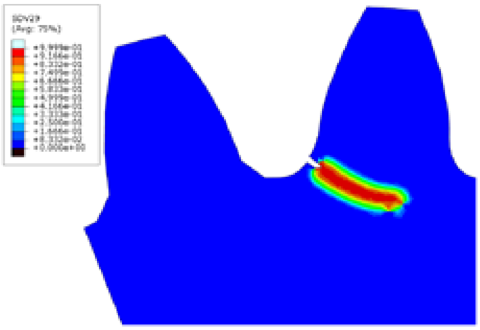
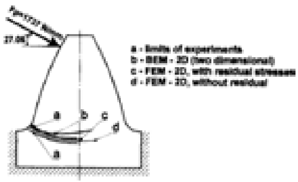
Quasi-brittle damage, gear tooth problem

Gear tooth pre-existing crack



Damage evolution for homogeneous material of internal length scale l = 0.15 mm



Experimentally and numerically determined crack paths limits [Pehan et al. (1995)]

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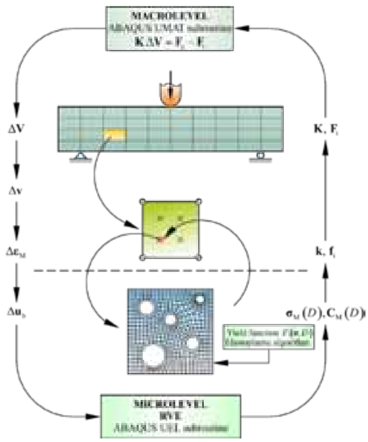
Modeling of ductile damage

Scheme of the first-order computational homogenization multiscale algorithm



Ref.: Lesičar, T., Sorić, J., Tonković, Z.: Ductile Damage Modelling of Heterogeneous Materials Using a Two-Scale Computational Approach, Comput. Methods Appl. Mech. Engrg. 355 (2019) 113-134.

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Nonlocal implicit ductile damage model

J_2 plasticity yield function

$$F\left(\boldsymbol{\sigma},\varepsilon_p,\bar{\varepsilon}_p\right)=\sigma_e\left(\boldsymbol{\sigma}\right)-\left(1-D\left(\bar{\varepsilon}_p\right)\right)\sigma_y\left(\varepsilon_p\right)$$

Exponential damage law

$$D\left(\bar{\varepsilon}_p\right)=1-e^{-\beta\bar{\varepsilon}_p}$$

Linear isotropic hardening

$$\sigma_y\left(\varepsilon_p\right)=\sigma_{y0}+H\varepsilon_p$$

Implicit gradient formulation (Helmholtz equation)

$$\bar{\varepsilon}_p-l^2\nabla^2\bar{\varepsilon}_p=\varepsilon_p$$

$\bar{\varepsilon}_p$ – nonlocal equivalent plastic strain, ε_p – local equivalent plastic strain
l – microstructural parameter

Governing equations

$$\nabla\boldsymbol{\sigma}+\mathbf{f}=\mathbf{0}$$

$$\bar{\varepsilon}_p-l^2\nabla^2\bar{\varepsilon}_p=\varepsilon_p$$

Finite element equation

$$\begin{bmatrix}\mathbf{K}_{uu} & \mathbf{K}_{u\bar{\varepsilon}_p}\\ \mathbf{K}_{\bar{\varepsilon}_p u} & \mathbf{K}_{\bar{\varepsilon}_p\bar{\varepsilon}_p}\end{bmatrix}\begin{bmatrix}\Delta\mathbf{u}\\ \Delta\bar{\varepsilon}_p\end{bmatrix}=\begin{bmatrix}\mathbf{F}_e^u-\mathbf{F}_i^u\\ \mathbf{F}_i^{\bar{\varepsilon}_p}\end{bmatrix}$$

Mixed four-node quadrilateral finite element

Ref.: Engelen R.A.B., Geers M.G.D., Baaijens F.P.T.: Nonlocal implicit gradient-enhanced elasto-plasticity for the modelling of softening behaviour. *International Journal of Plasticity,* 2003,19(4),403-433.

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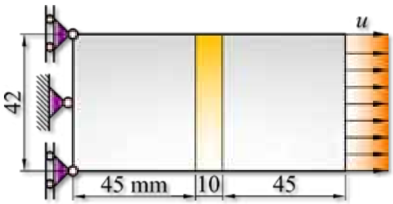
Example, ductile damage modeling

Plate with an imperfect zone subjected to tensile load

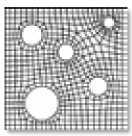
Young's modulus: $E=210\,000\,\text{MPa}$
Poisson's ratio: $\nu=0.3$
Yield stress: $\sigma_y=250\,\text{MPa}$
Hardening modulus: $E_T=20000\,\text{MPa}$
Length scale: $l=0.01\,\text{mm}$

Weakened region
Yield stress: $\sigma_y=200\,\text{MPa}$

Damage model: $D\left(\bar{\varepsilon}_p\right)=1-e^{-\beta\bar{\varepsilon}_p}$
$\beta=500$



24 CPE8R finite elements



MVE side length: 0.2 mm
508 quadrilateral finite elements
Void ratio: 0.13

Ref.: Lesičar, T., Sorić, J., Tonković, Z.: Ductile Damage Modelling of Heterogeneous Materials Using a Two-Scale Computational Approach, Comput. Methods Appl. Mech. Engrg. 355 (2019) 113-134.

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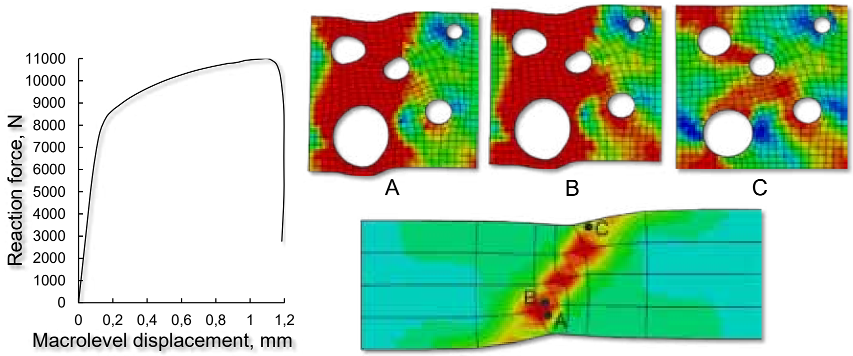
Example, ductile damage modeling

Plate with an imperfect zone subjected to tensile load



Distribution of damage

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Example, ductile damage modeling

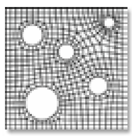
Shear band problem

H = 50 mm
Thickness = 1 mm
$v = 1\,\text{mm}$

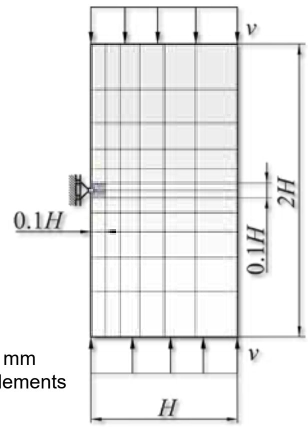
Damage model:
$D(\bar{\varepsilon}_p) = 1 - e^{-\beta \bar{\varepsilon}_p}$
$\beta = 100000$

Young's modulus: $E = 210\,000\,\text{MPa}$
Poisson's ratio: $\nu = 0.3$
Yield stress: $\sigma_y = 250\,\text{MPa}$
Hardening modulus: $E_T = 20000\,\text{MPa}$
Length scale: $l = 0.1\,\text{mm}$

Weakened region
Yield stress: $\sigma_y = 200\,\text{MPa}$



RVE side length: 0.2 mm
508 quadrilateral finite elements
Void ratio: 0.13



Ref.: Lesičar, T., Sorić, J., Tonković, Z.: Ductile Damage Modelling of Heterogeneous Materials Using a Two-Scale Computational Approach, Comput. Methods Appl. Mech. Engrg. 355 (2019) 113-134.

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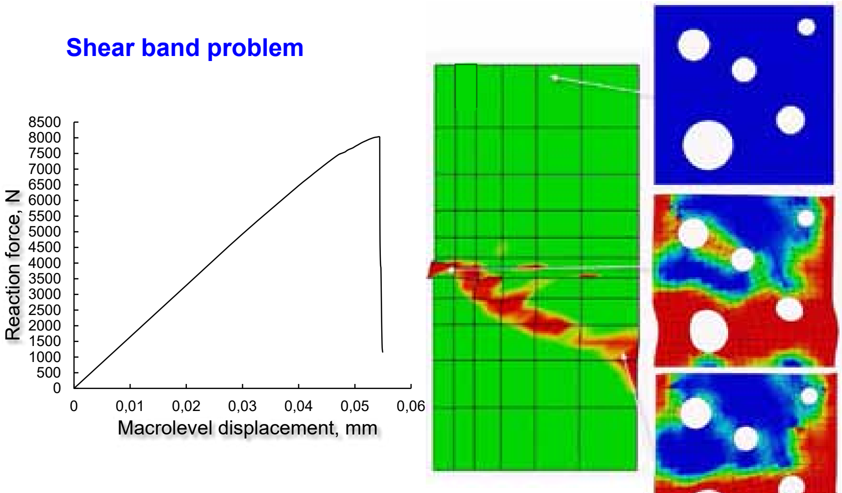
Example, ductile damage modeling

Shear band problem



Distribution of damage

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Modeliranje rasta pukotine metodom faznih polja

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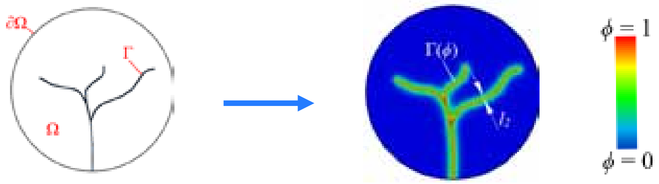
Phase-field approach to crack modelling



Discrete crack surface Γ (sharp crack discontinuity)   Diffusive crack surface Γ(ϕ)

Energy functional

$$\Psi = \int_{\Omega} g(\phi)\psi(\varepsilon)\,\mathrm{d}\Omega + G_c \int_{\Omega} \gamma(\phi)\,\mathrm{d}\Omega$$

$\psi(\varepsilon)$ - elastic strain energy density
$g(\phi)$ - degradation function
ϕ - phase-field scalar parameter,
G_c - Griffith's fracture energy density
$\gamma(\phi)$ - crack density function

$\phi = 0$ - intact state, $\phi = 1$ - fully broken

$$g(\phi) = (1-\phi)^2$$

$$\gamma(\phi) = \frac{1}{2}\left[\frac{1}{l}\phi^2 + l\left|\nabla\phi\right|^2\right]$$

Ref.: Seleš, K., Lesičar, T., Tonković, Z., Sorić, J., A Residual Control Staggered Solution Scheme for the Phase-Field Modeling of Brittle Fracture. *Engineering fracture mechanics*, 205 (2018), 1; 370-386.

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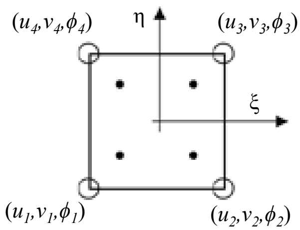
Phase-field approach to crack modelling

FEM implementation

$$\begin{bmatrix} \mathbf{K}^{\mathbf{uu}} & \mathbf{K}^{\mathbf{u}\phi} \\ \mathbf{K}^{\phi\mathbf{u}} & \mathbf{K}^{\phi\phi} \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \phi \end{bmatrix} = \begin{bmatrix} \mathbf{F}^{\mathrm{ext}} - \mathbf{F}^{u,\mathrm{int}} \\ \mathbf{F}^{\phi,\mathrm{int}} \end{bmatrix} = \begin{bmatrix} \mathbf{R}^{\mathbf{u}} \\ \mathbf{R}^{\phi} \end{bmatrix}$$



Staggered algorithmic approach

$\Psi = \Psi(\mathbf{u},\phi)$ - convex to the variable $\{\mathbf{u},\phi\}$ separately

The staggered algorithm based on the residual norm control decouples the system and solves it in an iterative manner. The finite element software Abaqus is used.

Ref.: Seleš, K., Lesičar, T., Tonković, Z., Sorić, J., A Residual Control Staggered Solution Scheme for the Phase-Field Modeling of Brittle Fracture. *Engineering fracture mechanics*, 205 (2018), 1; 370-386.

Lesičar, T., Polančec, T., Tonković, Z., Convergence Check Phase-Field Scheme for Modelling of Brittle and Ductile Fractures. *Applied Sciences* (2023), 13, 7776. https://doi.org/10.3390/app13137776.

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Phase-field approach to crack modelling

Single edge notched shear test

Young's modulus: $E = 210\,000\,\text{MPa}$

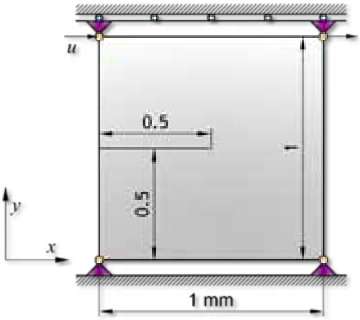
Poisson's ratio: $\nu = 0.3$

Critical fracture energy density: $G_c = 2.7\,\dfrac{\text{N}}{\text{mm}}$

Length scale: $l = 0.0075\,\text{mm}$

$u = 0.013\,\text{mm}$

100 loading increments



Ref.: Lesičar, T., Polančec, T., Tonković, Z., Convergence Check Phase-Field Scheme for Modelling of Brittle and Ductile Fractures. *Applied Sciences* (2023), 13, 7776. https://doi.org/10.3390/app13137776.

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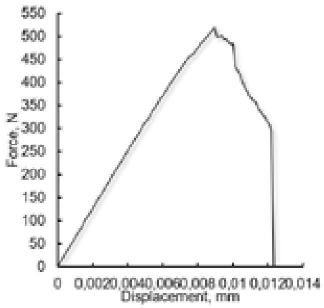
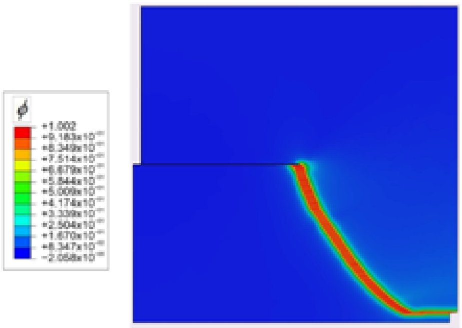
Phase-field approach to crack modelling

Single edge notched shear test





Ref.: Lesičar, T., Polančec, T., Tonković, Z., Convergence Check Phase-Field Scheme for Modelling of Brittle and Ductile Fractures. *Applied Sciences* (2023), 13, 7776. https://doi.org/10.3390/app13137776.

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Phase-field approach to crack modelling

Asymmetrically notched specimen under tension

Material: aluminium alloy Al-5005.

Young's modulus: $E = 70{,}9\ \text{GPa}$

Poisson's ratio: $\nu = 0.34$

Critical fracture energy density:

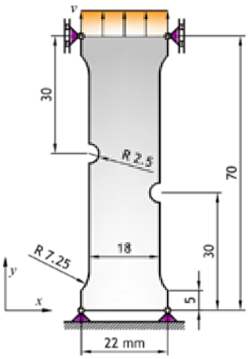
$$G_c = 254{,}66 \frac{\text{N}}{\text{mm}}$$

Length scale: $l = 1\,\text{mm}$

Nonlinear isotropic hardening

Vertical displacement $v = 3\ \text{mm}$

100 loading increments



Geometry and boundary conditions

Ref.: Lesičar, T., Polančec, T., Tonković, Z., Convergence Check Phase-Field Scheme for Modelling of Brittle and Ductile Fractures. *Applied Sciences* (2023),13, 7776. https://doi.org/10.3390/app13137776.

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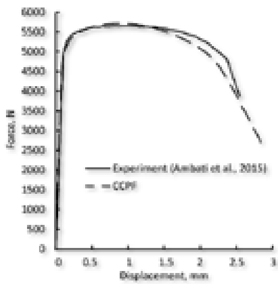
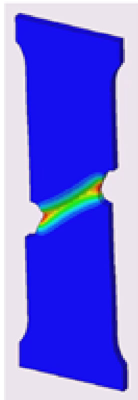
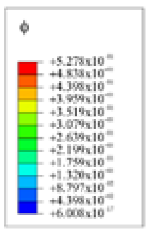
Phase-field approach to crack modelling

Asymmetrically notched specimen under tension







Distribution of phase-field variable

Ref.: Lesičar, T., Polančec, T., Tonković, Z., Convergence Check Phase-Field Scheme for Modelling of Brittle and Ductile Fractures. *Applied Sciences* (2023),13, 7776. https://doi.org/10.3390/app13137776.

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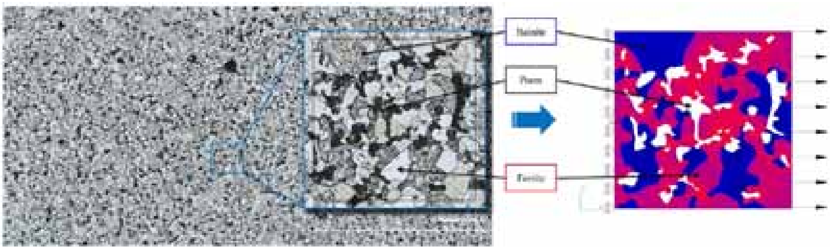
Phase-field approach to crack modelling

Modelling of heterogeneous material
Deformation responses of sintered steel



Selection of the 2D model from metallographic image of sintered steel and corresponding model for numerical simulations.

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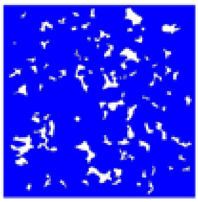
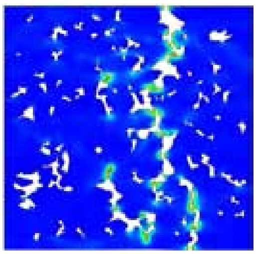
Phase-field approach to crack modelling

Modeling of microcrack propagation in sintered steel

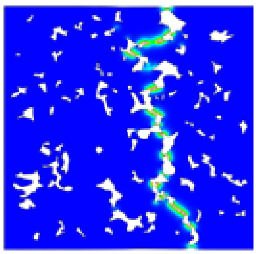
Metallographic model of sintered steel



Brittle fracture



Ductile fracture



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Modeliranje deformiranja bioloških tkiva. Primjena MKE u medicini

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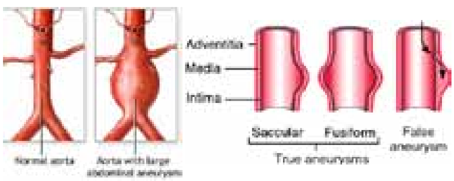
Modeliranje aneurizme abdominalne aorte

Aneurizma abdominalne aorte (AAA)

O AAA:
- Najčešće asimptomatska bolest
- Lokalno ireverzibilno proširenje aorte – dijagnosticira se ako je maksimalni primjer 3 cm u odnosu na zdravi promjer od 2 cm (povećanje promjera minimalno 50%)
- Komplikacija: ruptura – visoka stopa smrtnosti

Rizični faktori:
- Starost
- Muški spol
- Pušenje
- *Dijabetes*
- Hipertenzija
- Ateroskleroza
- Genetika?

Kirurško liječenje:
- Temeljeno na maksimalnom promjeru AAA > 5 cm
- Dodatni kriterij: brzina rasta AAA (ako je poznata)



http://en.wikipedia.org/wiki/Abdominal_aortic_aneurysm

http://www.lnm.mw.tum.de/

80% aneurizama sadrži intraluminalni tromb (IL)

Ref.: Virag L, Horvat N, Karšaj I. 2023. A computational study of bio-chemo-mechanics of thrombus-laden aneurysms. J. Mech. Phys Solids. 171:105140. https://doi.org/10.1016/j.jmps.2022.105140.
Virag L, Živić J, Horvat N, Karšaj I. Fluid-solid-growth model framework: application to the growth of thrombus during abdominal aortic aneurysm progression. Biomechanics and Modeling in Mechanobiology, u tisku.

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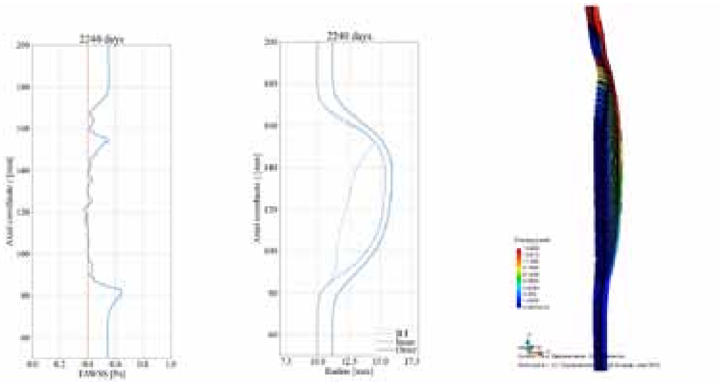
Modeliranje aneurizme abdominalne aorte



Dodavanje elemenata tromba na mjestima definiranim hemodinamikom (računalne dinamike fluida, CFD).

Pretpostavlja se da je za nastanak tromba odgovorno vremenski usrednjeno posmično naprezanje (TAWSS) koje mora biti dovoljno malo da omogući agregaciju trombocita.

Ref.: Virag L., Živić J, Horvat N., Karšaj I. Fluid-solid-growth model framework: application to the growth of thrombus during abdominal aortic aneurysm progression. Biomechanics and Modeling in Mechanobiology, u tisku.

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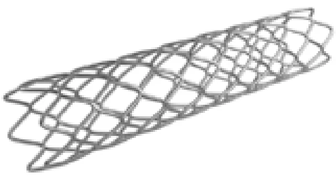
Modeliranje proširenja krvnih žila ugradnjom stenta

- Ateroskleroza – kardiovaskularna bolest u kojoj se plak stvara taloženjem lipida, pjenastih stanica; sužava arterijski lumen.
- Opasnosti – stvaranje krvnih ugrušaka ili otkidanje plaka; moždani/srčani udar.
- Stent – mrežasta cijevčica koja se ugrađuje s ciljem uspostavljanja normalnog protoka krvi kroz krvne žile.



https://www.shutterstock.com/video/clip-1097915819-atherosclerosis-animation-cholesterol-plaque-heart-attack-build

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Istraživačka grupa
Igor Karšaj, Lana Virag

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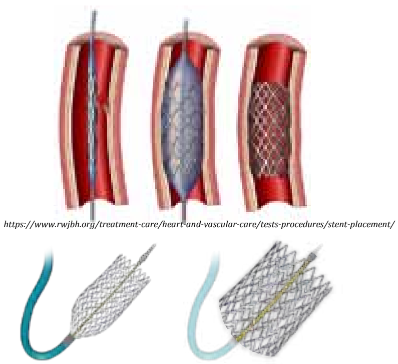
Modeliranje proširenja krvnih žila ugradnjom stenta



https://www.rwjbh.org/treatment-care/heart-and-vascular-care/tests-procedures/stent-placement/

MEDTRONIC PERIPHERAL | Prokardiyo

- Proširenje balonom
(nedostaci: nepotrebna prevelika deformacija i elastični povrat uzrokuju nepotrebno oštećenje stijenke; puno ograničenja na geometriju stenta)
- Samoekspandirajući stentovi
- Materijal:
  - Metal
  - Polimer (nedostaci: lošija radijalna čvrstoća)

LNM, FSB
Istraživačka grupa
Igor Karšaj, Lana Virag

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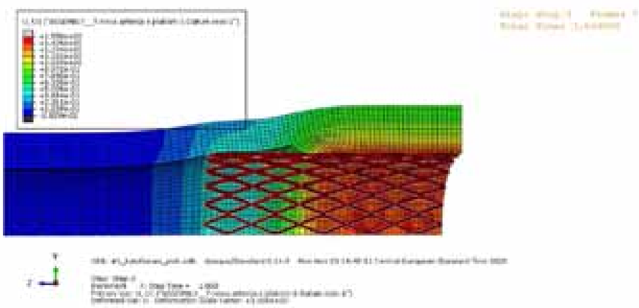
Modeliranje proširenja krvnih žila ugradnjom stenta

Ugradnja balonom ekspandirajućih stentova



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Istraživačka grupa
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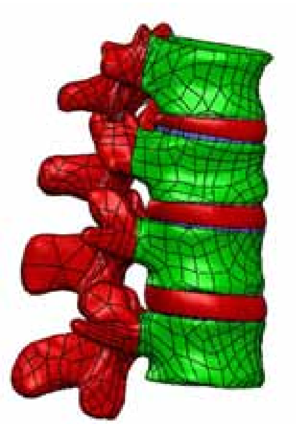
Modeliranje stabilizacijskog sustava kralježnice



Model torakolumbalnog prijelaza

Diskretizirani model torakolumbalnog prijelaza,

Doktorski rad: Krešimir Saša Đurić, Medicinski fakultet
Mentori: Marin Stančić, Medicinski fakultet
Jurica Sorić, FSB

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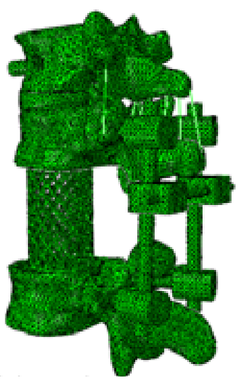
Modeliranje stabilizacijskog sustava kralježnice

Diskretizirani model prednje i stražnje stabilizacije na modelu korporektomije



Diskretizirani model prednje i stražnje stabilizacije na modelu spondilektomije

Doktorski rad: Krešimir Saša Đurić, Medicinski fakultet
Mentori: Marin Stančić, Medicinski fakultet
Jurica Sorić, FSB

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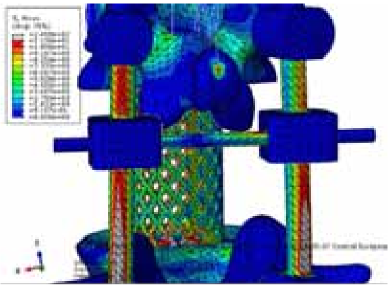
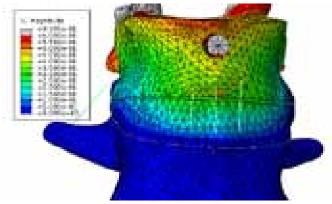
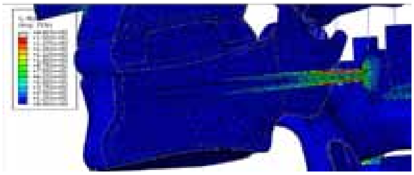
Modeliranje stabilizacijskog sustava kralježnice



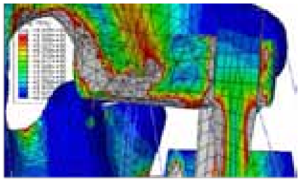
Naprezanje u šipkama u modelu spondilektomije uslijed savijanja



Pomaci u dijelu modela spondilektomije uslijed savijanja



Naprezanje u vijku u modelu spondilektomije uslijed savijanja



Naprezanje u kukicama i dijelu kostiju u modelu spondilektomije uslijed savijanja

Doktorski rad: Krešimir Saša Đurić, Medicinski fakultet
Mentori: Marin Stančić, Medicinski fakultet
Jurica Sorić, FSB

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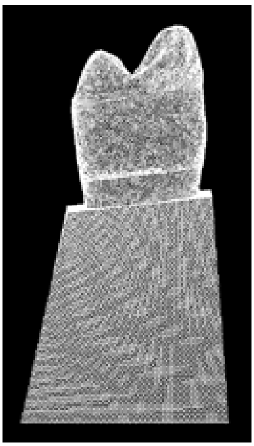
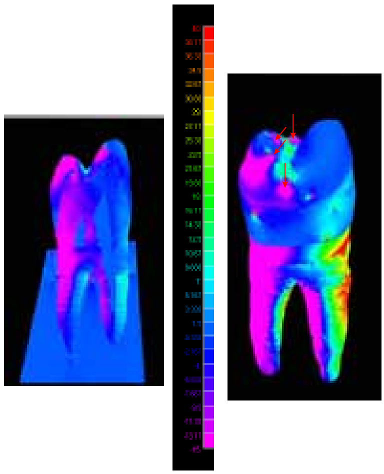
MKE analiza rekonstruiranog zuba

Model rekonstruiranog zuba



MKE model



Ekvivalentna naprezanja prema von Misesu

I. Smojver, FSB

Laboratory of Numerical Mechanics University of Zagreb

Primjena neuronskih mreža u mehanici čvrstih tijela

Laboratory of Numerical Mechanics University of Zagreb

Neural networks in solid mechanics

Artificial intelligence (AI)

- Machine learning (ML)
  - Feedforward neural network (FFNN)
    Deep learning (DL) (FFNN with multiple hidden layers)
  - Convolutional neural network (CNN)
  - Recurrent neural network (RNN)
    - Long short-term memory (LSTM) network
    - Gated recurrent unit (GRU)
  - Physics-informed neural network (PINN)
  - ⋮

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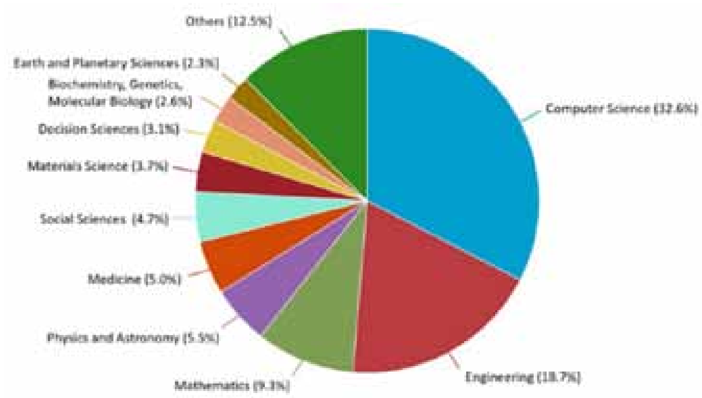
Neural networks in solid mechanics



Distribution of publications about deep learning in each subject area on SCOPUS, January 2022

Ref.:Yinli Wang, Y. et al. : Application of deep neural network learning in composites design, *European Journal of Materials*, 2:1, (2022) 117-170.

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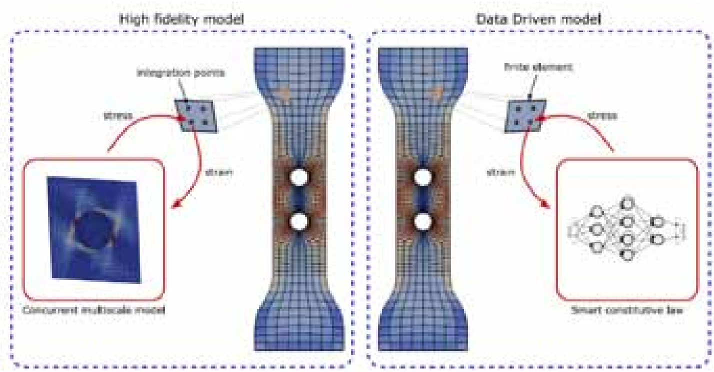
Neural networks in solid mechanics



Schematics for the high fidelity model and the data-driven model

In the DD model, the same SCL is applied to all integration points. On the other hand, the high fidelity model requires to perform a full FE simulation of the microstructure for each integration point at each load increment.

Ref.: H.J. Logarzo et al.: Smart constitutive laws: Inelastic homogenization through machine learning. *Computer Methods in Applied Mechanics and Engineering* 373 (2021) 113482

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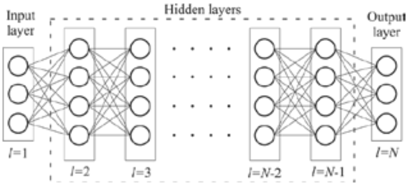
Neural networks in solid mechanics

Feedforward neural network with multiple layers



$$u_j^l = \sum_{j=1}^{n^{l-1}} w_{ji}^{l-1} o_i^{l-1} + b_j^l$$

$$\Downarrow$$

$$o_j^l = f(u_j^l)$$

Activation functions

Loss function (mean squared error)

$$L = \frac{1}{2} \sum_{s=1}^{n_s} \sum_{j=1}^{n_N} ({}^s o_j^N - {}^s o_j^*)^2$$

Backpropagation

$$\Delta w_{ji}^{l-1} = \frac{\partial L}{\partial w_{ji}^{l-1}} \qquad \Delta b_j^l = \frac{\partial L}{\partial b_j^l}$$

$$w_{ji} = w_{ji}^{l-1} - \alpha \Delta w_{ji}^{l-1} \qquad b_j^l = b_j^l - \beta \, \Delta b_j^l$$

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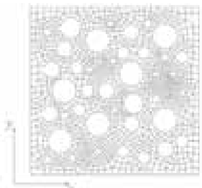
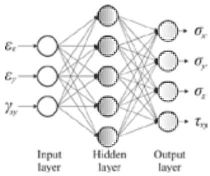
Neural networks in solid mechanics

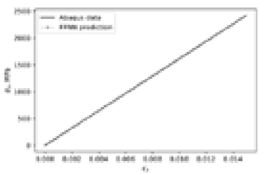
Application of FFNN to computation of an elastic problem



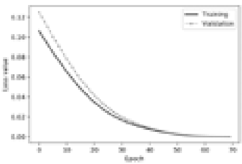
Discretized porous square plate under periodic boundary conditions



Schematic of the used FFNN



FFNN stress-strain diagram



Loss value changes over epochs

FFNN CPU time comparison

	CPU time [s]
Abaqus FEM simulation	9.9
FFNN prediction	0.109

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Ref.: J. Sorić, M. Stanić, T. Lesičar: On Neural Network Application in Solid Mechanics, *Transactions of FAMENA* 47 (2023), 45-66.

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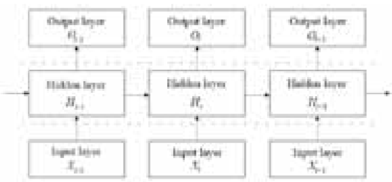
Neural networks in solid mechanics

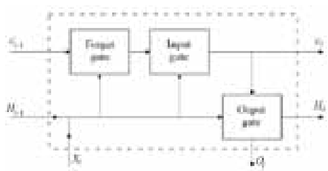
Recurrent neural network (RNN)
Long short-term memory network (LSTM)

RNN deals with sequential data, where the learning process is performed over several time steps. The information flows not only forward, but it is also temporarily stored in the working memory and then it flows into the hidden neurons along with the input at the next time step.

To solve the vanishing gradient problem in RNN, long short-term memory networks (LSTMs) are proposed.



Time-unrolled RNN computational graph



Schematic of internal structure of LSTM unit

LNM, FSB

Ref.: J. Sorić, M. Stanić, T. Lesičar: On Neural Network Application in Solid Mechanics, *Transactions of FAMENA* 47 (2023), 45-66.

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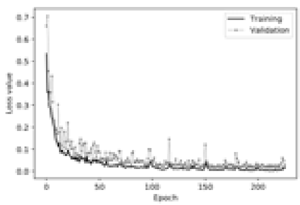
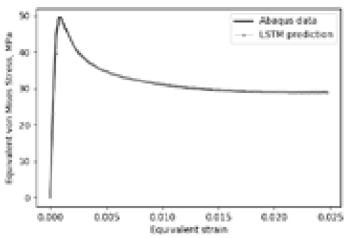
Neural networks in solid mechanics

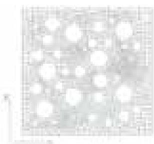
Application of the LSTM neural network to an elastoplastic problem



Loss value changes over epochs



Equivalent von Mises stress-strain diagram



LSTM CPU time comparison

	CPU time [s]
Abaqus FEM simulation	15.5
LSTM prediction	0.25

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Ref.: J. Sorić, M. Stanić, T. Lesičar: On Neural Network Application in Solid Mechanics, *Transactions of FAMENA* 47 (2023), 45-66.

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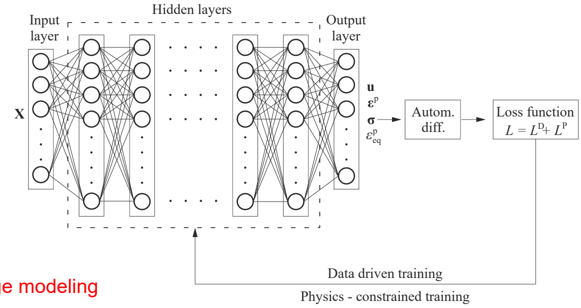
Neural networks in solid mechanics

Physics-informed neural network (PINN)

Schematic of PINN



Current research:

PINN ductile damage modeling

L^D - Data loss function

Displacement
Plastic strain
Stress
Nonlocal equivalent plastic strain
Approximated values and target values obtained by means of FEM simulation

L^P - Physics-based loss function

Equilibrium condition
Constitutive law
Flow rule
Helmholtz equation
Boundary condition
Kuhn-Tucker complementarity conditions

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Zahvala suradnicima

Laboratorij za numeričku mehaniku
Fakulteta strojarstva i brodogradnje
Sveučilišta u Zagrebu

Zahvala suradnicima koji su sudjelovali u istraživanjima i doprinijeli prikazanim rezultatima:

Zdenko Tonković
Igor Karšaj
Tomislav Jarak
Ivica Skozrit
Tomislav Lesičar
Filip Putar
Boris Jalušić
Lana Virag
Karlo Seleš
Matej Stanić
Krešimir Saša Đurić

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Više o metodi konačnih elemenata
Finite Element Procedures
O.C. ZIENKIEWICZ & R.L. TAYLOR
The FINITE ELEMENT METHOD
Volume 1 THE BASIS
FIFTH EDITION
O.C. ZIENKIEWICZ & R.L. TAYLOR
The FINITE ELEMENT METHOD
Volume 2 SOLID MECHANICS
FIFTH EDITION
Jurica Sorić
METODA KONAČNIH ELEMENATA
Multiscale Modeling of Heterogeneous Structures
Laboratory of Numerical Mechanics
University of Zagreb

DOI 10.21857/9e31lhzq8m

Prezentacija predavanja

RAČUNALNA DINAMIKA FLUIDA-MOGUĆNOSTI I OGRANIČENJA

Prof. dr. sc. Milovan Perić
University of Duisburg-Essen, Duisburg, Njemačka

Milovan Perić

RAČUNALNA DINAMIKA FLUIDA – MOGUĆNOSTI I OGRANIČENJA

Sažetak predavanja

Računalna dinamika fluida (CFD – Computational Fluid Dynamics) se u zadnjih četiri desetljeća razvila od mlade znanstvene discipline u napredne alate za rješavanje problema u industriji, razvoj novih proizvoda te njihovo optimiranje. Danas je inženjerima na raspolaganju nekoliko računalnih alata, iza kojih stoje velike tvrtke poput Siemens-a, a u mnogim inženjerskim tvrtkama računalne simulacije su djelomično ili potpuno zamijenile eksperimente.

Predavač će u prezentaciji obrazložiti ideju CFDa i pokušati odgovoriti na nekoliko pitanja vezanih za mogućnosti i ograničenja računalne dinamike fluida i na njoj zasnovanih računalnih paketa, kao i pravce budućeg razvoja:

- Koje klase problema je danas moguće riješiti koristeći CFD?
- Gdje su danas granice za praktično korištenje CFD-simulacija i kako se one mijenjaju s vremenom?
- Koju ulogu će u budućnosti imati eksperimentalna istraživanja u području mehanike fluida?
- Kako procijeniti greške u CFD-rješenjima i osigurati njihovu vjerodostojnost?
- Koju ulogu ima sveučilišno obrazovanje u ovom polju i što je za očekivati od „umjetne inteligencije“?
- Kakvi su izgledi hrvatskih znanstvenih institucija i tvrtki za uspješno angažiranje na razvoju i korištenju CFD-metoda i software-proizvoda?

O predavaču

Milovan Perić je studirao strojarstvo u Sarajevu od 1976. do 1980. Doktorirao je na Imperial College u Londonu 1985, a od 1986. do danas živi i radi u SR Njemačkoj. Od svog diplomskog rada do danas bavi se razvojem i primjenom računalne dinamike fluida, posebno metodama za proračun strujanja fluida u domenama s kompleksnom geometrijom i pokretnim granicama te višefaznim strujanjima sa slobodnim površinama, simulacijom interakcije između strujanja fluida i plovnih objekata te simulacijom turbulencije. Radio je kao istraživač i predavač na Sveučilištima u Erlangenu, Stanfordu, Hamburgu i Duisburgu. Suosnivač je tvrtke koja je od 1997 do 2001 razvijala CFD-software „Comet“. Tvrtku i software je 2002. preuzela tvrtka CD-adapco pri čemu je u navedenu tvrtku prešao na poziciju direktora razvoja, direktor tehnologije i na kraju kao „vice president for technology“. Od 2014. do danas Milovan Perić radi kao samostalni konzultant za industriju (uglavnom za Siemens i Mercedes-Benz) te drži predavanja iz područja primijenjene računalne dinamike fluida na sveučilištu Duisburg-Essen, gdje je član Fakulteta za tehničke znanosti.

Dr. Perić je autor ili koautor velikog broja članaka u znanstvenim časopisima i zbornicima radova specijaliziranih konferencija te nekolicine poglavlja u knjigama. Koautor je (s dvojicom kolega sa sveučilišta Stanford) popularne knjige „Computational methods in fluid dynamics“ koju je izdao Springer na engleskom, njemačkom, japanskom, kineskom, grčkom i ruskom jeziku.

Računalna dinamika fluida (CFD) – mogućnosti i ograničenja

Milovan Perić

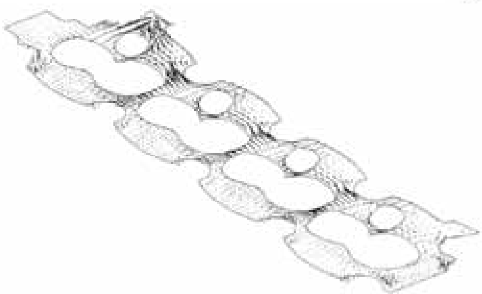
CFD povijest

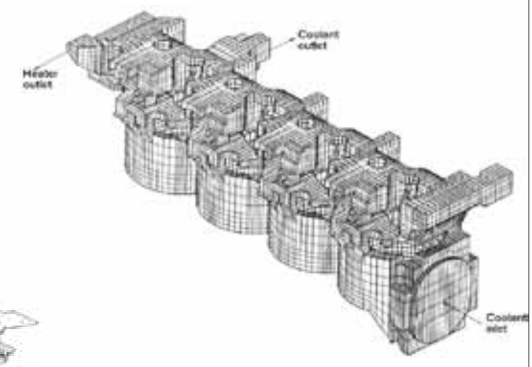
- Začeci u doba hladnog rata
- Potencijalno strujanje
- Granični sloj
- Neviskozno strujanje – Euler jednadžbe
- Viskozno strujanje – Navier-Stokes jednadžbe
- Neortogonalne računalne mreže
- Paralelno računanje, hardware-inovacije
- Komplikovana geometrija, sprega sa CAD
- Komercijalni software, masovna primjena

2

Početak primjene u industriji

- Jedan od prvih pokušaja rješavanja praktičnih problema u industriji: simulacija toka sredstva za hlađenje u bloku motora (1988; software STAR-CD)

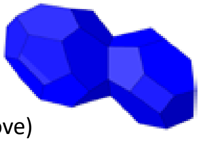




3

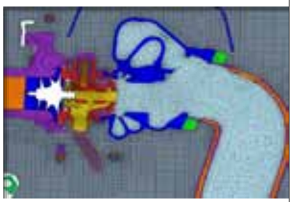
CFD software danas - I

- Metoda konačnih zapremina (Fluent, Simcenter STAR-CCM+, OpenFOAM,...)
- Kontrolne zapremine proizvoljnog oblika (poliedri)
- Geometrija računalnog domena definisana u CAD-formatu
- Automatsko generiranje računalne mreže (sa slojevima prizmi uz zidove)



CAD-model

Površinska mreža



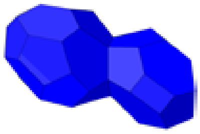
Presjek kroz zapreminsku mrežu

Slike: Siemens

4

CFD software danas - II

- Jednadžbe bazirane na zakonima o održanju mase, impulsa, energije itd…
- Integralni oblik jednadžbi za pokretne kontrolne zapremine:



Prostor: $$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \mathrm{d}V - \int_S \mathbf{v}_\mathrm{b} \cdot \mathbf{n}\,\mathrm{d}S = 0\,,$$

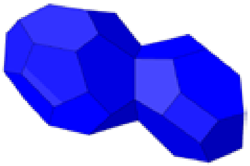
Masa: $$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho\,\mathrm{d}V + \int_S \rho(\mathbf{v} - \mathbf{v}_\mathrm{b}) \cdot \mathbf{n}\,\mathrm{d}S = 0\,,$$

Impuls: $$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho u_i\,\mathrm{d}V + \int_S u_i \rho(\mathbf{v} - \mathbf{v}_\mathrm{b}) \cdot \mathbf{n}\,\mathrm{d}S = \int_S (\tau_{ij}\mathbf{i}_j - p\,\mathbf{i}_i) \cdot \mathbf{n}\,\mathrm{d}S + \int_V \rho b_i\,\mathrm{d}V$$

Brzina fluida ($\mathbf{v}$) — Brzina granice kontrolne zapremina ($\mathbf{v}_\mathrm{b}$)

5

CFD software danas - III



- Aproksimacije 2. reda točnosti:
  - Pravilo srednje točke za integrale (*midpoint rule*)
  - Linearna interpolacija (ponekad kvadratna, kubna)
  - Centralne razlike za gradijente (*central differences*)
- Specijalizirane metode višeg reda za specijalna područja primjene:
  - Metode konačnih razlika (do 6. reda točnosti, za kartezijske mreže)
  - Spektralne metode (za periodične granične uvjete, jednostavnije geometrije)
  - Metode konačnih elemenata (za kruta tijela, magnetna polja, viskoelastične fluide itd.)
- Sekvenciono (SIMPLE) i kuplovano rješavanje jednadžbi
- Široko područje primjene (od vrlo malih do vrlo visokih Reynoldsovih brojeva)

6

Što možemo dobro računati?

- Riješiti jednadžbe sa zadovoljavajućom točnošću za industrijsku primjenu…
- Simulirati kretanje krutih tijela u sprezi sa strujanjem fluida…
- Predvidjeti sile na zidovima (otpor, potisak, moment…).
- Predvidjeti prenos topline…
- Utvrditi kako promjene određenih parametara utječu na učinkovitost uređaja…
- Uzeti u obzir stvarnu geometriju i granične uvjete…
- Testirati ideje za oblikovanje novih proizvoda…
- Ubrzati istraživanja (rješavanje problema; optimizacija)…
- Predvidjeti i objasniti fenomene u strujanju (Magnus-efekt, Coanda-efekt, …).

7

Što još ne možemo?

- Garantirati točnost rješenja (jer jednadžbe nisu uvijek točne)…
- Predvidjeti sa dovoljnom točnošću fenomene za koje nemamo dobre matematske modele (neke vrste višefaznih tokova, kemijske reakcije i sl.)…
- Efikasno predvidjeti kompleksne interakcije toka fluida i deformacije čvstih tijela…
- Predvidjeti detalje turbulencije u nekim vrstama strujanja…

8

Izvori grešaka u CFD i njihova procjena

- Izvori greškaka:
  - Iteracione greške,
  - Diskretizacione greške,
  - Greške u matematskim modelima (prije svega u modeliranju turbulencije),
  - Greške korisnika.
- Procjena greškaka:
  - **Iteracione greške:** Redukcija ostataka u iteracionom procesu ca. 4 reda veličine;
  - **Diskretizacione greške:** Sistematsko ufinjavanje mreže;
  - **Modelske greške:** Usporedba s točnim rješenjem (koje je rijetko kad poznato…).

9

Modeliranje turbulencije - I

- Kod *direktne numeričke simulacije* (DNS), kada rješavamo Navier-Stokes jednadžbe u izvornom obliku, ne treba nam nikakav model za turbulenciju…
- Problem: Veliki raspon prostornih i vremenskih skala u turbulentnom strujanju pri visokim Reynoldsovim brojevima…
- „Large-Eddy“ Simulacija (LES): Rješavanje filtriranih Navier-Stokes jednadžbi s modelom za „sub-grid scales“ (SGS)…
- Rješavanje „Reynolds-averaged“ Navier-Stokes (RANS) jednadžbi s modelom za sveukupnu turbulenciju…

$$\frac{\partial(\rho\bar{u}_i)}{\partial x_i}=0$$

Filtrirane (LES) ili osrednjene (RANS) brzine i pritisak

$$\frac{\partial(\rho\bar{u}_i)}{\partial t}+\frac{\partial(\rho\bar{u}_i\bar{u}_j)}{\partial x_j}=\frac{\partial\tau^s_{ij}}{\partial x_j}-\frac{\partial\bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial\bar{u}_i}{\partial x_j}+\frac{\partial\bar{u}_j}{\partial x_i}\right)\right]$$

Dodatni članovi u jednadžbama:

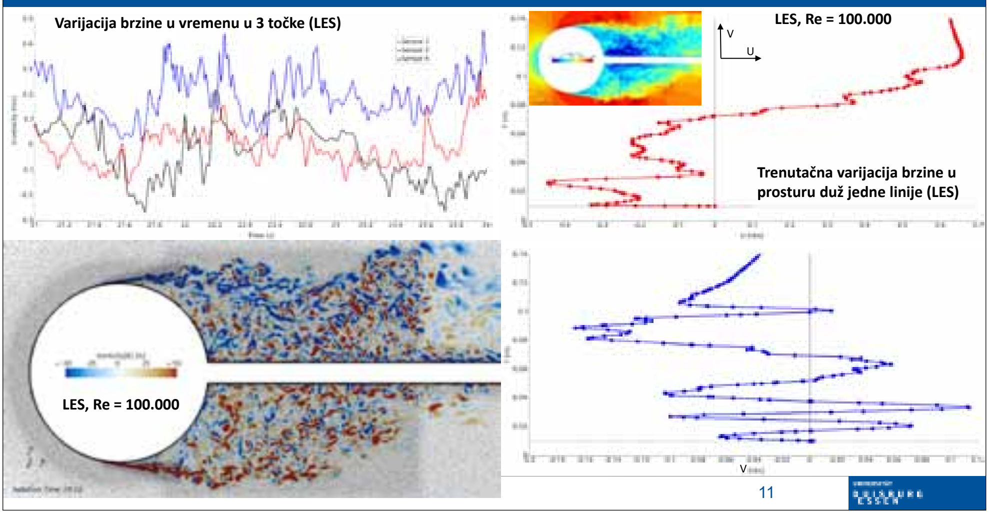
LES: $\tau^s_{ij}=-\rho(\overline{u_i u_j}-\bar{u}_i\bar{u}_j)$

RANS: $\tau^s_{ij}=-\rho\overline{u'_i u'_j}$

Fluktuacije oko srednje vrijednosti brzine

10

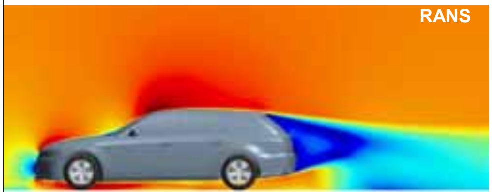
Modeliranje turbulencije - II

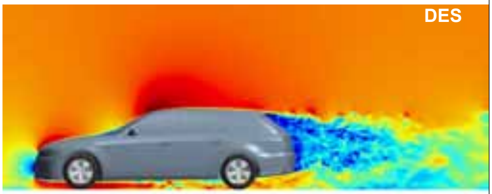


11

Modeliranje turbulencije - III

- LES → DNS kada se vremenski korak smanjuje…
- RANS-rješenje se ne može se popraviti ufinjavanjem ni mreže ni vremenskog koraka – ono uvijek sadrži grešku modela turbulencije…
- *Detached-Eddy Simulation* (DES): kombinacija RANS (blizu zida) i LES (u zonama recirkulacije).



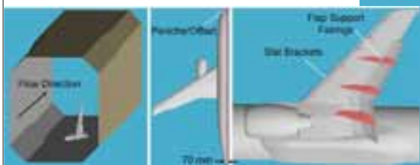


Slike: Siemens

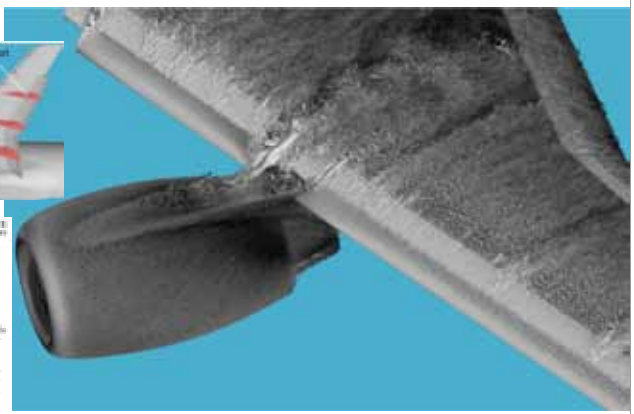
12

Modeliranje turbulencije - IV

Wall-modeled LES




Large eddy simulation of aircraft at affordable cost: a milestone in CFD

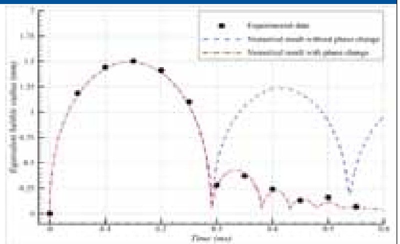


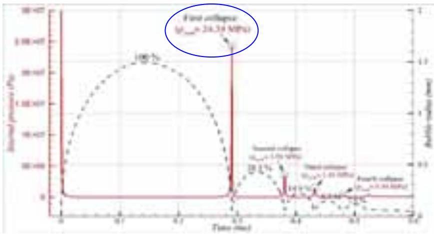
Detalji turbulentnog strujanja oko modela aviona – simulacija eksperimenta (185 miliona kontrolnih zapremina).

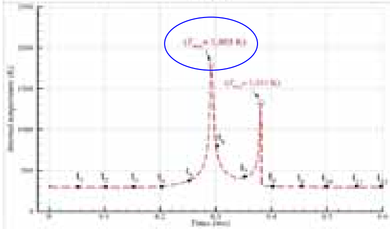
13

Modeliranje višefaznog strujanja

- „Volume-of-Fluid“ metoda za strujanja sa slobodnom površinom
- Promjene stanja: kavitacija, ključanje, isparavanje, topljenje, ukrućenje…





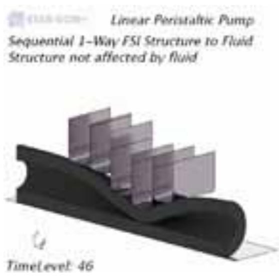


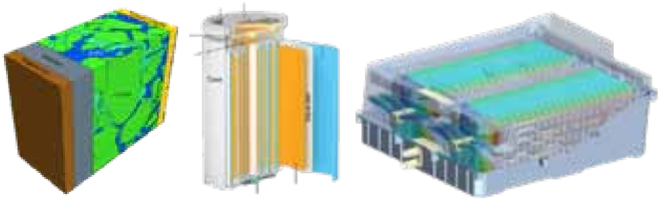
Simulacija s *OpenFOAM*, Phan et al, Universität Duisburg-Essen: Efekti promjene stanja na oscilacije mjehura vodene pare pored zida.

14

Modeliranje multifizičkih procesa

- Kemijske reakcije (sagorijevanje, katalizatori, elektro-kemijski procesi itd.)
- Elektro-magnetne pojave
- Viskoelastični fluidi
- Interakcija fluida i elastičnih tijela, itd.





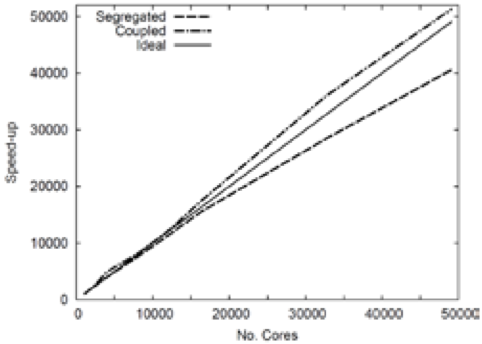
Simulacija procesa u Li-Ion baterijama: kemijski procesi na mikro-skali (lijevo); procesi unutar jedne ćelije (u sredini); hlađenje jednog paketa s mnogo ćelija (desno).

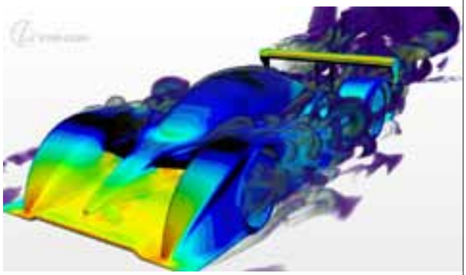
Slike: Siemens

15

Paralelno računanje

Primjer: Strujanje oko trkaćeg automobila, RANS, k-ω model turbulencije, AMG-solver, **1,02 milijarde ćelija**; Simcenter STAR-CCM+ Software. Super-linearna efikasnost kod kuplovanog rješavanja (manje komunikacije a više računanja po iteraciji)!

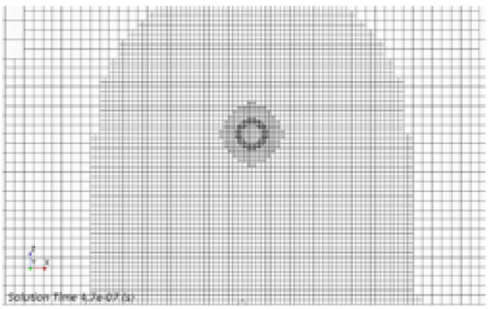


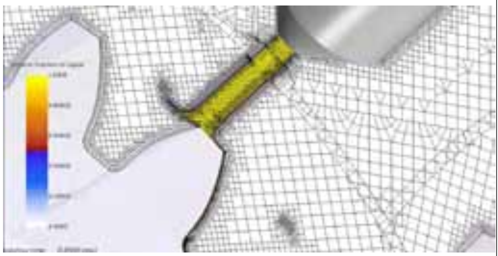


Slike: Siemens

16

Adaptivno ufinjavanje mreže

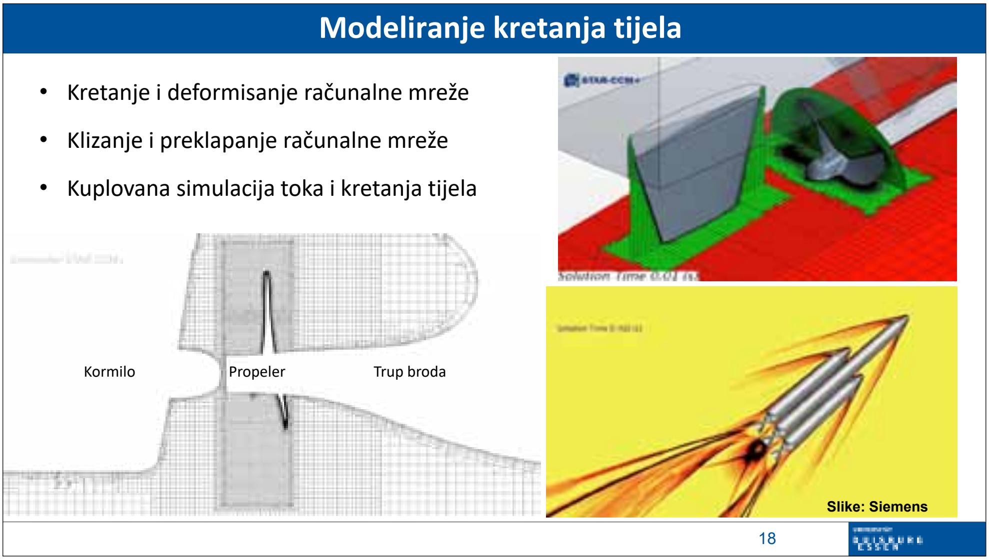


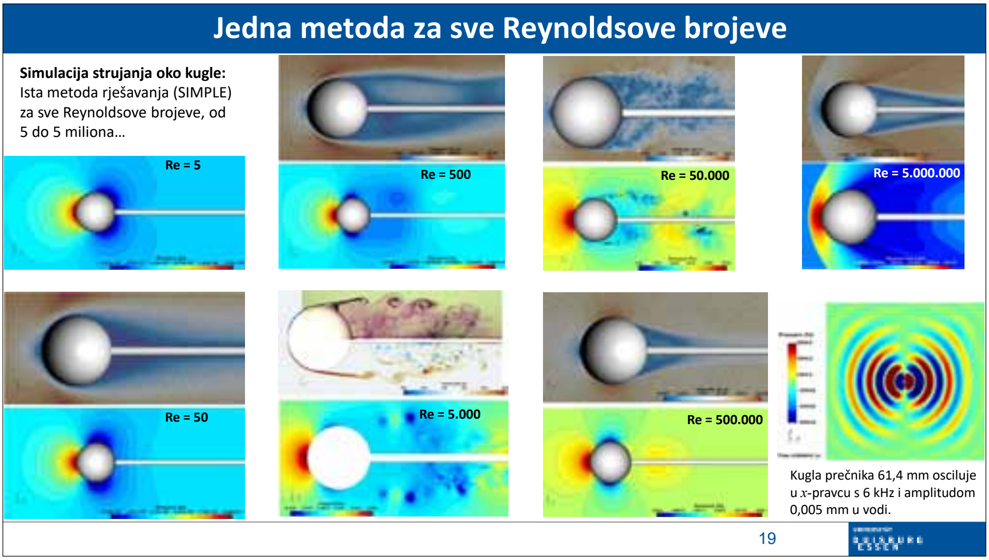


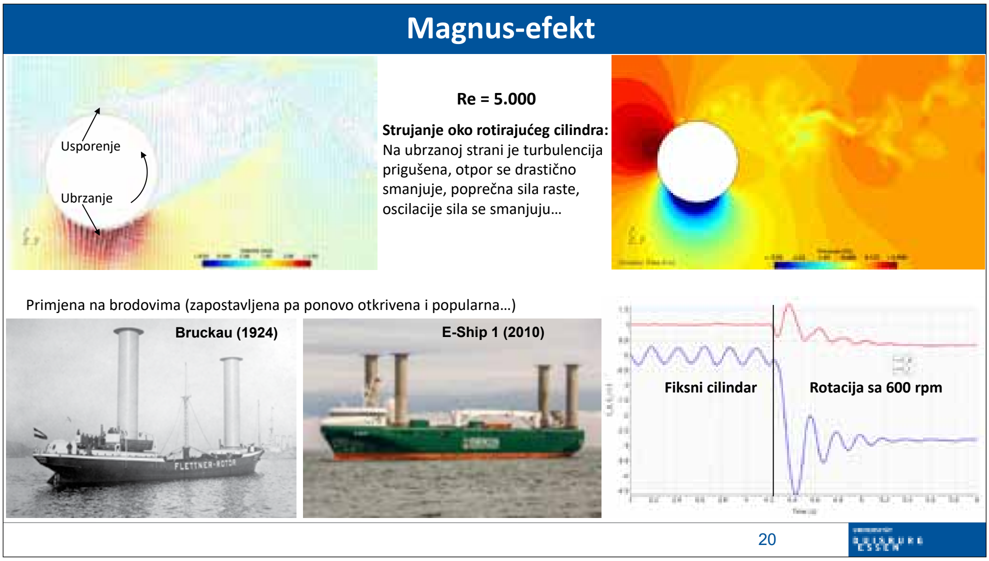
Adaptivno ufinjavanje mreže omogućava efikasniju kontrolu diskretizacionih grešaka…

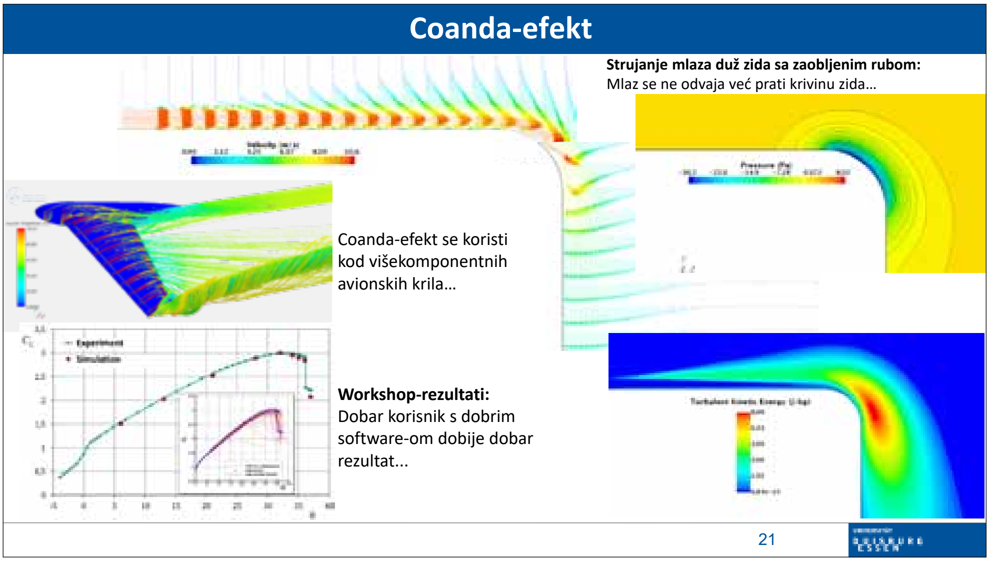
Primjeri: Kolaps gasnog mjehura u blizini zida (lijevo) i hlađenje zupčanika mlazom ulja (desno); Simcenter STAR-CCM+ Software.

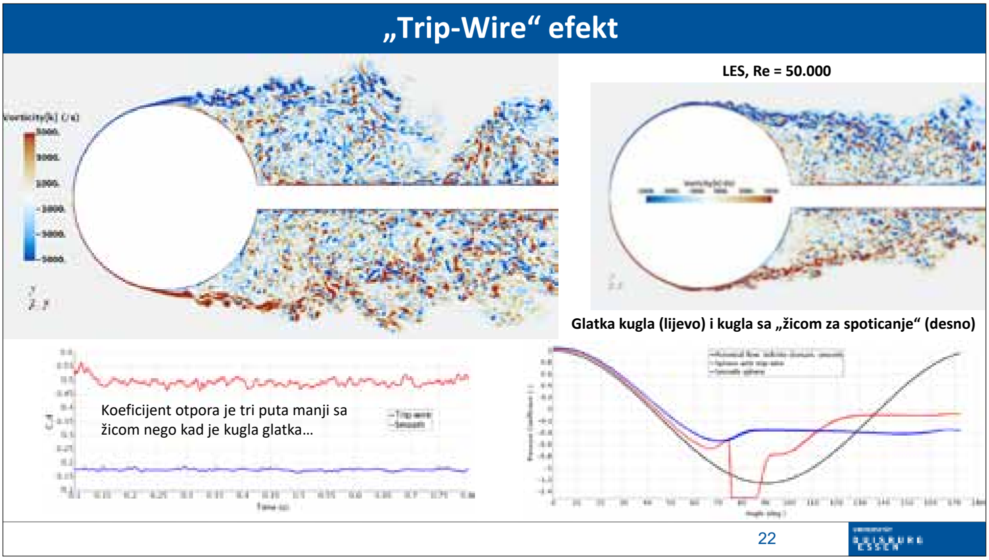
17

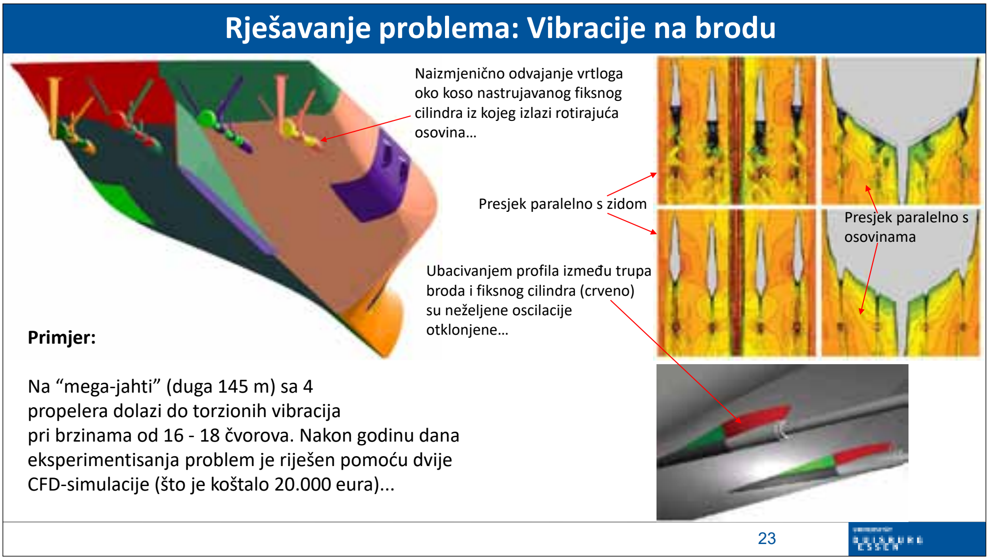

Modeliranje kretanja tijela
• Kretanje i deformisanje računalne mreže
• Klizanje i preklapanje računalne mreže
• Kuplovana simulacija toka i kretanja tijela
Kormilo
Propeler
Trup broda
Slike: Siemens
18


Jedna metoda za sve Reynoldsove brojeve
Simulacija strujanja oko kugle:
Ista metoda rješavanja (SIMPLE) za sve Reynoldsove brojeve, od 5 do 5 miliona…
Re = 5
Re = 500
Re = 50.000
Re = 5.000.000
Re = 50
Re = 5.000
Re = 500.000
Kugla prečnika 61,4 mm osciluje u x-pravcu s 6 kHz i amplitudom 0,005 mm u vodi.
19


Magnus-efekt
Usporenje
Ubrzanje
Re = 5.000
Strujanje oko rotirajućeg cilindra:
Na ubrzanoj strani je turbulencija prigušena, otpor se drastično smanjuje, poprečna sila raste, oscilacije sila se smanjuju…
Primjena na brodovima (zapostavljena pa ponovo otkrivena i popularna…)
Bruckau (1924)
E-Ship 1 (2010)
Fiksni cilindar
Rotacija sa 600 rpm
20


Coanda-efekt
Strujanje mlaza duž zida sa zaobljenim rubom:
Mlaz se ne odvaja već prati krivinu zida…
Coanda-efekt se koristi kod višekomponentnih avionskih krila…
Experiment
Simulation
Workshop-rezultati:
Dobar korisnik s dobrim software-om dobije dobar rezultat…
21


„Trip-Wire“ efekt
LES, Re = 50.000
Glatka kugla (lijevo) i kugla sa „žicom za spoticanje“ (desno)
Koeficijent otpora je tri puta manji sa
žicom nego kad je kugla glatka…
22

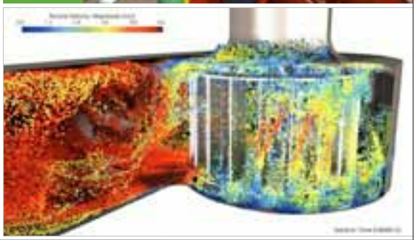

Rješavanje problema: Vibracije na brodu
Naizmjenično odvajanje vrtloga
oko koso nastrujavanog fiksnog
cilindra iz kojeg izlazi rotirajuća
osovina…
Presjek paralelno s zidom
Presjek paralelno s
osovinama
Ubacivanjem profila između trupa
broda i fiksnog cilindra (crveno)
su neželjene oscilacije
otklonjene…
Primjer:
Na “mega-jahti” (duga 145 m) sa 4
propelera dolazi do torzionih vibracija
pri brzinama od 16 - 18 čvorova. Nakon godinu dana
eksperimentisanja problem je riješen pomoću dvije
CFD-simulacije (što je koštalo 20.000 eura)…
23

Vizualizacija strujanja

Photo-realism

Virtual reality

Truly „Colorful Fluid Dynamics“



24

Zaključci

- CFD je sazrela za industrijsku primjenu i u mnogim oblastima je već zamijenila eksperimente.
- Uloga eksperimenata se postepeno mijenja u pravcu stavljanja na raspolaganje podataka za validaciju fizikalnih modela u simulacijama.
- CFD daje ne samo integralne veličine (sile, momente, prijenos topline…) već i uvid u detalje strujanja, što doprinosi boljem razumijevanju fizikalnih pojava (separacija toka, recirkulacija, sekundarno strujanje, mrtve zone itd.).
- U slučaju nužde analize pomoću CFD se mogu ubrzati (više ljudi, više računara → brže do rješenja problema ili do optimuma); kod eksperimenata to nije moguće.
- Na području CFD i male firme u malim državama mogu postići vrhunske rezultate…
- Razvoj računara pomaže širenju primjene CFD u svim oblastima…

25


Literatura
Joel H. Ferziger
Milovan Perić
Robert L. Street
Computational Methods for Fluid Dynamics
Fourth Edition
Springer
Joel H. Ferziger
Milovan Perić
Robert L. Street
Numerische Strömungsmechanik
2. Auflage
EXTRAS ONLINE
Springer
コンピュータによる
流体力学
COMPUTATIONAL METHODS FOR FLUID DYNAMICS
Computational Methods for Fluid Dynamics
26

DOI 10.21857/90836c24gy

Prezentacija predavanja

RAČUNALNA DINAMIKA FLUIDA - PRIMJENE U INŽENJERSTVU

Dr. sc. Inno Gatin
Insilico, Zagreb, Hrvatska

Inno Gatin

RAČUNALNA DINAMIKA FLUIDA – PRIMJENE U INŽENJERSTVU

Sažetak predavanja

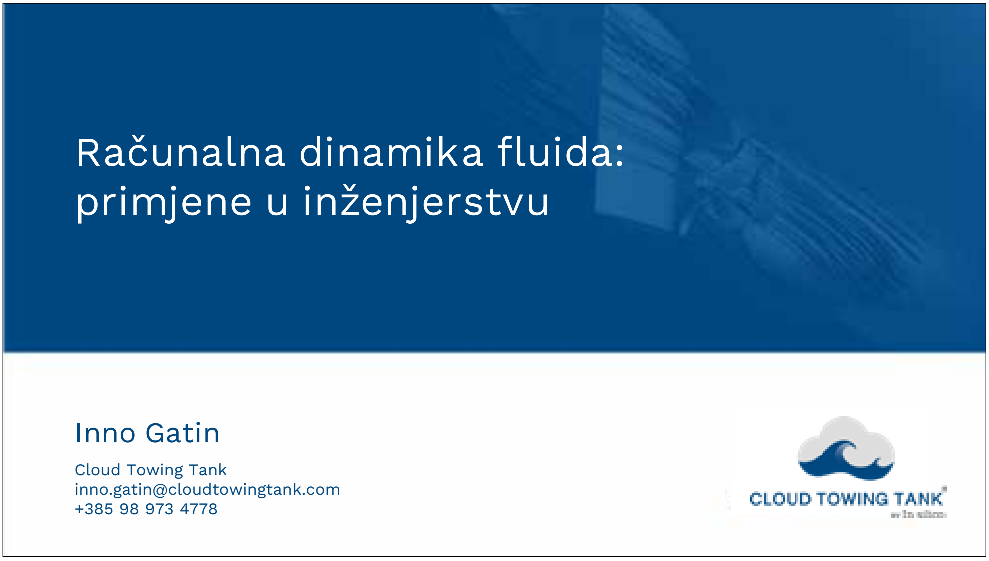
Računalna Dinamika Fluida (eng. „Computational Fluid Dynamics", CFD) je numerička metoda rješavanja parcijalnih diferencijalnih jednadžbi, koje su često nelinearne te međusobno spregnute. Najčešća primjena računalne dinamike fluida je na Navier-Stokesove jednadžbe koje opisuju općenito strujanje fluida. Računalna dinamika fluida se kao metoda danas koristi u raznim područjima, kao što su strojarstvo, brodogradnja, građevinarstvo, aeronautika, zrakoplovno inženjerstvo, meteorologija i medicina. U području strojarstva i brodogradnje se računalna dinamika fluida danas koristi na redovitoj razini, te je postala neizostavna metoda u postupku projektiranja kompleksnih strojeva i vozila. Glavni doprinos metode u projektnom procesu je mogućnost ispitivanja detaljnih karakteristika sustava prije izrade prototipa, i to bez visokih troškova eksperimentalnog ispitivanja. Često se metoda koristi kako za pripremu samih eksperimentalnih ispitivanja, smanjujući broj i opseg eksperimentalnih mjerenje. Dodatno, računalna dinamika fluida omogućuje da se dobije uvid u detalje rada raznih sustava koji eksperimentalnim metodama nije moguće dobiti. Kao rezultat korištenja računalne dinamike fluida, snižava se cijena i skraćuje vrijeme trajanja projektiranja te je često ishod proizvod koji je efikasniji. Tema predavanja je pregled primjene CFD u raznim inženjerskim granama, poput brodogradnje, auto-industrije, elektroničke opreme i slično. Pregled će obuhvaćati relevantne primjere iz pojedinih grana, uz kratak opis izazova i problema specifičnih za područje, te druge vezane zanimljivosti.

O predavaču

Inno Gatin diplomirao je na studiju brodogradnje na Fakultetu strojarstva i brodogradnje, Sveučilišta u Zagrebu 2015. godine, pri čemu je diplomski rad bio na temu razvoja metode za spregu računalne dinamike fluida i nelinearne potencijalne metode opisa morskih valova. Doktorirao je na temu numeričke hidrodinamike 2018.

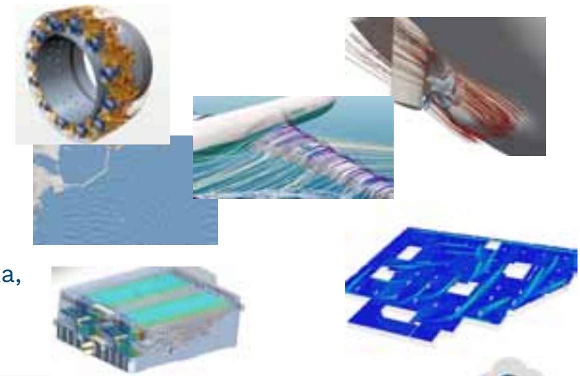
godine na Fakultetu strojarstva i brodogradnje, Sveučilište u Zagrebu, pri čemu se bavio razvojem i primjenom metode računalne dinamike fluida za proračune vezane za pomorstvenost plovnih objekata i udarna valna opterećenja. Sudjelovao je u razvoju softvera računalne dinamike fluida specijaliziranog za proračune vezane za brodograđevnu industriju pod nazivom „Naval Hydro Pack". Od 2018. do 2022. godine radio je kao post-doktorand, gdje nastavlja istraživanje vezano za morske valove, te provodi istraživanja vezana za otpor i propulziju broda, te upravljivost broda. Tijekom rada na Fakultetu sudjelovao je i u industrijskim komercijalnim projektima, baveći se problemima udara vala uz utjecaj stlačivosti zraka u zračnoj šupljini između vala i konstrukcije, kao i prilikom udara konstrukcije o slobodnu površinu (eng. „slamming"). Od 2022. godine se nastavlja baviti numeričkom brodskom hidrodinamikom u tvrtki „Cloud Towing Tank", čiji je su-osnivač, gdje se bavi provođenjem proračuna otpora, propulzije i pomorstvenosti brodova i drugih plovnih objekata u komercijalnim projektima, ali i daljnjim razvojem metode i istraživanjem, osobito na temu optimizacije brodske forme.

Bilt. Razreda teh. znan., god. 17: br. 1 (2024), str. 9-171



Grane inženjerstva u kojima se primjenjuje CFD

- Strojarstvo,
- Brodogradnja,
- Zrakoplovstvo,
- Građevinarstvo,
- Elektrotehnika i elektronika,
- Itd.



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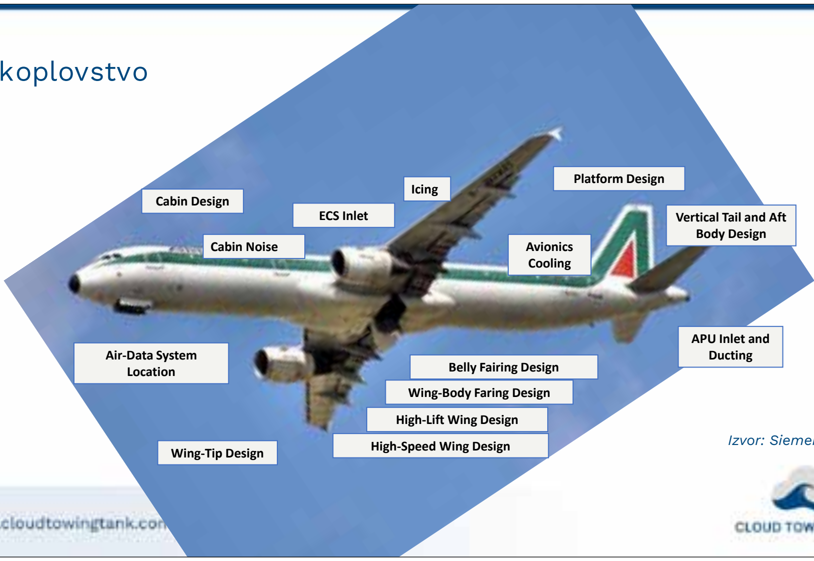
Zrakoplovstvo



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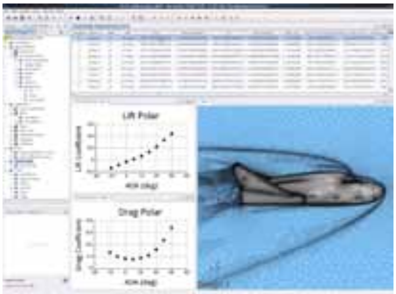
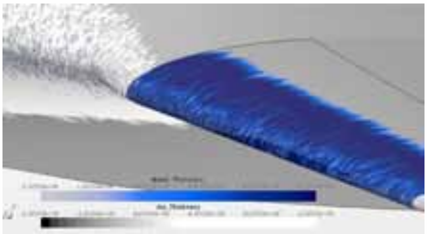
Zrakoplovstvo





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Zrakoplovstvo

Izvor: Siemens

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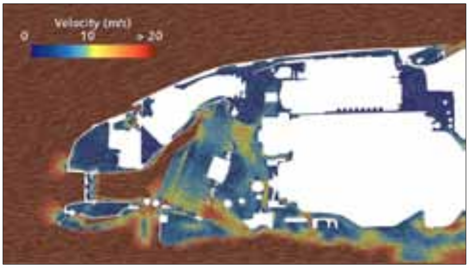
Strojarstvo

- Automobilska industrija



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Strojarstvo

- Automobilska industrija

Izvor: Siemens

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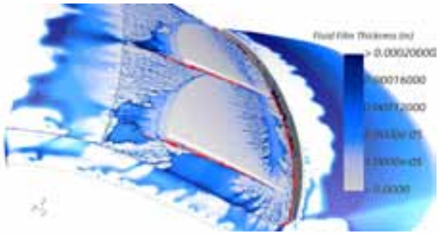
Strojarstvo

- Automobilska industrija



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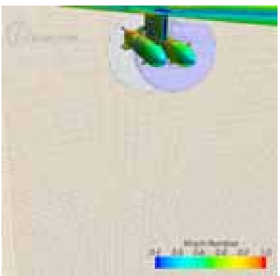
Strojarstvo

- Vojna industrija



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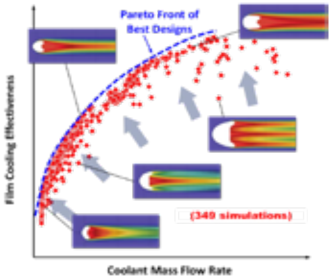
Strojarstvo

- Turbostrojevi



Izvor: Siemens

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Strojarstvo

- Motori s unutarnjim izgaranjem: dinamika spreja

Vukcevic, V., Keser, R., Jasak, H., Battistoni, M. et al., "Development of a CFD Solver for Primary Diesel Jet Atomization in FOAM-Extend," SAE Technical Paper 2019-24-0128, 2019

Time: 0.1 μs

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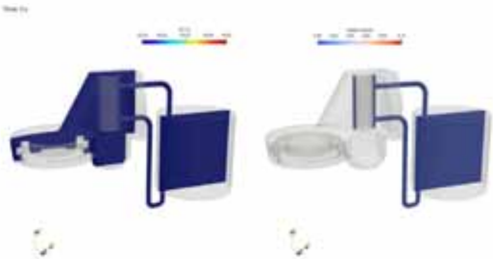
Strojarstvo

- Kućanski aparati



Izvor: Siemens

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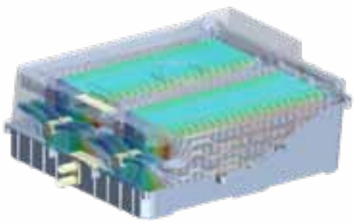
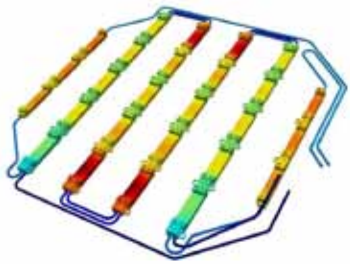


Izvor: Siemens



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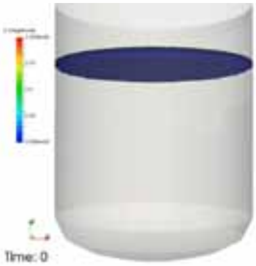

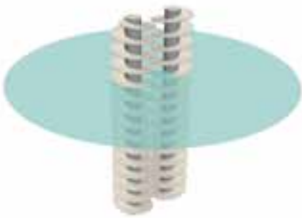

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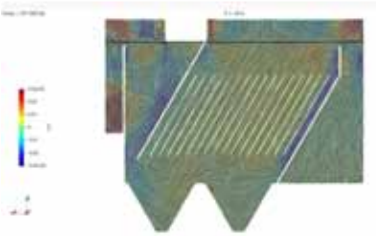

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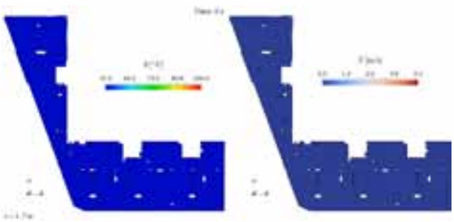
- Proračuni požara



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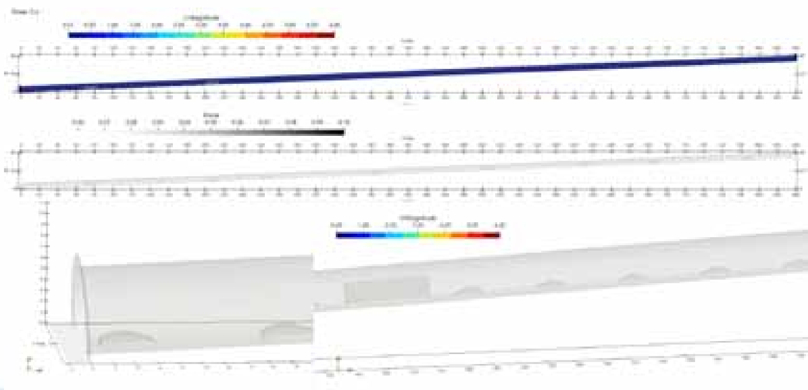
Građevinarstvo



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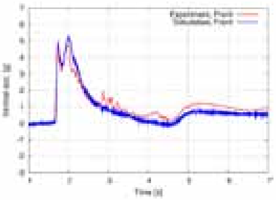
- Pučinska tehnika



H.J. Mørch, S. Enger, M. Perić, E. Schreck: Simulation of lifeboat launching under storm conditions, Proc. 6th Int. Conf. on CFD in Oil & Gas, Metalurgical and Process Industries, SINTEF/NTNU, Trondheim, Norway, June 10-12, 2008.

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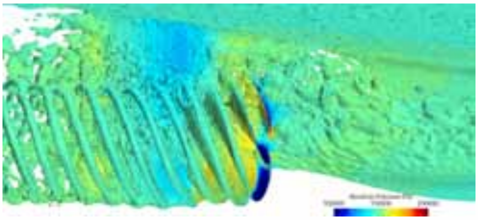
Brodogradnja

- Propulzija broda



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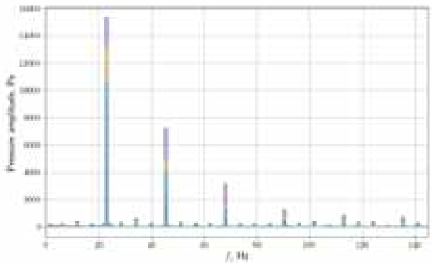
Brodogradnja

- Propulzija broda i tlačna uzbuda



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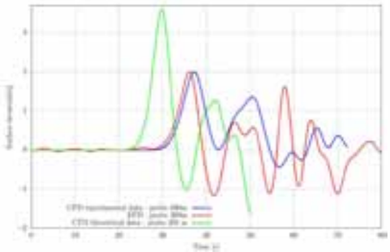

Senjanović, Ivo; Katavić, Josip; Vukčević, Vuko; Vladimir, Nikola; Jasak, Hrvoje
Launching of ships from horizontal berth by tipping tables – CFD simulation of wave generation //
Engineering Structures, 210 (2020), 110343, 10 doi:10.1016/j.engstruct.2020.110343

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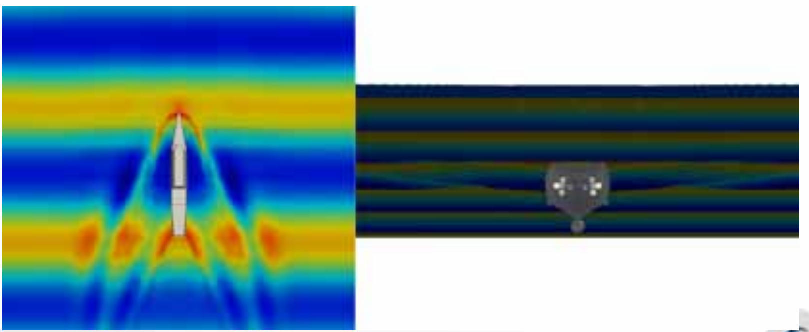
- Upravljivost



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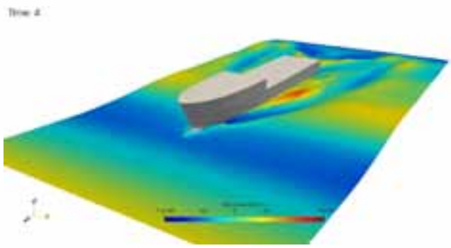
Brodogradnja

- Pomorstvenost



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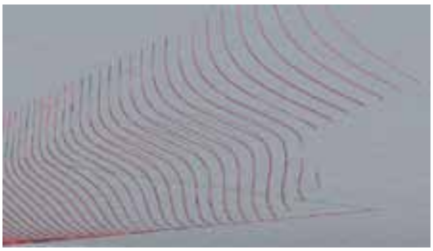
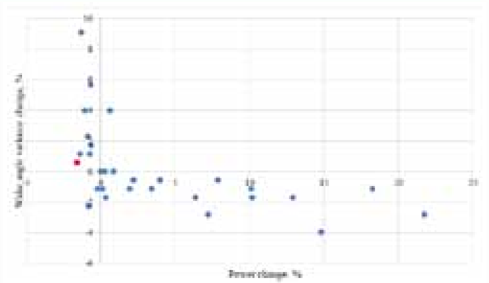
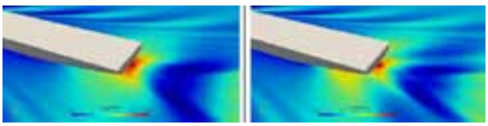
Brodogradnja

- Optimizacija trupa







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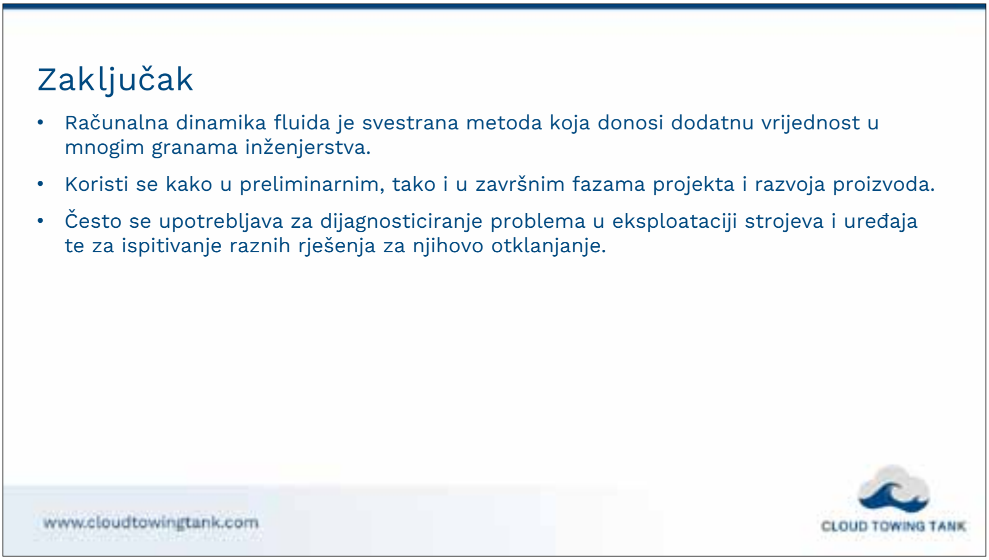
Zaključak
• Računalna dinamika fluida je svestrana metoda koja donosi dodatnu vrijednost u mnogim granama inženjerstva.
• Koristi se kako u preliminarnim, tako i u završnim fazama projekta i razvoja proizvoda.
• Često se upotrebljava za dijagnosticiranje problema u eksploataciji strojeva i uređaja te za ispitivanje raznih rješenja za njihovo otklanjanje.
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DOI 10.21857/m8vqrt3j19

Prezentacija predavanja

NUMERIČKE METODE U ANALIZI UDARNIH OŠTEĆENJA ZRAKOPLOVNIH KONSTRUKCIJA

Prof. dr. sc. Ivica Smojver
Fakultet strojarstva i brodogradnje Sveučilišta u Zagrebu

Ivica Smojver

NUMERIČKE METODE U ANALIZI UDARNIH OŠTEĆENJA ZRAKOPLOVNIH KONSTRUKCIJA

Sažetak predavanja

Rad predstavlja pregled 30-godišnjih istraživanja u području numeričke analize kompozitnih konstrukcija, posebice zrakoplovnih, u okviru AeroDamage.Lab na Fakultetu strojarstva i brodogradnje Sveučilišta u Zagrebu. Početkom 1990-ih započet je rad na numeričkom modeliranju kompozitnih konstrukcija razvojem ljuskastog konačnog elementa s 9 čvorova primjenjivog u analizi višeslojnih kompozita, pri čemu je razvijen MATLAB program. U sljedećoj fazi istraživanja proveden je razvoj numeričkih algoritama za analizu raslojavanja pri udaru kompozitnih ploča udaračima male brzine/mase. To dovodi do jedva vidljivih vanjskih oštećenja (BVID) te je veza između pojave pukotina u matrici i međuslojnih raslojavanja primijenjena u razvoju odgovarajućih algoritama. Udari u kompozitne konstrukcije predstavljaju poseban problem zbog inherentne osjetljivosti krhkog materijala pri takvoj vrsti opterećenja. Stoga je za simulaciju oštećenja pri udaru korišten u početnom periodu istraživanja Abaqusov ugrađeni model inicijacije i propagacije oštećenja. U ovom modelu koristi se Hashinov kriterij popuštanja kao kriterij inicijacije oštećenja. Nakon toga, oštećenje u kompozitu je modelirano korištenjem principa *Continuum Damage Mechanics*. Kako bi se dodatno povećala pouzdanost numeričkog modeliranja oštećenja u kompozitnim konstrukcijama, unutar istraživačke skupine AeroDamage.Lab razvijen je višerazinski pristup. Takav pristup povezuje računalno vrlo učinkovit poluanalitički mikromehanički model *High Fidelity Generalized Method of Cells (HFGMC)* i Abaqus/Explicit solvera za simulacije na razini čitave konstrukcije. Trenutni fokus istraživanja je na modeliranju samozacjeljujućih polimernih kompozita, budući da su dokazali svoju primjenjivost u kompozitnim konstrukcijama tako što mogu samozacijeliti oštećenja matrice kao i delaminacije. Razvijen je konstitutivni model koji je numerički verificiran LVI, HVI, DCB i 3PB testovima.

O predavaču

Prof. Ivica Smojver djeluje na Zavodu za zrakoplovno inženjerstvo Fakulteta strojarstva i brodogradnje Sveučilišta u Zagrebu. Prije toga radio je na Zavodu za tehničku mehaniku istog fakulteta kao i Tehničkoj vojnoj akademiji u Zagrebu, Katedra raketne tehnike. U razdoblju od 2004. – 2018. bio je voditelj Katedre za aerodinamiku te Katedre za zrakoplovne konstrukcije. Voditelj je Projektnog laboratorija za numeričko modeliranje oštećenja u zrakoplovnim konstrukcijama od 2009. (AeroDamage.Lab). Znanstveni interesi uključuju primjenu metode konačnih elemenata u analizi kompozitnih zrakoplovnih konstrukcija; analizu ponašanja zrakoplovnih konstrukcija pri udarnim opterećenjima; primjenu višerazinskih metoda u analizi pojave oštećenja u kompozitnim konstrukcijama; numeričko modeliranje kao i samoobnavljajuće kompozitne konstrukcije. Prof. Smojver podučava predmete u području avionskih konstrukcija te mehanike kompozitnih zrakoplovnih konstrukcija na studijima zrakoplovstva i strojarstva na FSB-u, kao i predmete iz područja raketne tehnike na Sveučilišnom vojnom studiju. Kao voditelj brojnih projekata ima više od 60 radova u referentnim publikacijama i zbornicima radova, te je imao pozvana predavanja, među ostalim institucijama i u NASA Glenn Laboratory, Airbus, Bombardier, TsAGI (Rusija) INCAS (Rumunjska) i dr. Od 2018. obnaša dužnost voditelja Preddiplomskog vojnog studija Vojno inženjerstvo Sveučilišta u Zagrebu. Među ostalim članstvima, prof. Smojver je *Senior Member* u *American Institute of Aeronautics and Astronautics* (AIAA), član *European Association of Computational Mechanics*, predstavnik Hrvatske u *Programskom odboru za transport Obzora 2020 te Obzora Europe*. 4 godine je obnašao dužnost supredsjedatelja u *Advisory Council for Aeronautical Research and Innovation in Europe - Member States Group (ACARE – MSG)* te je bio predstavnik RH u *Clean Sky 2 States Representatives Group*. Član je *Materials Technical Committee* u *American Institute of Aeronautics and Astronautics* od 2022.

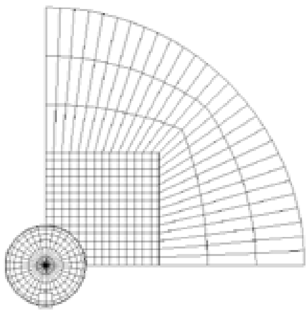

SUVREMENE METODE U PROJEKTIRANJU I ANALIZI INŽENJERSKIH KONSTRUKCIJA
HAZU, Zagreb, 20.10.2023.
HDM
FSB
100
Numeričke metode u analizi udarnih oštećenja zrakoplovnih konstrukcija
Ivica Smojver
Fakultet strojarstva i brodogradnje Sveučilišta u Zagrebu,
Zavod za zrakoplovno inženjerstvo
Projektni laboratorij za numeričko modeliranje oštećenja
zrakoplovnim konstrukcijama - AeroDamageLab
1

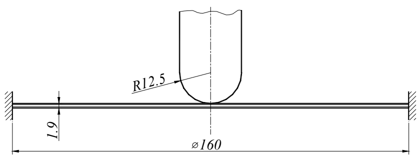
Contents

2

Impact damage in composite plates – matrix cracks and delaminations

- geometry of the impactor and the clamped circular glass/epoxy plate





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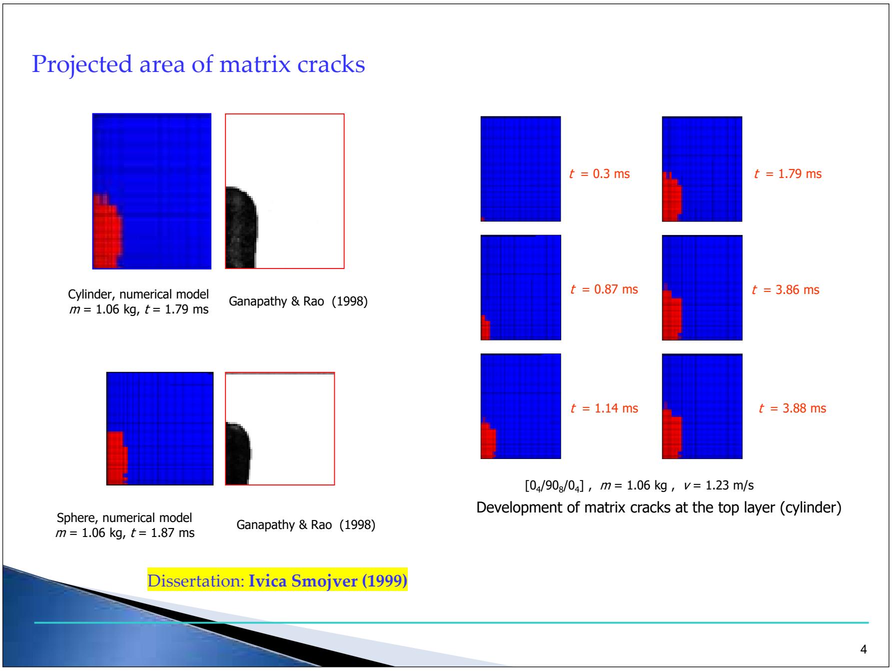
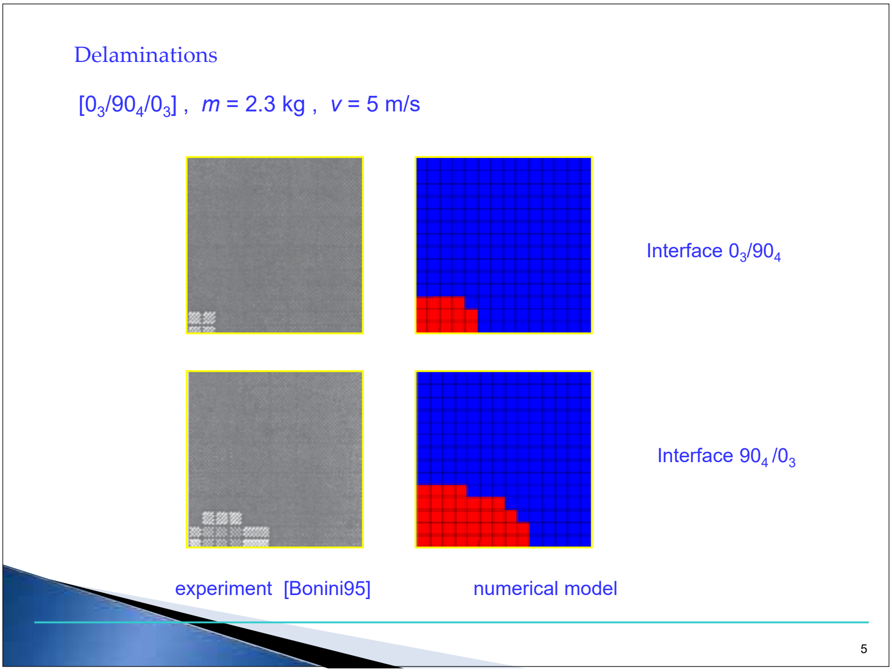
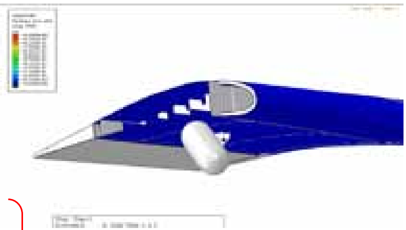

Projected area of matrix cracks
Cylinder, numerical model
m = 1.06 kg, t = 1.79 ms
Ganapathy & Rao (1998)
Sphere, numerical model
m = 1.06 kg, t = 1.87 ms
Ganapathy & Rao (1998)
t = 0.3 ms
t = 1.79 ms
t = 0.87 ms
t = 3.86 ms
t = 1.14 ms
t = 3.88 ms
[0_4/90_8/0_4] , m = 1.06 kg , v = 1.23 m/s
Development of matrix cracks at the top layer (cylinder)
Dissertation: Ivica Smojver (1999)
4


Delaminations
[0_3/90_4/0_3] , m = 2.3 kg , v = 5 m/s
Interface 0_3/90_4
Interface 90_4 /0_3
experiment [Bonini95]
numerical model
5

Application of numerical methods in high strain-rate problems

- Examples:
  - High velocity impact
  - Crashworthiness applications
  - Ballistic perforation



Simulation: Outboard Flap penetration

- Problems:
  - **Extreme material deformations**
  - Excessive FE distortion
  - Complex contact conditions
  - **Strain-rate dependent constitutive models**
  - **Failure and damage models**

} Reliable numerical solutions

- **AeroDamageLab** – established in 2009 within the Technology project TP-07/0120-30 „Numerical Modelling of Damage in Aeronautical Structures"

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Example: Bird strike simulation

- **major threat to aircraft safety**

Statistical distribution of impact damage

Outboard Flap penetration – Airbus A319/320

- **Numerical solution:**
  - finite element method
  - nonlinear explicit transient dynamic analysis (Abaqus/Explicit)
  - very detailed finite element models
  - multiple failure and damage models

}
- Lagrangian model
- Coupled Eulerian Lagarangian CEL
- Smoothed Particle Hydrodynamics SPH

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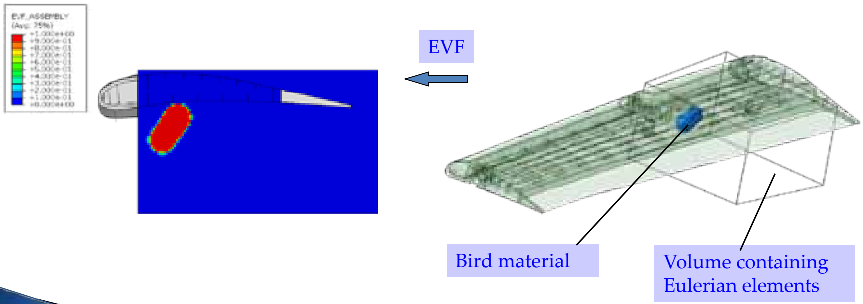
Coupled Eulerian Lagrangian bird model

- Modeling of fluids and solids that undergo extreme deformation
- Multi material finite element formulation – Eulerian Volume Fractions (EVF)
- General contact is used to couple the Eulerian and Lagrangian models
- Eulerian finite element model – EC3D8R elements



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Importance of Bird material: Accurate modelling of impact forces

- bird strike - soft body impact
- hydrodynamic modelling of bird replacements – EOS materials
- Hugoniot pressure: $p_H = \rho_0 U_s(U_0)U_0$
- stagnation pressure: $p = \frac{1}{2}\rho_0 U_0^2$

ρ_0 - initial density
U_0 – impact velocity
U_s – shock velocity

- linear Mie-Grüneisen (Us-Up) equation of state :

$$U_s = c_0 + sU_p$$

- linear relation between shock and particle speeds

c_0 – speed of sound
s – material constant

$$p = \frac{\rho_0 c_0^2 \eta}{(1-s\eta)^2}\left(1 - \frac{\Gamma_0 \eta}{2}\right) + \Gamma_0 \rho_0 E_m$$

- pressure to density relation

$\eta = 1 - \rho_0/\rho$ - nominal volumetric compressive strain

Γ_0 - material constant – “Grüneisen gamma”

E_m – internal energy per unit mass

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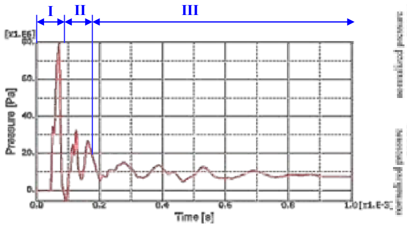
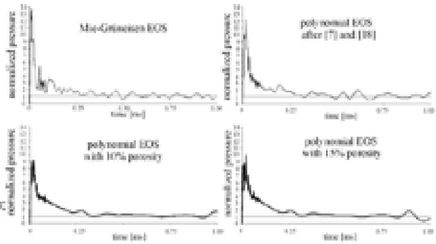
Bird modeling:
- cylinder with hemispherical ends
- length to diameter ratio equal to 2
- bird material density = 938 kg/m^3

Material model validation:



Pressure time history at the impact location



I Shock wave stage (Hugoniot pressure)

II Pressure release stage

III Stagnation pressure stage

- VUMAT EOS material
- modelling of porosity effects
- more realistic modelling of impact pressures

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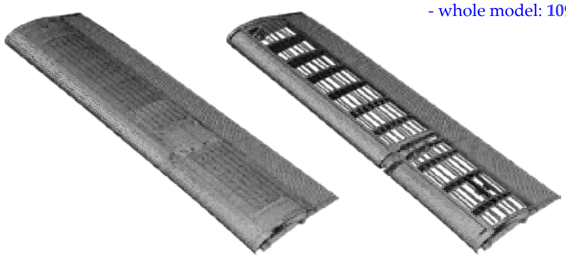
Finite element model



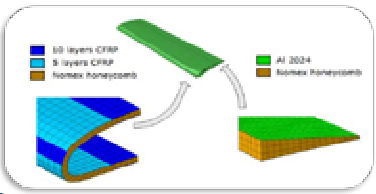
- whole model: **109585** elements

69696 conventional shell (S4R & S3R)

16020 continuum shell (SC8R)

23665 solid elements (C3D8R)

204 beam elements (B31)



- CFRP skin, gradually variable skin thickness (14 - 41 layers)
- Typical layup: $[45/0/-45/90/-45/0/45]_S$
- layer thickness: 0.125 mm (1.75 - 5.125 mm)
- spars and ribs made of Aluminum alloy
- leading and trailing edge sandwich structures
- kinematic constraints: SC8R & S4R elements

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Structural damage modeling

Composite materials:

- Hashin’s damage initiation criterion
- 4 failure modes:
  1. fibre rupture in tension
  2. fibre buckling and kinking in compression
  3. matrix cracking under transverse tension and shearing
  4. matrix crushing under transverse compression and shearing

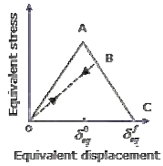
- Degradation of material stiffness – damage parameters

$$\mathbf{C_d} = \frac{1}{D}\begin{bmatrix} (1-d_f)E_1 & (1-d_f)(1-d_m)\nu_{21}E_1 & 0 \\ (1-d_f)(1-d_m)\nu_{12}E_2 & (1-d_m)E_2 & 0 \\ 0 & 0 & (1-d_s)G_{12}D \end{bmatrix}$$

$$D = 1-(1-d_f)(1-d_m)\nu_{12}\nu_{21}$$

$E_1, E_2, G_{12}, \nu_{12}, \nu_{21}$ – unidirectional CFRP ply properties

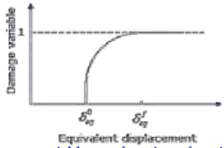
d_f – fibre damage parameter
d_m – matrix damage parameter
d_s – shear damage



Equivalent stress-displacement diagram

- Damage evolution: parameter of a particular failure mode evolves as

$$d = \frac{\delta_{eq}^f(\delta_{eq}-\delta_{eq}^0)}{\delta_{eq}(\delta_{eq}^f-\delta_{eq}^0)}$$



Damage variable as a function of equivalent displacement

Aluminium alloys (Al 2024 & Al 7075):

- Elastoplastic material model
- Shear failure criterion:

$$\bar{\varepsilon}^{pl} = \bar{\varepsilon}_0^{pl} + \int_0^t \sqrt{\frac{2}{3}\dot{\varepsilon}^{pl}:\dot{\varepsilon}^{pl}}\,dt$$

– damage parameter: $$\omega = \frac{\bar{\varepsilon}_0^{pl} + \sum \Delta\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_f^{pl}}$$

– suitable for high strain rate dynamic problems

$\bar{\varepsilon}_0^{pl}$ - initial value of equivalent plastic strain

$\dot{\varepsilon}^{pl}$ - the equivalent plastic strain rate

$\bar{\varepsilon}_f^{pl}$ - strain at failure

$\Delta\bar{\varepsilon}^{pl}$ - plastic strain increment

- Cowper-Symonds strain rate dependent model (VUMAT)

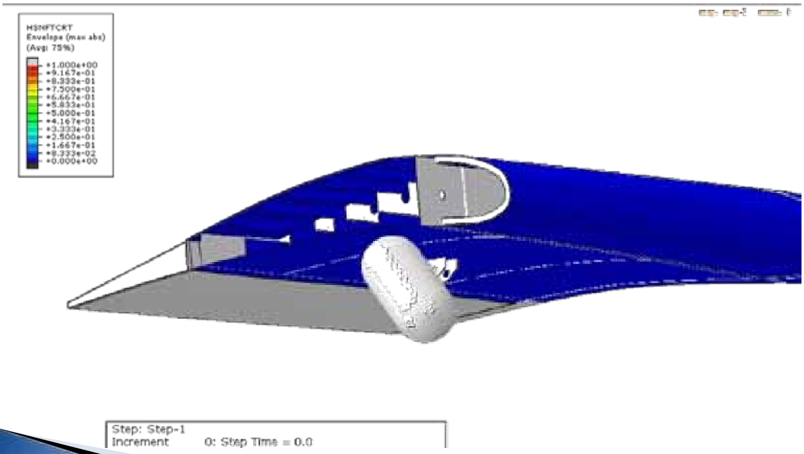
$$\sigma(\varepsilon,\dot{\varepsilon}) = \left[a + b(\varepsilon^{pl})^n\right]\left[1+\left(\frac{\dot{\varepsilon}}{D}\right)^{1/p}\right]$$

a,b [MPa], D [s^{-1}], p,n [–] - material parameters for CS model (yield stress)

Results – bird impact in flap structure

Hashin's fiber tensile failure criterion (cross – sectional view)

m = 1.81kg (mass of the bird)
t = 5 ms (impact duration)
v = 100 m/s (impact velocity)
EVF = 0.5



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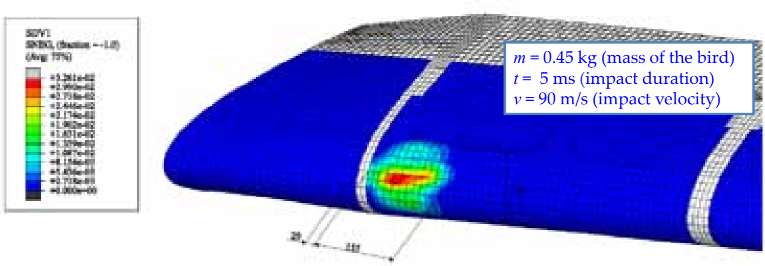
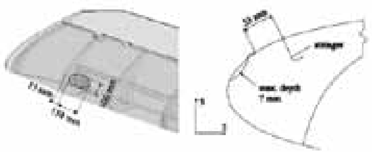
Results – bird impact in metallic slat structure

Equivalent plastic strain [-]

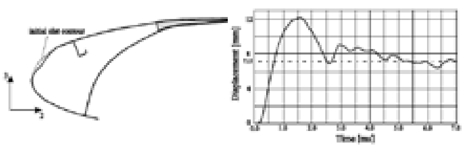


m = 0.45 kg (mass of the bird)
t = 5 ms (impact duration)
v = 90 m/s (impact velocity)

Example of real impact damage on slat structure:



Visual inspection



Numerical results

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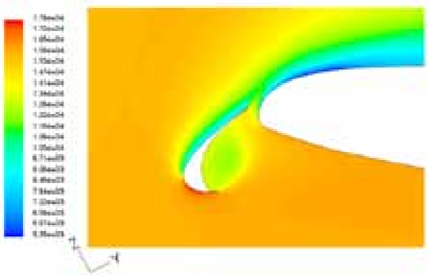
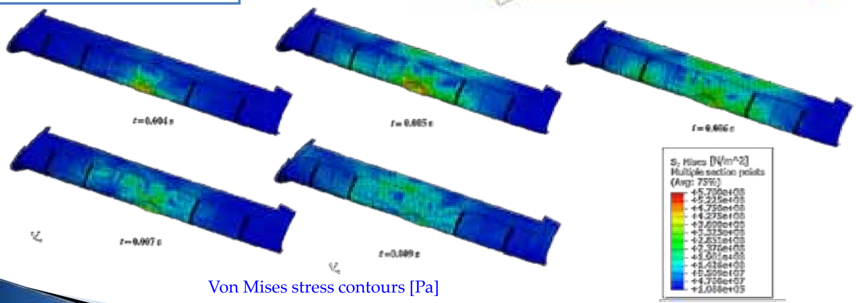
- aerodynamic and birdstrike loading
- CFD analysis and VDLOAD subroutine



Total pressure distribution at 15°AOA and full slat deflection (27°) [Pa]

m = 1.81 kg (mass of the bird)
t = 5 ms (impact duration)
v = 100 m/s (impact velocity)



Von Mises stress contours [Pa]

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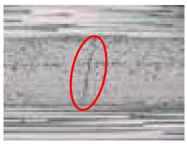
Multiscale Analyses of Composite Structures

Problem:

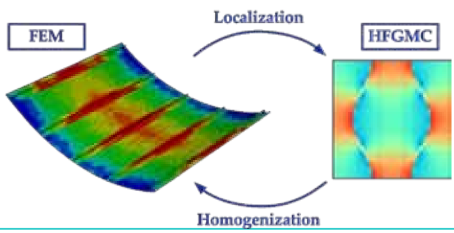
Numerical modelling of failure and damage of laminated composite structures:

- failure modes of composite materials are closely related to the material microstructure
- analyses on the constituent level using micromechanical principles
- modelling of damage effects on the micro-level
- in order to solve engineering problems analyses have to be performed on two length scales



Solution:

- High Fidelity Generalized Method of Cells (HFGMC)
- Abaqus/Explicit
- multiscale approach



Dissertation: Darko Ivančević (2015)

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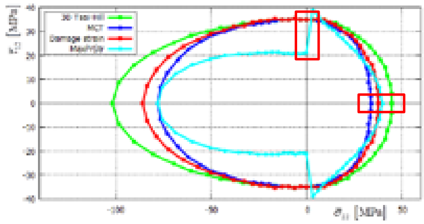
$\bar{\sigma}_{22} - \bar{\tau}_{12}$ loading:

Table: Comparison of damage initiation stresses [MPa]

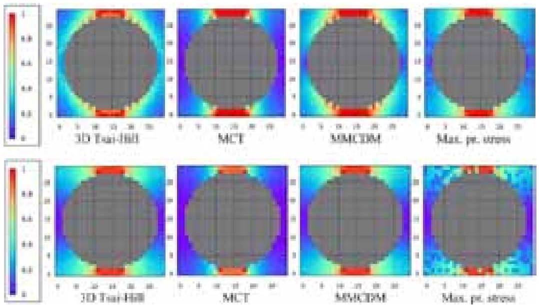
	3D Tsai-Hill	MCT	MMCDM	Max. principal stress
$+\bar{\sigma}_{22}$	44.4	32.7	37.2	50.4
$-\bar{\sigma}_{22}$	-100.4	-77.2	-95.1	-77.2
$\bar{\tau}_{12}$	34.8	34.8	34.8	30.1



RUC distribution:

transverse tensile loading:

in-plane shear loading:



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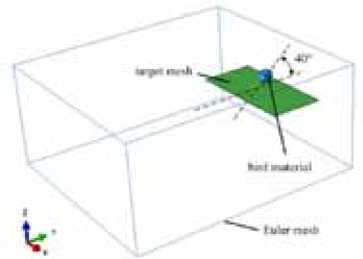
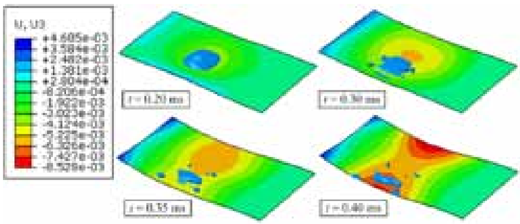
Multiscale soft-body impact analyses:

- Coupled Eulerian Lagrangian (CEL) formulation
- micromechanical damage models
- example: Composite plate: GFRP and CFRP @ [(0/90)5/ $\bar{0}$]$_S$ layup (860 shell FE)
- impactor: m = 10 g, d = 25 mm
- CEL model: 487920 Eulerian elements (0.45 x 0.4 x 0.2 m)
- 30 x 30 HFGMC model



Visualisation of impact event, displacements in z direction [mm]:

(CFRP plate, 200 m/s impact, MMCDM model)



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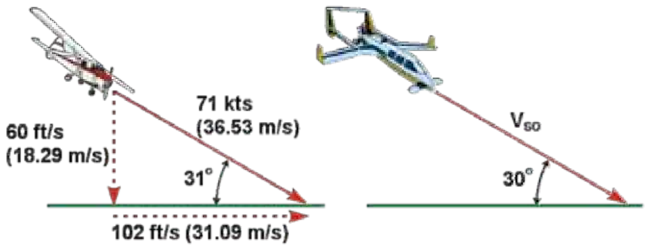
Crashworthiness Applications

Crashworthiness analysis of a small aircraft fuselage structure

- **AGATE requirements** (Advanced General Aviation Transport Experiments)
- Taking into account the influence of the whole structure, stalling speed and type of impacted surface



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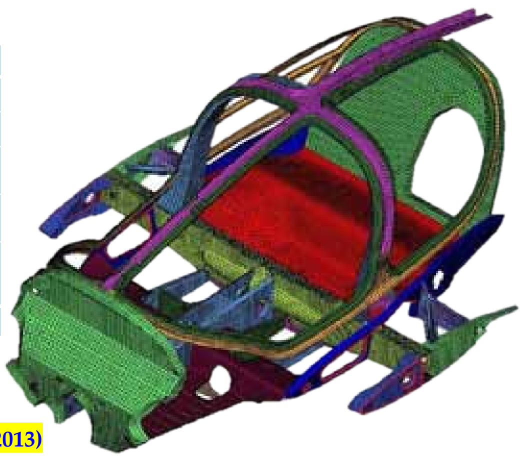
Analysis

- Final model

Total number of elements	41354
Total number of nodes	55195
Beam elements	344
4-noded shell elements	39378
3-noded shell elements	1632
Total number of shell elements	41010
Number of 3D elements	0



MEng Thesis: **Kristina Šarović (2013)**

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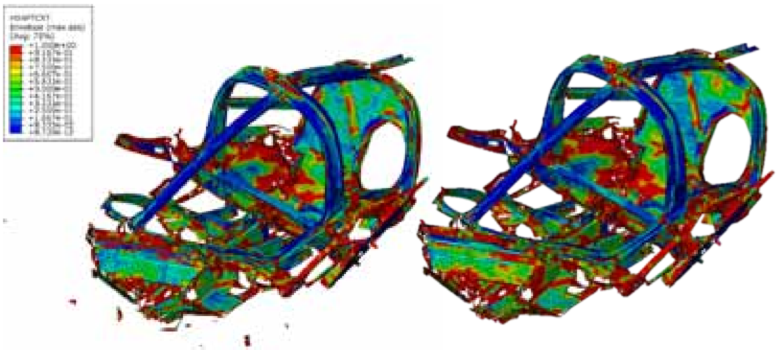
Results

- Values of Hashin failure index (max. value through layers)



Fiber tensile stresses   Fiber compressive stresses

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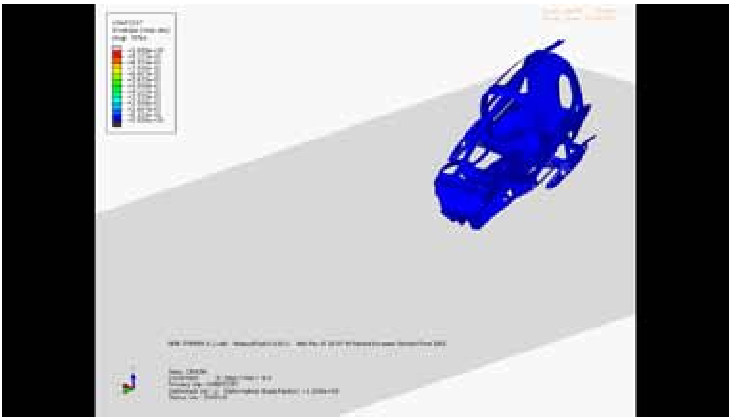
- Hashin compressive fibre failure criterion

t = 0.3 s (impact duration)
v = 30.3 m/s (impact velocity)
α= 30° (impact angle)



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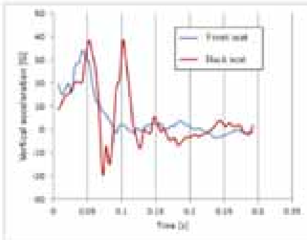
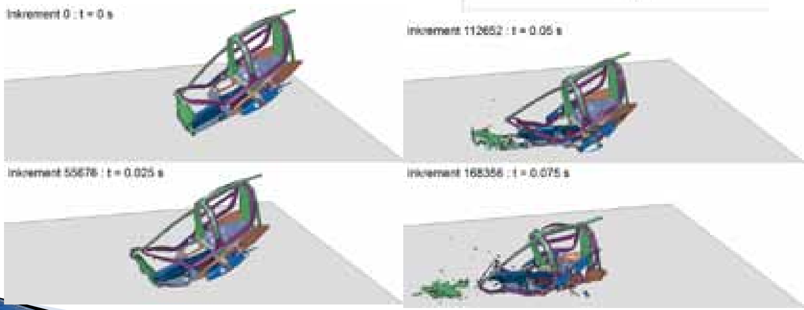
- Results of analysis with MPC connecting engine as concentrated mass

vertical acceleration at the passenger locations:





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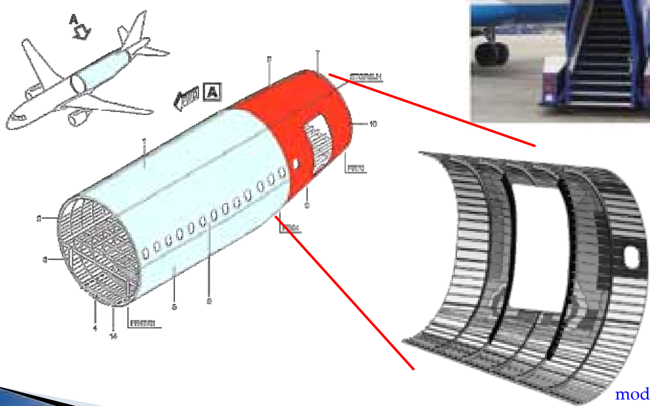
Low-Velocity Impact Loading Analyses

Applications:

- ground equipment impact damage on fuselage structure



modelled structure

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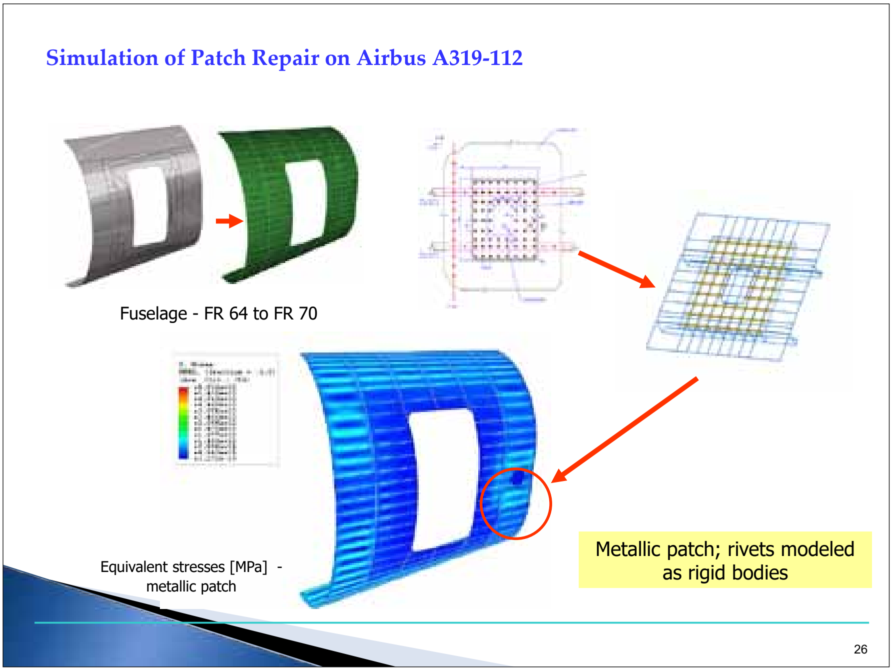
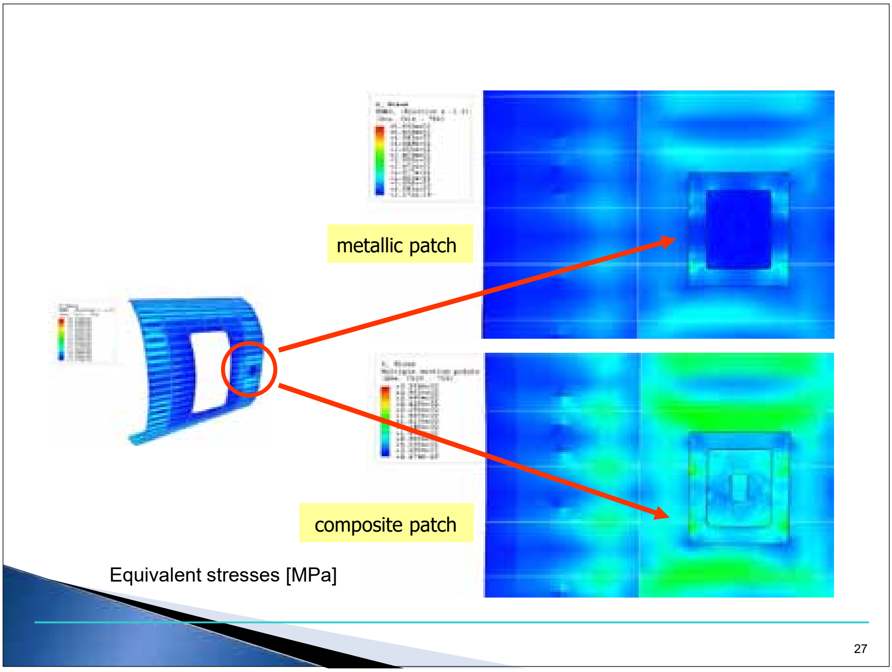
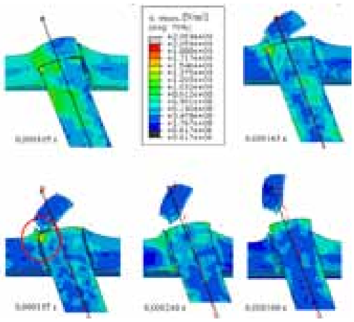

Simulation of Patch Repair on Airbus A319-112
Fuselage - FR 64 to FR 70
Equivalent stresses [MPa] - metallic patch
Metallic patch; rivets modeled as rigid bodies
26


metallic patch
composite patch
Equivalent stresses [MPa]
27

High-Velocity Impact Loading Analyses

Applications:

- numerical simulation of impact on armour plates
- high-velocity perforation phenomena



Impact - 330 m/s @ 20deg angle

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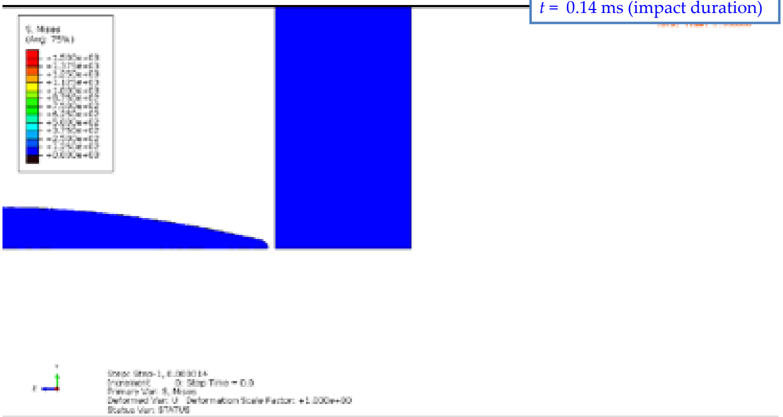
Impact of a realistic 12.7 mm anti-aircraft ammunition - Von Mises stress distribution in [MPa]

t_p = 20 mm (plate thickness)
v = 903 m/s (impact velocity)
t = 0.14 ms (impact duration)



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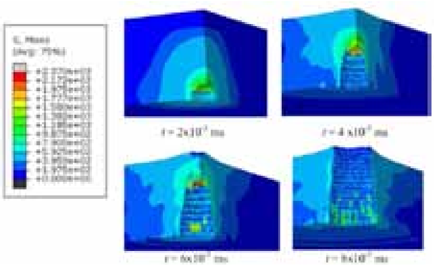
Effect of design parameters on perforation resistance:

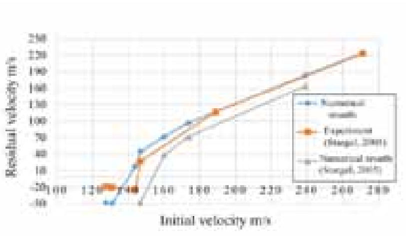
- material
- aircraft skin thickness
- curvature

t_p = 10 mm (plate thickness)
v = 903 m/s (impact velocity)



Von Mises stress [MPa] distribution

t_p = 2.03 mm (plate thickness)
R = 111.6 mm (curvature radius)



ballistic curves

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Modelling of advanced composites: ACCESS project

- **ACCESS: AdvanCed CompositE Selfhealing Simulation**
- funded by the Croation Science Foundation
- project duration: **10/2018 – 10/2022**
- objective: development of a numerical methodology for modelling of advanced composite structures with self-healing capabilities
- **intrinsic self-healing capability** - Surlyn copolymer
- numerical methodology for self-healing composites will be based on multiscale concepts, since the failure modes of composite structures appear at different length scales

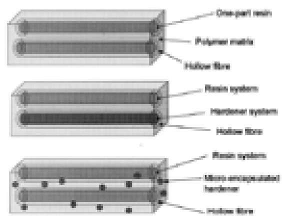

Figure: Schematic of self-healing composite materials [Bleay2001]

S.M. Bleay, L. Humberstone: Mechanical and electrical assessment of hybrid composites containing hollow glass reinforcement, Composites Science and Technology 59 (9), 1321-1329 (1999)

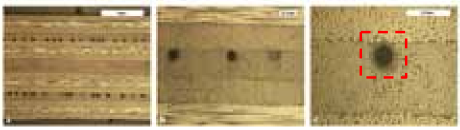

Figure: Application of Hollow Glass Fibres in CFRP composites [Williams2007]

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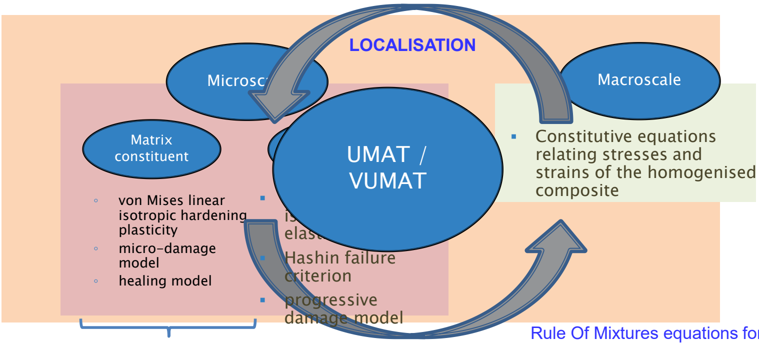
Constitutive model description

Voigt (iso-strain) and Reuss (iso-stress) approximations



validated in (Smojver et al., 2022a)

HOMOGENISATION

Rule Of Mixtures equations for calculation of homogenised composite properties

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Constitutive model description

- Matrix constituent at the microscale

- Micro-damage-healing model, after (Darabi et al. 2012)

$$\dot{\phi} = \Gamma^{vd}\left(\frac{\bar{\bar{Y}}}{Y_{th}}\right)^{q}(1-\phi)^{2}\cdot e^{k\cdot\bar{\varepsilon}_{eff}}$$

$$\dot{h} = \Gamma^{h}(1-h)^{m}(1-\phi)^{m}$$

$$\phi_{eff} = \phi(1-h)$$

$\phi, \dot{\phi}$ – damage variable; damage rate

Γ^{vd} – damage viscosity parameter, 1/s

$\bar{\bar{Y}}$ – damage driving force, Pa

Y_{th} – threshold damage force, Pa

q, k – damage model parameters

$\bar{\varepsilon}_{eff}$ – effective (equivalent) strain

$h, \dot{h}$ –healing variable; healing rate

Γ^{h} – healing viscosity parameter, 1/s

m – healing model parameter

ϕ_{eff} – effective damage variable

- Plasticity model
  - Von Mises linear isotropic hardening plasticity

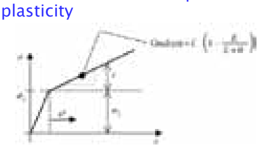

Fig. 3: Stress-strain diagram for linear strain hardening

$$\sigma_y = \sigma_{y0} + r(\varepsilon^p)$$

$$r(p) = \int H \cdot d\varepsilon^p$$

Dissertation: **Dominik Brezetić (2023)**

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Constitutive model description

- Reinforcing fibres at the micro scale
  - Hashin failure criterion + progressive damage model

$$\phi_f^t = \frac{\delta_{eq}^f \left(\delta_{eq}^{T/C} - \delta_{eq}^0\right)}{\delta_{eq}^{T/C}\left(\delta_{eq}^f - \delta_{eq}^0\right)}$$

δ_{eq}^0 initial equivalent displacement;

δ_{eq}^f equivalent displacement at which the material has failed;

$\delta_{eq}^{T/C}$ current equivalent displacement for the case of tension or compression

- Homogenisation

$$E_{11} = E_{11}^f V^f + E^m (1 - V^f)$$

$$\frac{1}{E_{22}} = \frac{V^f}{E_{22}^f} + \frac{1 - V^f}{E^m}$$

$$\nu_{12} = \nu_{12}^f V^f + \nu^m (1 - V^f)$$

$$\frac{1}{G_{12}} = \frac{V^f}{G_{12}^f} + \frac{(1 - V^f)}{G^m}$$

- Localisation
  - Voigt (iso-strain) assumption

$$d\varepsilon_{11}^m = d\varepsilon_{11}^f = d\varepsilon_{11}$$

  - Reuss (iso-stress) assumption

$$(1 - V^f) \cdot d\varepsilon_{ii}^m + V^f \cdot d\varepsilon_{ii}^f = d\varepsilon_{ii}, \text{where } i = 2{,}3;$$

$$(1 - V^f) \cdot d\gamma_{ij}^m + V^f \cdot d\gamma_{ij}^f = d\gamma_{ij}, \text{where } i,j = 1,2,3.$$

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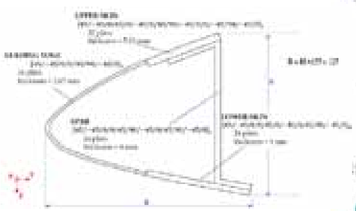
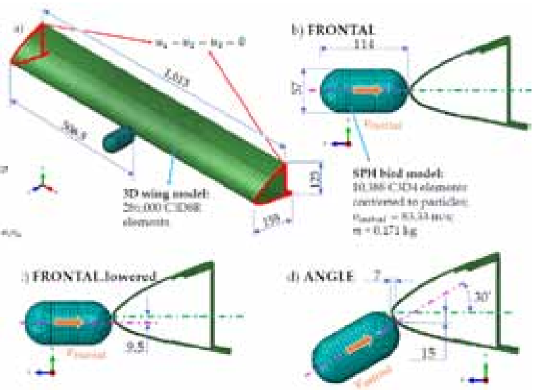
Composite aircraft wing bird strike

- EponTM 828EL + PCL
  +
- UD T700 carbon fibre



Schematic representation of composite aircraft wing structure with layup sequences, thicknesses and the main material coordinate system.



Abaqus model of the bird impact experiment with composite wing structure and SPH bird model, for three different initial configurations, dimensions in mm.

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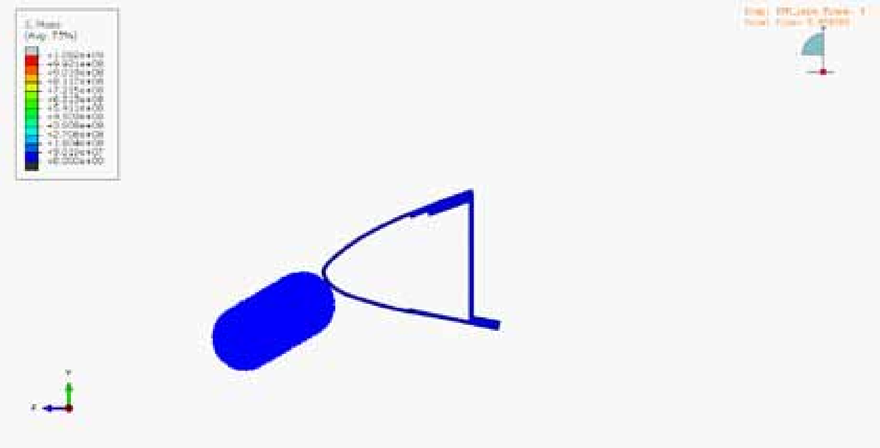

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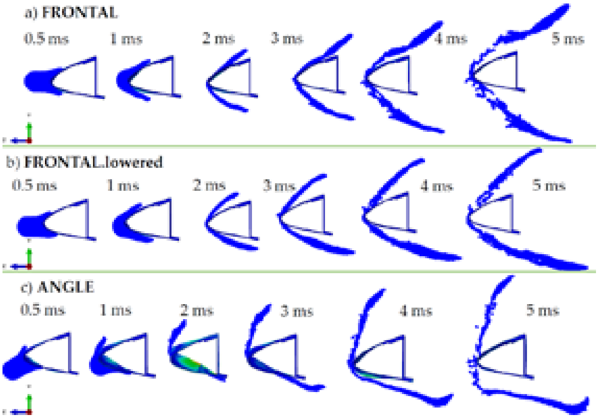

A time-lapse of the bird impact experiment starting from 0.5 ms to the end of the analysis, 5 ms.

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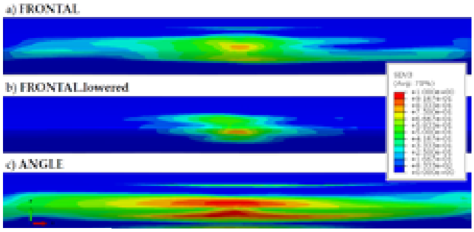
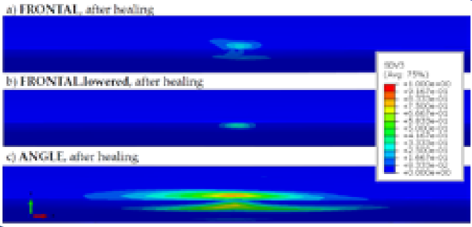
Distribution of the **effective matrix damage variable** in the wing structure **before the healing** process, first outer ply (45˚), front view.





Distribution of the **effective matrix damage variable** in the wing structure **after the healing** process, first outer ply (45˚), front view.

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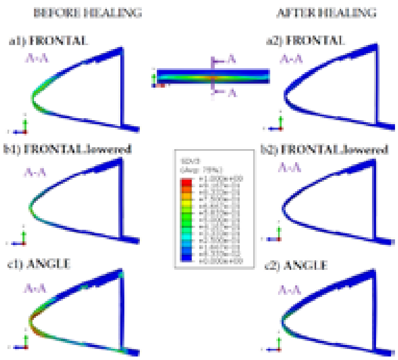
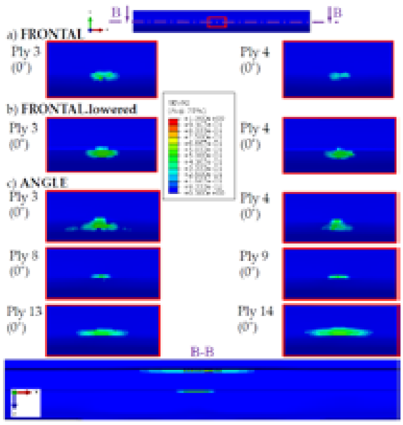


Distribution of the **effective matrix damage variable** in the wing structure **before** and **after the healing** process; a cross-section view.



Distribution of **compressive fibre damage** in the wing structure for each impact case, and a longitudinal section view showing fibre damage in regions with geometry discontinuities (change of thickness), and the element deletion in the joint of the spar and the lower skin.

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Conclusions

- importance of accurate impactor modeling
  - impactor material behavior
  - numerical impactor model (CEL or SPH)
- realistic simulation of the structural behavior of aeronautical structures:
  - detailed finite element models
  - complex failure models
- wide range of problems: various impact velocities, material behavior and overall numerical approaches
- common elements: complex contact conditions
  - nonlinear and anisotropic material behavior
  - complex damage and failure models
- numerical methodology: Abaqus/Explicit & FORTRAN subroutines

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DOI 10.21857/ydkx2cv759

Prezentacija predavanja

HIDROELASTIČNOST BRODSKIH I POMORSKIH KONSTRUKCIJA

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Fakultet strojarstva i brodogradnje Sveučilišta u Zagrebu

Nikola Vladimir, Ivo Senjanović

HIDROELASTIČNOST BRODSKIH I POMORSKIH KONSTRUKCIJA

Sažetak predavanja

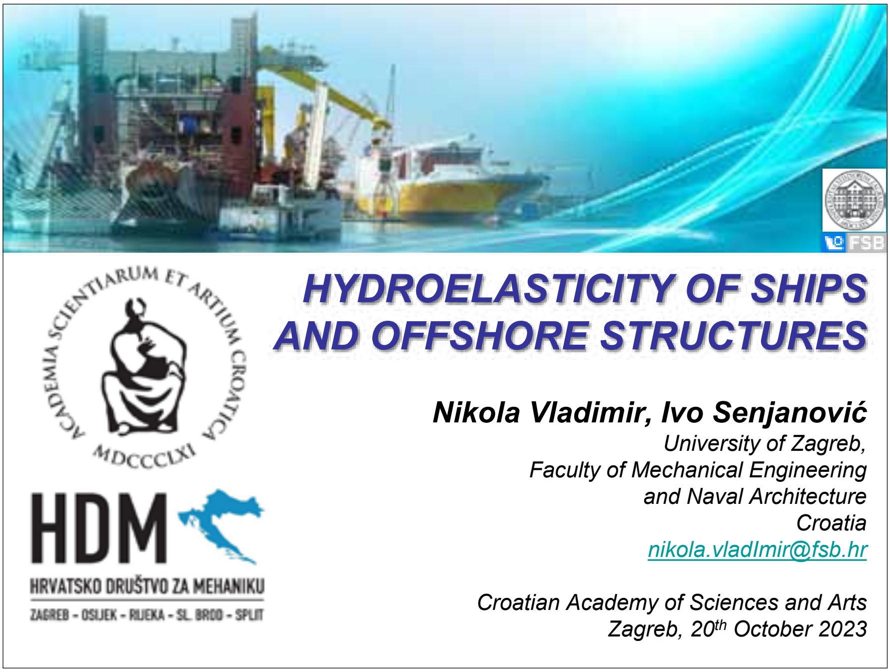
Predavanje obrađuje razvoj hidroelastičnosti kao znanstvene discipline, s naglaskom na primjene u brodogradnji i pomorskoj tehnici. Dan je pregled hidroelastičnih proračunskih modela (linearni, nelinearni, u frekvencijskoj domeni, u vremenskoj domeni), usporedba klasične teorije pomorstvenosti (koja podrazumijeva dinamiku plovnog objekta kao krutog tijela) i hidroelastičnog pristupa. Obuhvaćena je metodologija hidroelastične analize temeljena na modalnoj superpoziciji, jednadžba dinamičke ravnoteže plutajućeg elastičnog tijela, napredni gredni model za analizu hidroelastičnog odziva velikih kontejnerskih brodova, obuhvaćajući konstrukcijske specifičnosti: utjecaj smicanja na uvijanje, problem modeliranja diskontinuiteta (poprečne pregrade, konstrukcija strojarnice). Hidrodinamički model. Hidrostatički model (konzistentna formulacija povratne krutosti). Sprezanje strukturnog i hidrodinamičkog modela – „funkcija raspršivanja. Program STIFF za određivanje parametara krutosti poprečnog presjeka broda. Numerički primjeri obuhvaćaju ilustraciju komercijalnih i vlastitih alata za složene analize iz područja brodogradnje i pomorske tehnike, za domaće i strane naručitelje, kao što su primjerice: analize vibracija broda uslijed rada glavnog stroja i brodskog vijka, analiza čvrstoće broda podvrgnutog korozijskim oštećenjima u nasukanom stanju i u teglju, analize globalnog hidroelastičnog odziva ultra velikih kontejnerskih brodova, analize zamora konstrukcijskih detalja ultra velikih brodova (kontejnerski, FPSO) uslijed pruženja i podrhtavanja, problemi projektiranja vitkih brodskih privjesaka temeljem spregnutih CFD+FEM modela i sl.

O predavačima

Nikola Vladimir je izvanredni profesor na Fakultetu strojarstva i brodogradnje Sveučilišta u Zagrebu (FSB) i voditelj Katedre za strojeve i uređaje plovnih objekata. Na FSB-u je diplomirao 2007. godine na studiju brodogradnje, a 2011. godine i doktorirao s temom Hidroelastičnost i dinamička izdržljivost velikih kontejnerskih brodova. Njegovi istraživački interesi uključuju: energetsku učinkovitost, ekološku prihvatljivost i održivost brodova i drugih plovnih objekata, brodske energetske sustave, projektiranje i eksploataciju brodova specijalne namjene (ribarski, ro-ro putnički, brodovi unutarnje plovidbe), akvakulturu, cjeloživotne analize, međudjelovanja fluida i konstrukcije, statičke i dinamičke analize brodskih i pomorskih konstrukcija, itd. Na višemjesečnim znanstvenim usavršavanjima boravio je u Portugalu (Instituto Superior Tecnico, Lisbon), Francuskoj (Bureau Veritas, Research Department, Pariz) i Južnoj Koreji (Pusan National University, Busan). Tijekom karijere involviran je u niz projekata iz kompetitivnih programa financiranja (EU FP7, Horizon Europe, Interreg ADRION, Global Core Research Center for Ships and Offshore Plants (GCRC-SOP) Južna Koreja, Europski fond za pomorstvo i ribarstvo, Europski socijalni fond, Europski fond za regionalni razvoj, Hrvatska zaklada za znanost, Bilateralna hrvatsko-kineska suradnja, MZOŠ RH, itd.), od kojih većinu vodi ili je vodio. Proveo je veći broj stručnih projekata za ugledne domaće i strane naručitelje. Član je međunarodnih (ISSC) i domaćih (Znanstveno vijeće za pomorstvo HAZU) znanstvenih i stručnih tijela, uredničkih odbora nekoliko međunarodnih znanstvenih časopisa, recenzent niza članaka za časopise i konferencije, te autor preko 250 radova objavljenih u znanstvenim časopisima i zbornicima specijaliziranih domaćih i međunarodnih konferencija.

Ivo Senjanović je diplomirao u Zagrebu na tadašnjem Strojarsko-brodograđevnom fakultetu 1967., magistrirao na Građevinskom fakultetu 1969., a doktorirao na Fakultetu strojarstva i brodogradnje (FSB) 1970. Radio je na Brodarskom institutu u Zagrebu od 1967. do prelaska na FSB 1969, gdje je prošao sva znanstveno-nastavna zvanja od asistenta do redovitog profesora. Umirovljen je 2010. Usavršavao se kao gostujući znanstvenik na University of California, Berkeley, 1973. i kao istraživač u klasifikacijskom društvu Det norske Veritas, Oslo, 1974./75. Područja njegovog znanstvenog interesa su teorija ljusaka, teorija tankostijenih nosača, metoda konačnih elemenata, čvrstoća podmornica, čvrstoća, vibracije, pomorstvenost i hidroelastičnost brodskih i pomorskih konstrukcija, nelinearna dinamika, kaotično njihanje broda na valovima, porinuće broda s horizontalnog ležaja pomoću zakretnih saonika, projektiranje spremnika za prijevoz ukapljenog plina i dr. Sa svojim suradnicima pridonio je uvođenju suvremenih spoznaja i inženjerskih alata u brodograđevnu praksu i time povećao konkurentnost hrvatske brodogradnje na svjetskom tržištu.

Objavio je nekoliko udžbenika i preko 330 znanstvenih i stručnih radova. Prema studiji Stanford University svrstan je u 2% najutjecajnijih znanstvenika u svom području istraživanja. Bio je član međunarodnog udruženja *International Ships and Offshore Structures Congress (ISSC)* od 1977. do 2012., djelujući u radu desetak tehničkih komiteta. Redoviti je član HAZU od 2002. Dobitnik je nagrade „Nikola Tesla" 1974., te nagrade za životno djelo 2009. Počasno zvanje professor emeritus Sveučilišta u Zagrebu dodijeljeno mu je 2011.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HRVATSKO DRUŠTVO ZA MEHANIKU
ZAGREB - OSIJEK - RIJEKA - SL. BROD - SPLIT
HYDROELASTICITY OF SHIPS AND OFFSHORE STRUCTURES
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Zagreb, 20th October 2023

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Introduction

- HYDROELASTICITY
  - ✓ *A branch of science concerned with the motion and distortion of deformable bodies responding to environmental excitations in the sea* (Chen et al., 2006).
  - ✓ *A discipline concerned with phenomena involving interaction between inertial, hydrodynamic and elastic forces* (Heller and Abramson, 1959).
  - ✓ According to Heller and Abramson (1959): *the naval counterpart to aeroelasticity - the fluid pressure acting on the structure modifies its dynamic state and, in return, the motion and distortion of the structure disturb the pressure field around it*.
  - ✓ ***Hydroelasticity of Ships*** was brought to the attention of the Naval Architecture community in the 1970s through the work of Bishop and Price, culminating with the publication of the synonymous book in 1979.
- **Comprehensive reviews of advances in ship hydroelasticity**
  - ✓ Jensen and Madsen (1977), Wu (1987, 1994), Suo and Guo (1996), Kashiwagi (2000), Chen et al. (2006), Hirdaris and Temarel (2009), Hirdaris et al. (2023), Grammatikopoulos (2023), Jiang et al. (2023)...
  - ✓ ISSC reports regularly review advances in numerical approaches, model tests and full-scale measurements with hydroelastic effects included.

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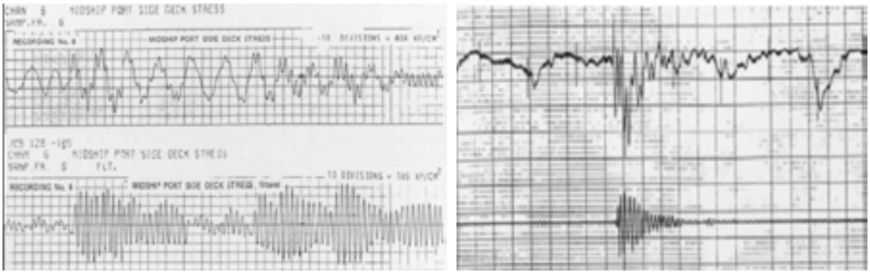
Important phenomena

- **SPRINGING & WHIPPING**
- Springing is usually defined as the continuous global ship structural vibrations induced by water waves. Springing is a resonant phenomenon in contrast to the whipping which is the transient ship vibrational response induced by impulsive loading (slamming, green water, underwater explosion,...).



Typical springing (left) and whipping (right) ship structural response;
Top - total signal, bottom - filtered signal (Malenica et al., 2008)

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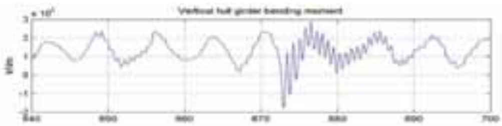
Background

- **Existing rules of Classification societies cover only limited size and types of structures**
  - ✓ Mainly quasi-static approach
  - ✓ High frequency hydroelastic contribution either neglected either included empirically

H / S	Linear	Weakly nonlinear	Impulsive nonlinear
Quasi static	X	X	X
Dynamic	X	X	X

- **Methodology for inclusion of hydroelastic effects still "open"**
  - ✓ Reliability of different hydroelastic models
  - ✓ Realistic operational profile
  - ✓ Statistical post-processing
    - *Extreme*
    - *Fatigue*



- **Harmonization of rules and direct calculation approaches**
  - ✓ Design methodology within direct calculation approach should not contradict the existing rule values for existing ships!
    - *Choice of reasonable operating conditions?*
    - *Choice of representative probability levels?*

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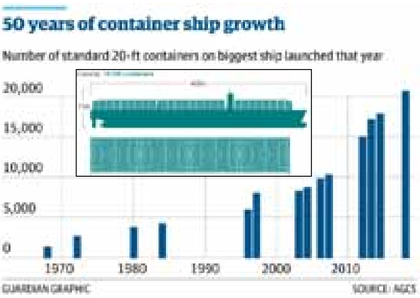
Motivation - why to investigate ship hydroelasticity?

- ✓ Mainly influenced by the building of large ships – particularly container ships.
- ✓ Due to their flexibility, natural frequencies of ULCS are close to encounter frequencies. Such conditions are not covered by present CR – direct calculations mandatory.



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Specialized events dedicated to ship hydroelasticity

➢ **Conferences, workshops...**

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Specialized events….

- 1st 1977 Tokyo
- 2nd 1983 Tokyo and Seoul
- 3rd 1987 Trondheim
- 5th 1992 Newcastle upon Tyne
- 6th 1995 Seoul
- 7th 1998 Hague
- 8th 2001 Shanghai
- 9th 2004 Lübeck
- 10th 2007 Houston
- 11th 2010 Rio de Janeiro
- 12th 2013 Changwon
- 13th 2016 Copenhagen
- 14th 2019 Yokohama

15th International Symposium on Practical Design of Ships and Other Floating Structures (PRADS 2022)

October 9 - 13, 2022
Dubrovnik, Croatia
https://prads2022.fsb.hr/

2022 PRADS 15th TRIENNIAL

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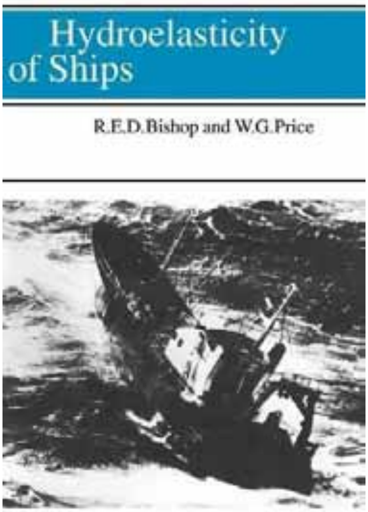
Specialized books….



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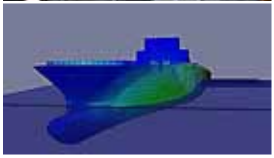
Znanstveni skup: SUVREMENE METODE U PROJEKTIRANJU I ANALIZI INŽENJERSKIH KONSTRUKCIJA
Bilt. Razreda teh. znan., god. 17: br. 1 (2024), str. 9-171

Research techniques

- **Model tests**
  - ✓ Expensive
  - ✓ Limited number of cases
  - ✓ Problem of similitude (hydroelasticity, viscosity...)
- **Numerical simulations**
  - ✓ Numerical modelling difficulties
  - ✓ Lack of full validation
  - ✓ CPU time
- **Full-scale measurements**
  - ✓ Limited number of operating conditions
  - ✓ Difficulties related to the measurement of the sea states
- **Overall**
  - ✓ Selection of the representative conditions (ship speed, loading conditions, scatter diagram, probability levels…)



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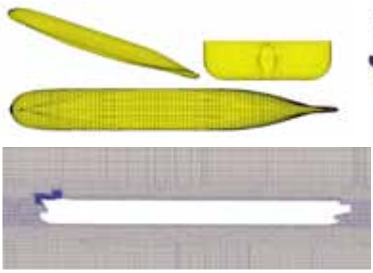
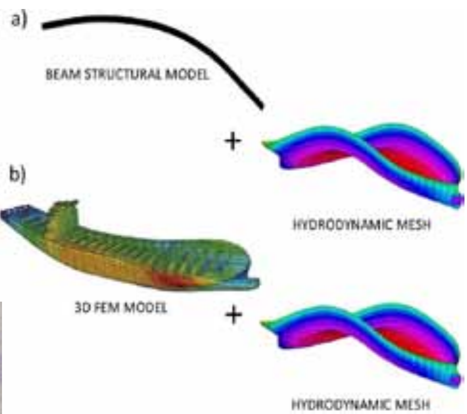
Mathematical models, tools & methodologies

- **Solving hydroelastic problem at different levels of complexity and accuracy**
  - ✓ Structural models
    - *Beam structural model*
    - *3D FEM structural model*
  - ✓ Hydrodynamic models
    - *Potential flow theories*
    - *CFD*





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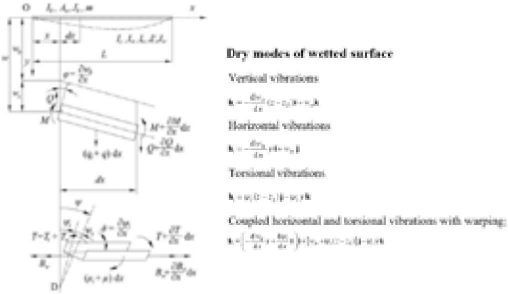
Sophisticated beam structural model

- **Beam model can give accurate results at global level**
  - ✓ Based on the advanced thin-walled girder theory
    - *shear influence on bending and torsion*
    - *accounting for contribution of transverse bulkheads to hull stiffness in a reliable way*
    - *accounting for closed engine room structure segment in a proper way*
  - ✓ Shear influence on torsion
    - *Analogy with shear influence on bending*

$$w = w_b + w_s, \qquad w_s = -\frac{EI_b}{GA_s}\frac{\partial^2 w_b}{\partial x^2}$$

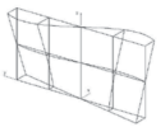
$$\psi = \psi_t + \psi_s, \qquad \psi_s = -\frac{EI_w}{GI_s}\frac{\partial^2 \psi_t}{\partial x^2}$$

Refs. Pavazza (2005), Senjanović et al. (2009)

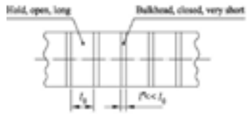


Sophisticated beam structural model

- ✓ Contribution of transverse bulkheads to the global hull stiffness
  - *Theory of torsion of thin-walled girders*
  - *Theory of bending of an ortothropic plate*
  - *Core idea: Increase St. Venant torsional modulus of open hull cross-section*



Bulkhead deformation due to hull cross-section warping

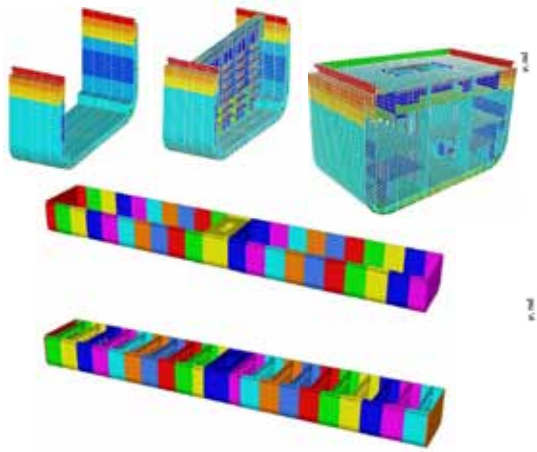


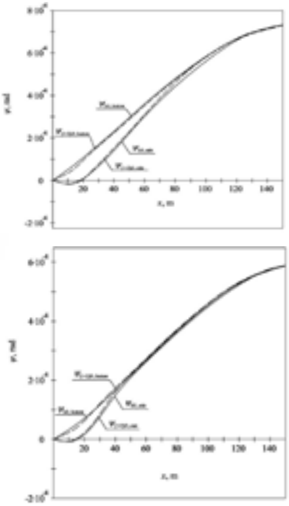
Discontinuities of ship hull

- ✓ Contribution of engine room structure to the hull stiffness (relatively short closed segment)
- ✓ Solution: Modelling of engine room structure as an open segment of increased torsional stiffness due to influence of the decks

Validation of sophisticated beam structural model

- ✓ Comparison of twist angles for segmented pontoons with and wihout bulkheads (Beam & 3D FEM models)





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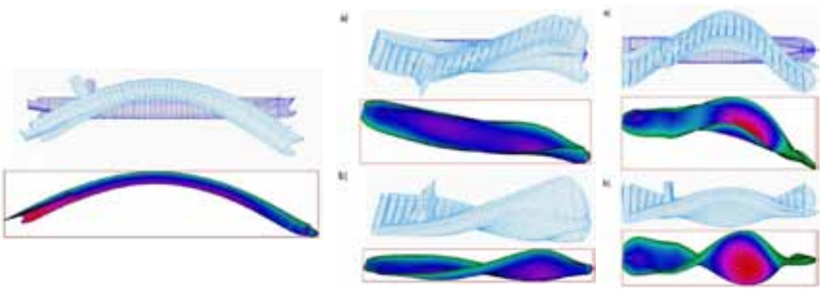
Validation of sophisticated beam structural model

- ✓ Comparison of natural vibrations of 11400 TEU CS obtained by beam model and 3D FEM model



Dry natural frequencies of the light container ship, ω_i[Hz]

	1D		3D		Discrepancy, %	
No.	Vertical	Coupled	Vertical	Coupled	Vertical	Coupled
1	1.149	0.640	1.159	0.639	-0.86	0.16
2	2.318	1.053	2.328	1.076	-0.43	-2.14
3	3.694	1.738	3.654	1.750	1.09	-0,69

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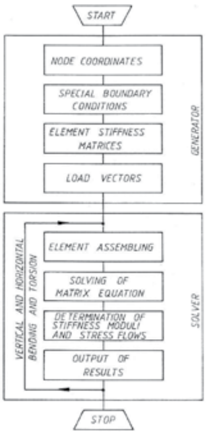
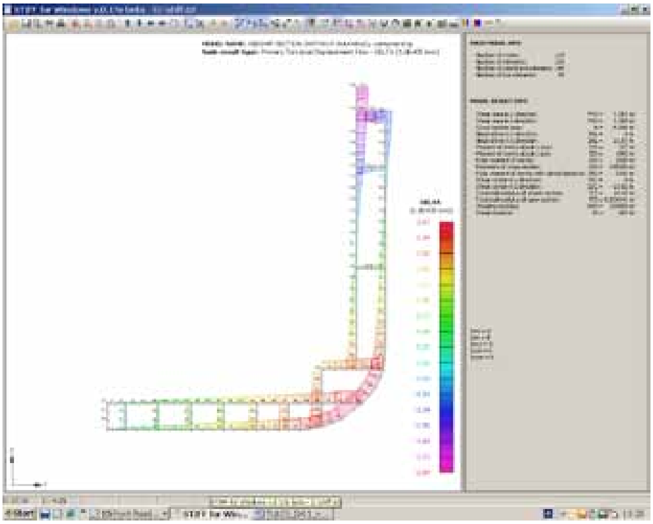
Assessing cross-sectional parameters (STIFF software)





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Equation of motion in frequency domain

➢ **The governing matrix differential equation for coupled ship motions and vibrations in frequency domain**

$$\left[\mathbf{k}+\mathbf{C}-i\omega\left(\mathbf{d}+\mathbf{B}(\omega)\right)-\omega^2\left(\mathbf{m}+\mathbf{A}(\omega)\right)\right]\xi=\mathbf{F}$$

$\mathbf{k}, \mathbf{d}, \mathbf{m}$ - structural stiffness, damping and mass matrix

$\mathbf{C}$ - restoring stiffness matrix

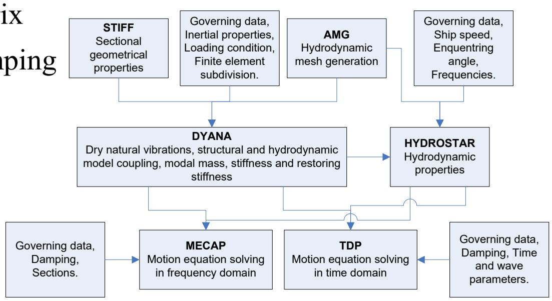
$\mathbf{B}(\omega)$ - hydrodynamic damping

$\mathbf{A}(\omega)$ - added mass

ξ - modal amplitudes

$\mathbf{F}$ - wave excitation

ω - encounter frequency



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Time domain simulation models

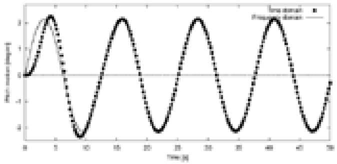
- **Hybrid method proposed by Cummins is adopted**
  - ✓ Frequency domain

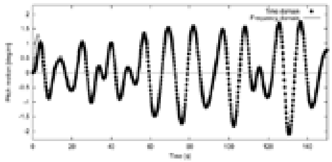
$$\{-\omega^2([\,\mathbf{m}\,]+[\,\mathbf{A}\,]) - i\omega[\,\mathbf{B}\,] + ([\,\mathbf{k}\,]+[\,\mathbf{C}\,])\}\{\xi\} = \{F^{DI}\}$$

  - ✓ Time domain

$$([\,\mathbf{m}\,]+[\,\mathbf{A}^{\infty}\,])\{\ddot{\xi}(t)\} + ([\,\mathbf{k}\,]+[\,\mathbf{C}\,])\{\xi(t)\} + \int_0^t [\,\mathbf{K}(t-\tau)\,]\{\dot{\xi}(\tau)\}d\tau = \{F(t)\} + \{Q(t)\}$$

  - ✓ Preliminary verifications for regular and irregular waves in linear conditions





- **Once the linear model verified the nonlinearities are included in the right hand side**
  - ✓ Froude Krylov
  - ✓ Nonlinear hydrostatics and large motions

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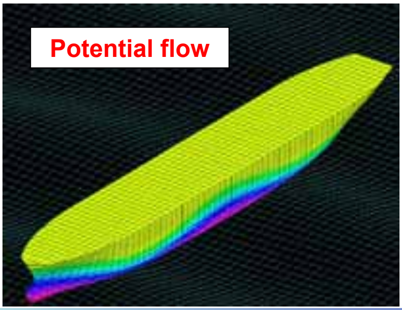
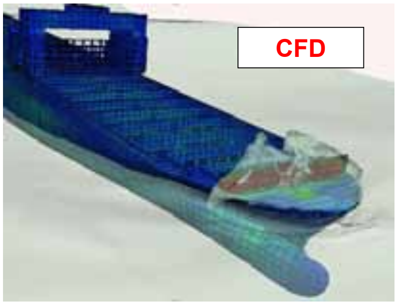
Numerical models – current trends (Potential flow &/or CFD)

- **Advantages**
  - ✓ Very fast and very precise
- **Limitations**
  - ✓ Handling of nonlinear effects
    - *Global (large waves and motions,...)*
    - *Local (slamming, green water...)*

- **Advantages**
  - ✓ No limitations vs. nonlinear effects
- **Limitations**
  - ✓ Numerical issues
    - *Meshing*
    - *Convergence & stability*
  - ✓ CPU time





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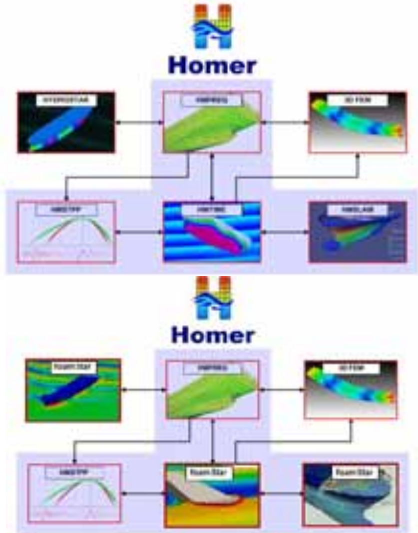
Numerical models – Leading commercial software

- **Summary of coupling schemes**
  - ✓ With Hydrostar



  - ✓ With foamStar

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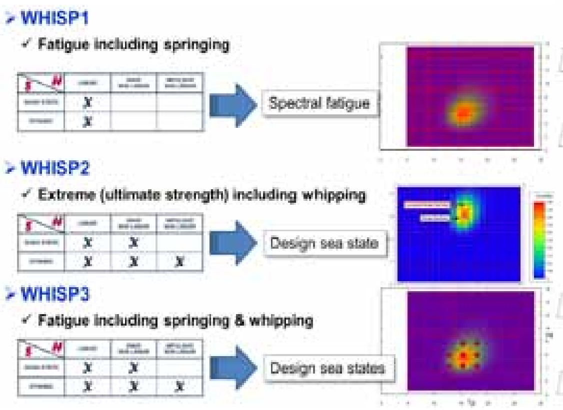
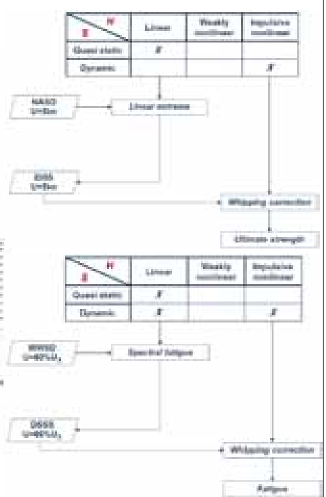
Direct calculation methodologies – Springing & Whipping

- **WhiSp methodology (Bureau Veritas NR583)**





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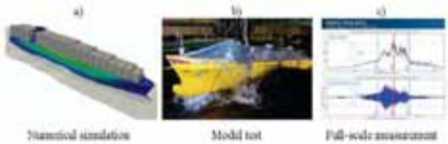
Selected projects on ship hydroelasticity

- **EU FP7 Project TULCS (June 2009 – November 2012)**
- **Goal**
  - ✓ … to deliver clearly validated design tools and guidelines, capable of analysing all hydro-structure interaction problems relevant to ULCS
- **Main physical problems**
  - ✓ Global quasi-static loading and responses
  - ✓ Global hydroelastic wave loading and responses
  - ✓ Local hydrodynamic loading and responses

TULCS

Tools for Ultra Large Container Ships



TULCS Partners:

Bureau Veritas, France (coordinator)
MARIN, The Netherlands
CMA-CGM, France
CEHIPAR, Spain
Ecole Centrale Marseille, France
Technical University Delft, The Netherlands
University of Zagreb, Croatia
Technical University of Denmark, Denmark
University of East Anglia, United Kingdom
SIREHNA, France
WIKKI, United Kingdom
HYDROCEAN, France
Brže Više Bolje, Croatia
Hyundai Heavy Industries, Korea

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GCRC-SOP

- **GCRC-SOP (Global Core Research Center for Ships and Offshore Plants)**
  - ✓ Establish the world premier research center at PNU through the strategic international collaboration with world-renowned researchers in the field of Ship & Offshore Plant Engineering (2011-2021)
- **GCRC-SOP Participants**
  - ✓ National Research Foundation of Korea, Pusan National University, Pusan Metropolitan City, Shipyards (HHI, DSME, SHI, STX , BNC, CreaTech), Classification societies (ABS, BV, NK, KR)
- **4 External Universities**
  - ✓ University of Michigan, University of Maryland, University of New Orleans, UNIZAG FSB (with Bureau Veritas, Paris, France)

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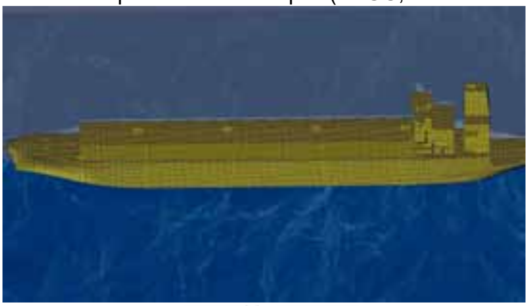
JRPs/JDPs within GCRC-SOP – Ships with internal liquid

➢ Global hydroelastic response of LNG ships

✓ Goal: to develop hydroelastic model for ships with internal liquid (LNGC, Tankers…)

- *Beam structural model*
- *3D FE structural model*



✓ Scope of work:

- *Example ship provided by HHI*
- *UNIZAG FSB - beam hydroelastic model*
- *BV & UNIZAG FSB - 3D FEM hydroelastic model*
- *PNU - semi analytical solution for validation purposes*

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JRPs/JDPs within GCRC-SOP – Design of new ULCS type

➢ Springing & Whipping Analysis of HHI SkyBench™ container carrier

➢ Evaluation of structural design of novel ULCS design on WhiSp 1, 2 and 3 levels

✓ Comparison between conventional design and SkyBench™ of 19,000 TEU class container carrier
✓ ULS; evaluation of hull girder stress
✓ FLS; fatigue evaluation of hatch and bench corners
✓ Joint Research Project (UNIZAG FSB & HHI)

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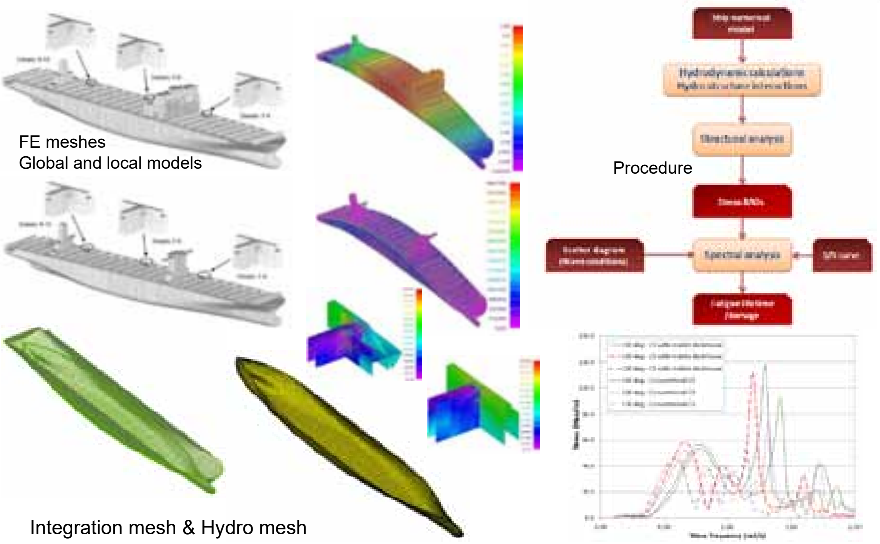
JRPs/JDPs within GCRC-SOP – Design of new ULCS type



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JRPs/JDPs within GCRC-SOP – Design of new ULCS type

- **Results**
  - ✓ WhiSp1 - Fatigue damage ratios

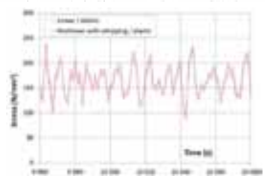
Detail	Damage ratio (Conventional CS/CS with mobile deckhouse)		Damage ratio (WhiSp1/Quasi-static linear)	
	Quasi-static linear	WhiSp1	CS with mobile deckhouse	Conventional CS
1	1.46	1.14	3.51	1.18
2	0.80	0.67	5.18	3.77
3	1.29	0.58	1.97	1.85
4	0.76	0.29	2.05	1.17
5	1.00	0.90	1.27	1.14
6	0.87	0.82	1.24	1.19
7	0.86	0.82	2.30	1.20
8	0.63	0.51	2.53	2.04
9	0.84	0.89	1.95	2.07
10	0.58	0.72	2.16	2.08
11	0.74	0.78	1.87	1.98
12	0.96	0.90	2.21	1.97

  - ✓ Whisp 2 – Relative influence of whipping on VBM

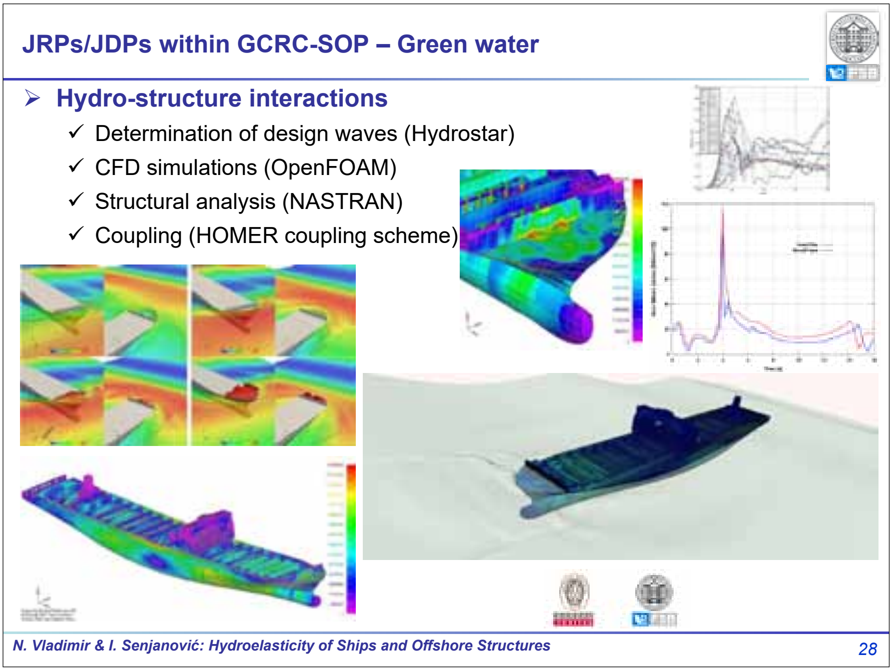
Item	CS with mobile deckhouse		Conventional CS	
	Sagging	Hogging	Sagging	Hogging
Still Water Bending Moment (SWBM)	1.023E+10		9.928E+09	
Quasi-static linear (without SWBM)	1.426E+10		1.494E+10	
Quasi-static nonlinear (without SWBM)	-2.542E+10	1.328E+10	-2.801E+10	1.309E+10
Whipping nonlinear (without SWBM)	-3.042E+10	1.743E+10	-3.434E+10	1.872E+10
Quasi-static total (with SWBM)	-1.519E+10	2.351E+10	-1.808E+10	2.302E+10
Whipping total (with SWBM)	-2.019E+10	2.766E+10	-2.441E+10	2.865E+10
Relative influence of Whipping	32.9%	17.7%	35.0%	24.5%

  - ✓ WhiSp 3 – Relative influence of whipping on fatigue

Detail	Damage ratio (WhiSp1/Quasi-static linear)	
	CS with mobile deckhouse	Conventional CS
1	3.83	3.21
8	2.77	2.46
11	2.01	2.34



N. Vladimir & I. Senjanović: Hydroelasticity of Ships and Offshore Structures 27


JRPs/JDPs within GCRC-SOP – Green water
Hydro-structure interactions
Determination of design waves (Hydrostar)
CFD simulations (OpenFOAM)
Structural analysis (NASTRAN)
Coupling (HOMER coupling scheme)
N. Vladimir & I. Senjanović: Hydroelasticity of Ships and Offshore Structures
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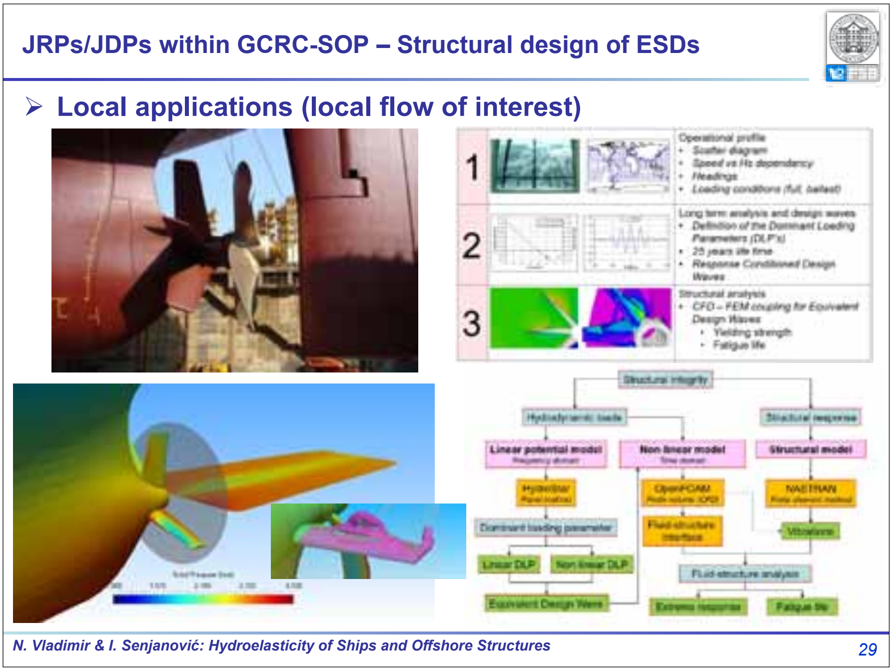
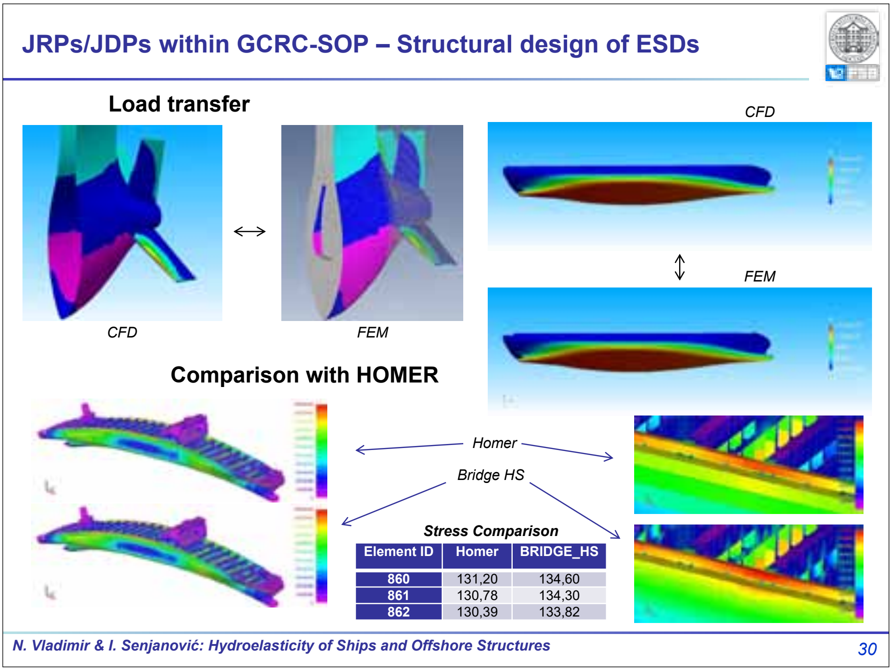
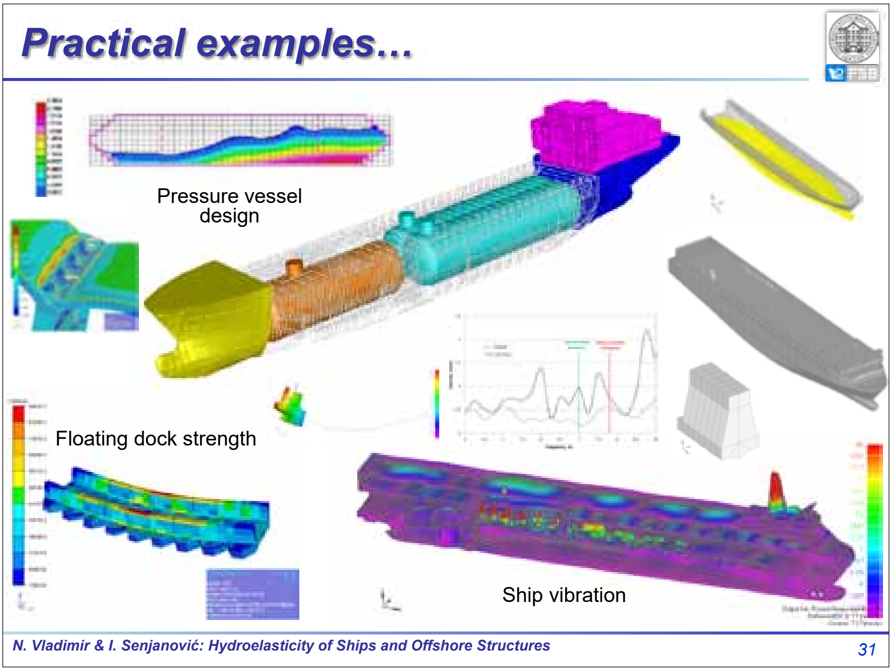
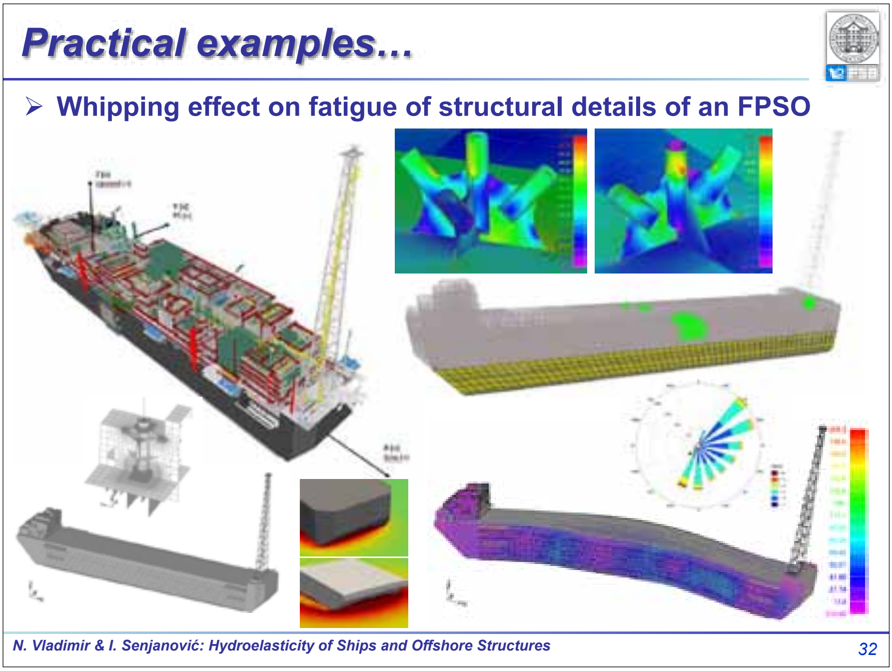

JRPs/JDPs within GCRC-SOP – Structural design of ESDs
Local applications (local flow of interest)
1
2
3
Operational profile
Scatter diagram
Speed vs Hs dependency
Headings
Loading conditions (full, ballast)
Long term analysis and design waves
Definition of the Dominant Loading Parameters (DLP's)
25 years life time
Response Conditioned Design Waves
Structural analysis
CFD – FEM coupling for Equivalent Design Waves
Yielding strength
Fatigue life
Structural integrity
Hydrodynamic loads
Structural response
Linear potential model
Non linear model
Structural model
Hydrostar
OpenFOAM
NASTRAN
Dominant loading parameter
Fluid-structure interface
Vibrations
Linear DLP
Non linear DLP
Fluid-structure analysis
Equivalent Design Wave
Extreme response
Fatigue life
N. Vladimir & I. Senjanović: Hydroelasticity of Ships and Offshore Structures
29


JRPs/JDPs within GCRC-SOP – Structural design of ESDs
Load transfer
CFD
FEM
CFD
FEM
Comparison with HOMER
Homer
Bridge HS
Stress Comparison

Element ID	Homer	BRIDGE_HS
860	131,20	134,60
861	130,78	134,30
862	130,39	133,82

N. Vladimir & I. Senjanović: Hydroelasticity of Ships and Offshore Structures
30


Practical examples…
Pressure vessel design
Floating dock strength
Ship vibration
N. Vladimir & I. Senjanović: Hydroelasticity of Ships and Offshore Structures
31


Practical examples…
Whipping effect on fatigue of structural details of an FPSO
N. Vladimir & I. Senjanović: Hydroelasticity of Ships and Offshore Structures
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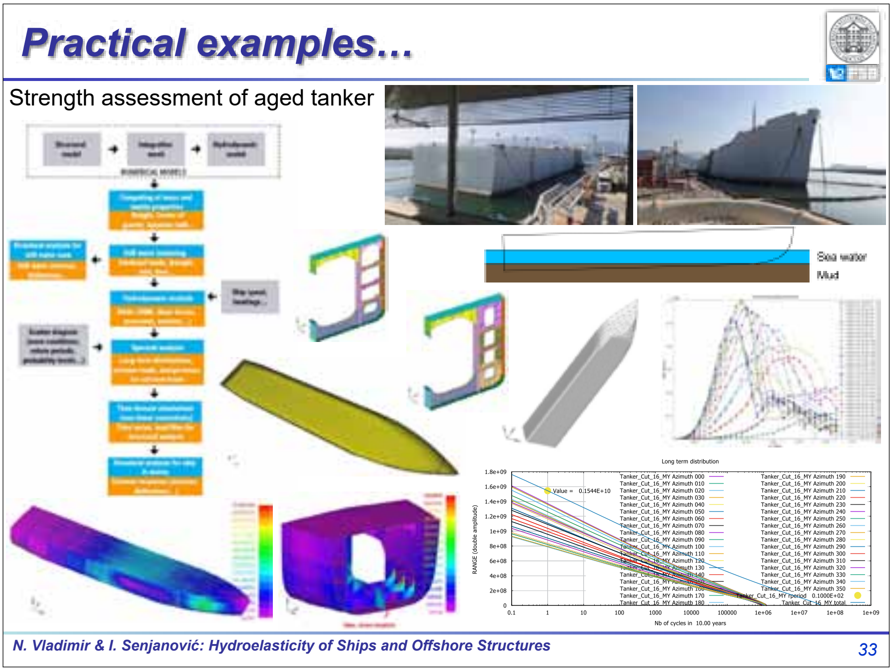
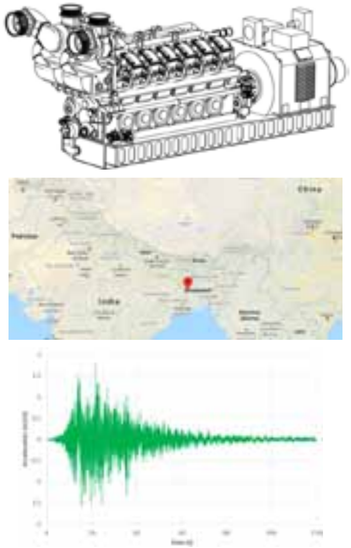
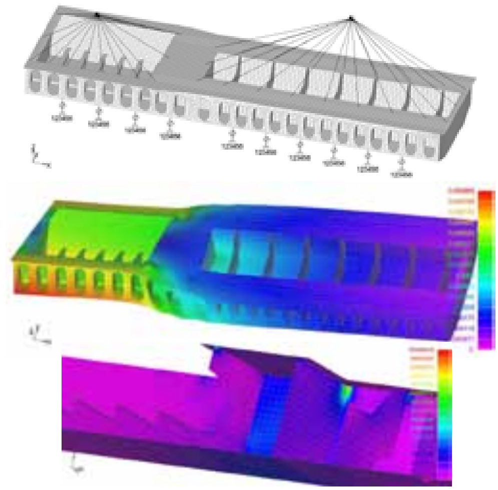

Practical examples…
Strength assessment of aged tanker
Sea water
Mud
Long term distribution
RANGE (double amplitude)
Nb of cycles in 10.00 years
N. Vladimir & I. Senjanović: Hydroelasticity of Ships and Offshore Structures
33

Practical examples…





Seismic analysis of Diesel Genset base frame for Nuclear Power Plants

N. Vladimir & I. Senjanović: Hydroelasticity of Ships and Offshore Structures 34

Conclusion

- **An overview of application of numerical methods in marine sector with emphasis on fluid-structure interactions**
  - ✓ Emphasis on numerical models developed within projects involving UNIZAG FSB and Partners (Bureau Veritas, Pusan Natl. Univ., Hyundai Heavy Industries, etc.) – particularly *TULCS* and *GCRC-SOP*
  - ✓ Hydroelasticity of ships is still „open" issue – beside numerical codes still should be investigated by model tests and full-scale measurements
  - ✓ Development of hydroelastic numerical codes and direct calculation methodologies should be done simultaneously (Example: HOMER & WhiSp)
  - ✓ Trends in development of numerical codes: coupling of 3D FEM with CFD tools
  - ✓ Application of hydroelastic theories becomes wider (simplified models including plates and stiffened panels, wedge-shaped bodies, ice-sheets, ships, very large floating structures, propellers, offshore structures, etc.)

"We have no choice; whether we like it or not, we have to do research."
Georg Vedeler, DnV President 1951

N. Vladimir & I. Senjanović: Hydroelasticity of Ships and Offshore Structures 35


Thanks for Your Attention!!!
Thanks to our Partners
HrZZ
Croatian Science Foundation
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National Technical University of Athens
울산대학교
UNIVERSITY OF ULSAN
HYUNDAI
HEAVY INDUSTRIES CO.,LTD.
DSME
BUREAU VERITAS
REPUBLIKA HRVATSKA
Ministarstvo znanosti i obrazovanja
武汉理工大学
GCRC SOP
Strathclyde
Ribarska zadruga Zadar
MINISTARSTVO POLJOPRIVREDE
Operativni program ZA POMORSTVO I RIBARSTVO
FSB

DOI 10.21857/m16wjcwq29

Prezentacija predavanja

SIGURNOST INŽENJERSKIH KONSTRUKCIJA I ULOGA KLASIFIKACIJSKIH DRUŠTAVA

Dr. sc. Šime Malenica
Bureu Veritas, Paris, Francuska

Šime Malenica

SIGURNOST INŽENJERSKIH KONSTRUKCIJA I ULOGA KLASIFIKACIJSKIH DRUŠTAVA

Sažetak predavanja

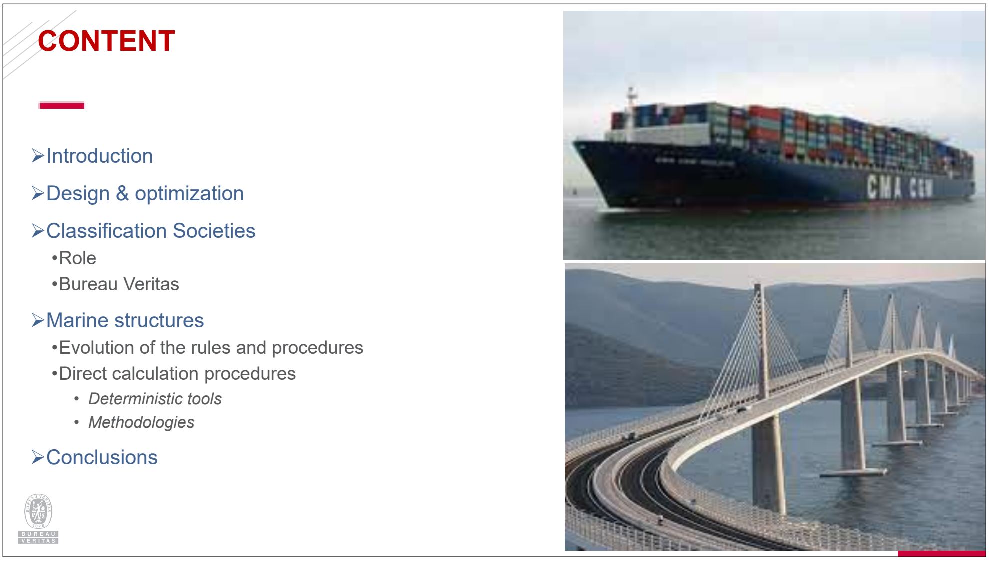
Sigurnost inženjerskih konstrukcija osigurana je u prvom redu kroz process detaljnog dizajna od strane inženjera koji sudjeluju u projektu. Čitav niz provjera izdržljivosti konstrukcije, uslijed očekivanog vanjskog opterećenja, provodi se putem suvremenih numeričkih i eksperimentalnih alata koji su danas postali jako pouzdani. Ipak, unatoč pažnji koja je posvećena sigurnom dizajnu konstrukcije, greške su uvijek moguće i iznimno je važno izvršiti provjeru rezultata od nezavisne institucije. U tome leži svrha klasifikacijskih društava koja će kritički provjeriti svaki detalj predloženog konstrukcijskog rješenja i dati konačnu ocjenu pouzdanosti konstrukcije. Nakon uvodnog izlaganja posvećenog općenitim inženjerskim konstrukcijama (mostovi, zgrade, zrakoplovi, industrijska postrojenja, brodovi…) predavanje će se prvenstveno koncentrirati na probleme sigurnosti brodskih i pomorskih konstrukcija. Jedan od najvažnijih problema, vezan uz pomorske objekte, odnosi se na opis vanjskog opterećenja prouzrokovanog morskim valovima i morskim strujama. Probabilistička priroda vanjskog opterećenja nameće potrebu kombinirane upotrebe determinističkih i probabilističkih metoda u cilju određivanja konačnih sigurnosnih kriterija. Predavanje će obuhvatiti razne nivoe provjere, polazeći od jednostavnih pravila do kompleksnih direktnih proračuna koji uključuju najsloženije suvremene hidrodinamičke i strukturne alate.

O predavaču

Šime Malenica rođen je u Splitu 1965. godine. Diplomirao je na Fakultetu strojarstva i brodogradnje u Zagrebu 1990. godine. Magistrirao je 1991., a doktorirao 1994. godine na Sveučilištu Pierre et Marie Curie (Paris VI). Za vrijeme doktorskog studija radio je na francuskom Institutu za naftu (IFP). Godine 1995. zaposlio se u istraživačkom odjelu klasifikacijskog društva Bureau Veritas (BV) u Parizu, gdje i danas radi na funkciji zamjenika direktora Istraživačkog odjela. Njegovo područje istraživanja uključuje teorijske i praktične aspekte brodske i off-shore hidrodinamike. Objavio je više od 200 članaka u znanstvenim časopisima i specijaliziranim konferencijama. Zajedno s dr. Xiao-Bo Chen glavni je djelatnik u razvoju renomiranih softvera HYDROSTAR i HOMER za analizu valnog opterećenja i odziva brodskih i pomorskih konstrukcija, koji se primjenjuju širom svijeta. Dr. Šime Malenica razvio je intenzivnu suradnju s Fakultetom strojarstva i brodogradnje Sveučilišta u Zagrebu gdje je izabran u znanstveno zvanje znanstvenog savjetnika i naslovno nastavno zvanje izv. profesora te sudjeluje u nastavi na poslijediplomskom studiju. Godine 2016. izabran je u članstvo Hrvatske akademije znanosti i umjetnosti kao dopisni član. Aktivan je u radu međunarodnog udruženja *International Ships and Offshore Structures Congress (ISSC)*, pri čemu je danas predstavnik Francuske u Stalnom odboru tog udruženja. Organizirao je nekoliko značajnijih međunarodnih konferencija u Republici Hrvatskoj, od kojih se ističu:

- 22nd International Workshop on Water Waves and Floating Bodies, Plitvice, 2007.
- 1st International Workshop on Springing and Whipping of Ships, Dubrovnik, 2010.
- 2nd International Workshop on Springing and Whipping of Ships, Split, 2012.
- 7th International Conference on Hydroelasticity in Marine Technology, Split, 2015.
- 15th International Symposium on Ships and other Floating Structures (PRADS), Dubrovnik, 2022.


BUREAU VERITAS
1828
SAFETY OF ENGINEERING CONSTRUCTIONS AND THE ROLE OF CLASSIFICATION SOCIETIES
Šime Malenica
October 2023


CONTENT
➢Introduction
➢Design & optimization
➢Classification Societies
•Role
•Bureau Veritas
➢Marine structures
•Evolution of the rules and procedures
•Direct calculation procedures
• Deterministic tools
• Methodologies
➢Conclusions
CMA CGM

INTRODUCTION

INTRODUCTION

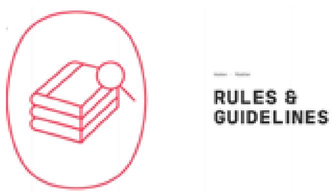
- Every engineering construction requires careful verification of the design before entering into service
- This includes several aspects
  - Concept verification
  - Construction survey
  - In service survey

MARINE STRUCTURES

CLASSIFICATION SOCIETIES

INTRODUCTION
Specificities of the Marine structures

- ➢In addition to the different industrial standards the Classification Societies (CS) rules need to be respected
- ➢The rules might differ from one CS to other
- ➢A certain degree of consistency is ensured by IACS
  - •International Association of Classification Societies
- ➢Classification Societies are intermediary between the unit owner and the insurrance company
  - •They guarantee the sufficient safety level in order for the unit to be built and operated
- ➢Basic principles of design verification
  - •Prescriptive rules
    - *Simple and easy to use*
    - *Applicable to standard units for which enough experience already exists*
  - •Guidances and procedures
    - *More omplex*
    - *Applicable for novel designs and for the units exceeding certain size*

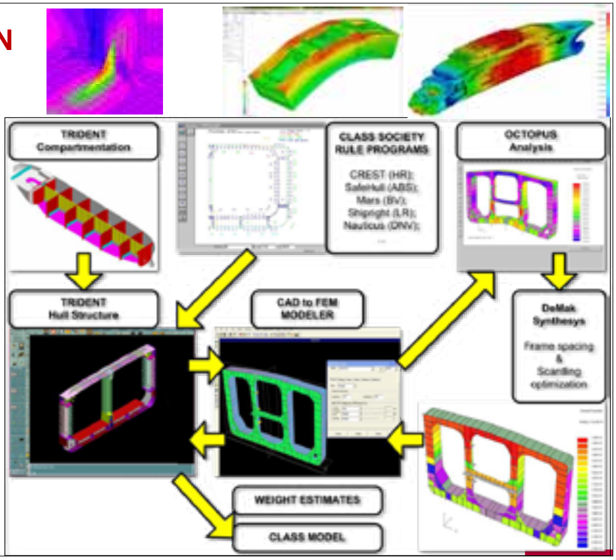


BUREAU VERITAS

DESIGN & OPTIMIZATION

DESIGN & OPTIMIZATION

- Design
  - Initial design
    - *Most often rule based*
  - Detailed design
    - *All aspects*
- Optimization
  - Compromoise between the weight (cost) and safety
  - Use of all the available tools
    - *Most often rule based*
- Important contribution of UNIZAG
  - Team of Prof. V.Zanic
    - *CREST, OCTOPUS …*



CLASSIFICATION SOCIETIES

Name	Abbreviation	Date	Head office
Lloyd's Register	LR	1760	London
Bureau Veritas	BV	1828	Paris
Registro Italiano Navale	RINA	1861	Genoa
American Bureau of Shipping	ABS	1862	Houston
DNV (Det Norske Veritas)	DNV	1864	Oslo
Germanischer Lloyd	GL	1867–2013	Hamburg
Nippon Kaiji Kyokai (ClassNK)	NK	1899	Tokyo
Russian Maritime Register of Shipping	RS	1913	Saint Petersburg
Hellenic Register of Shipping	HR	1919	Piraeus
Polish Register of Shipping	PRS	1936	Gdańsk
Korean Classification Society	KCS	1947	Pyongyang
Croatian Register of Shipping	CRS	1949	Split
Bulgarian Register of Shipping	BRS	1950	Varna
CR Classification Society	CR	1951	Taipei
China Classification Society	CCS	1956	Beijing
Korean Register of Shipping	KR	1960	Busan

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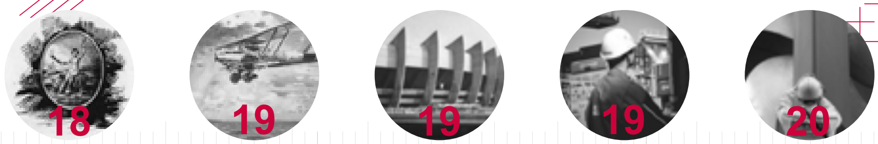
BUREAU VERITAS

Almost 200 Years of history



1828 — ORIGINS
Foundation of the **"Information Office for Maritime"**

1920' — MODERN INDUSTRIAL REVOLUTION
New activities to accompany industrial expansion

1960' — TECHNICAL PROGRESS
Active role in modernizing ship building standards for **classification of vessels**

Reinforcement of expertise in construction and energy efficiency

1990' — GLOBALIZATION
Development of **Certification & Government services**

Reinforcement of the network with new offices in Africa, China, the US and in Europe

2010' — TECHNICAL PROGRESS
Inspectorate and Maxxam joined BV group to develop the **Commodities business** and in **high-potential markets**

Expansion of the geographical footprint in the construction and consumer products industries in China

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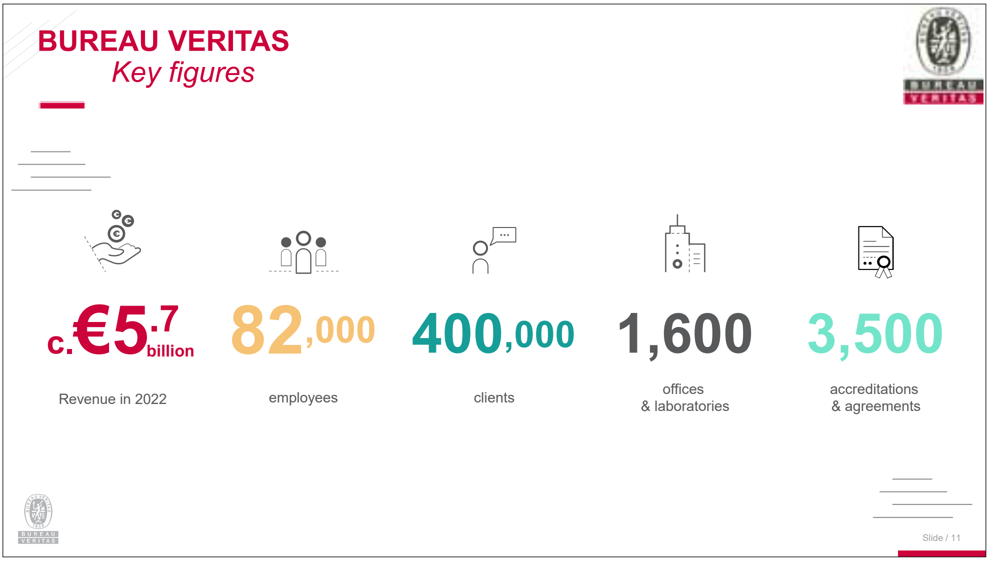
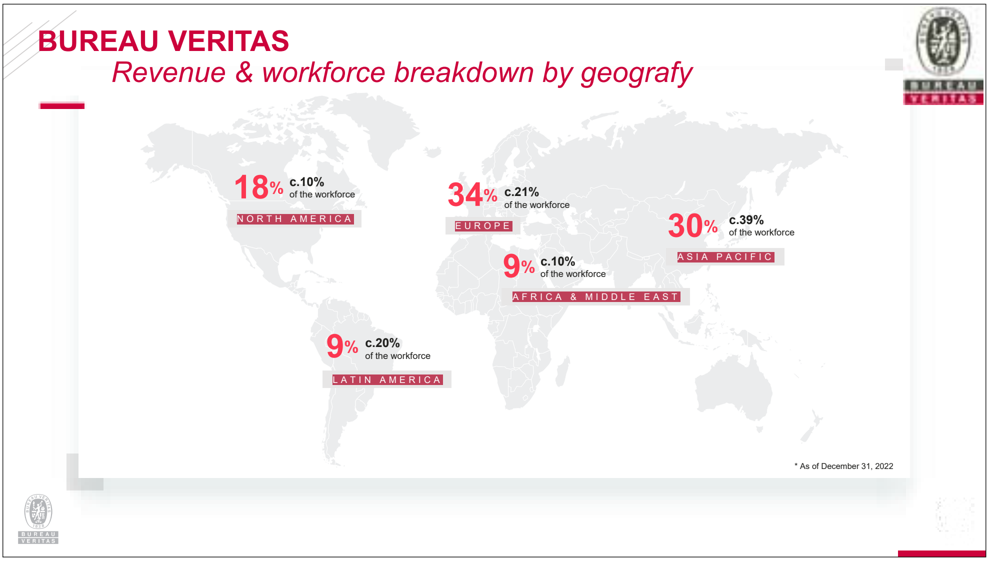
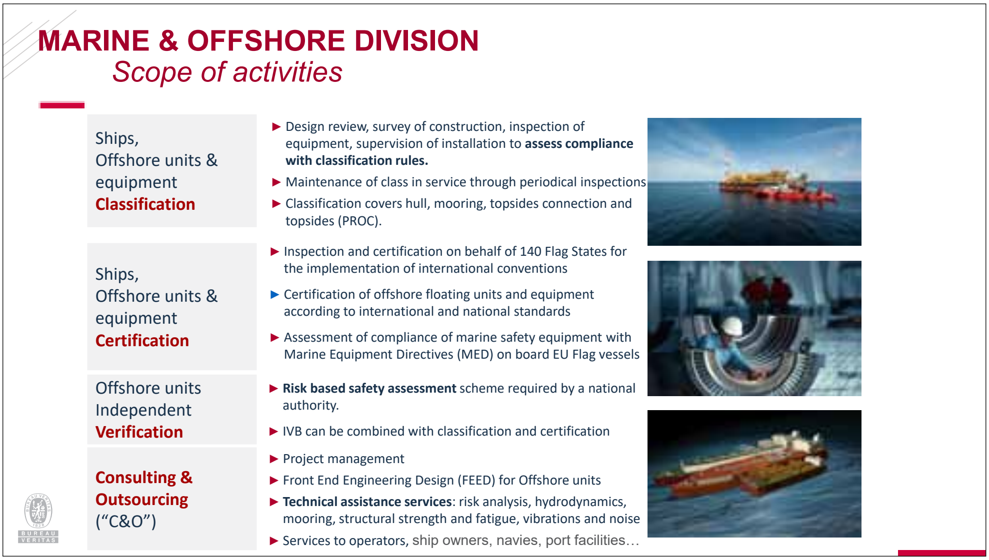

BUREAU VERITAS
Key figures
c.€5.7 billion
Revenue in 2022
82,000
employees
400,000
clients
1,600
offices & laboratories
3,500
accreditations & agreements
Slide / 11


BUREAU VERITAS
Revenue & workforce breakdown by geografy
18% c.10% of the workforce
NORTH AMERICA
34% c.21% of the workforce
EUROPE
30% c.39% of the workforce
ASIA PACIFIC
9% c.10% of the workforce
AFRICA & MIDDLE EAST
9% c.20% of the workforce
LATIN AMERICA
* As of December 31, 2022


BUREAU VERITAS
Strong positions
TOP 2
#1
#1
TOP 2
TOP 3
TOP 3
MARINE & OFFSHORE
8%*
Provide ship & offshore platform classification services and technical expertise to assess and manage risks as well as improving performance
INDUSTRY
23%*
Maintain the safety, reliability and integrity of industrial assets and assess compliance with national, international and voluntary QHSE standards
BUILDINGS & INFRASTRUCTURE
24%*
Provide assurance buildings & infrastructure in use or under construction are compliant and energy-efficient
Assess safety and performance of in-service facilities
CERTIFICATION
8%*
Certify that quality, health, safety and environmental management systems comply with international, national, industry or company-specific standards
AGRI-FOOD & COMMODITIES
23%*
Improve transparency and verify the composition, quality and quantity of commodities throughout the value chain, from drilling to trading, and from farm to fork
CONSUMER PRODUCTS
14%*
Test and verify consumer product compliance, quality, safety and performance and improve supply chain efficiency
Slide / 13


MARINE & OFFSHORE DIVISION
Scope of activities
Bureau Veritas provides QHSE services covering whole life cycle of Marine & Offshore installations
Concept Approval
Environment Impact
Assistance in permitting
QHSE regulations consultancy
Supplier Technical Assessment
Shop inspection (QA/QC)
Expediting
Product certification (CE-marking, ASME, etc.)
Asset Integrity Management
Fugitive emission measurement
Periodic inspection / Class Maintenance
Regulations conformity management
Non-destructive testing (NDT)
Feasibility
Design
Procurement
Construction
Operation
Decommissioning
Design review and validation
Independent verification
Risk analysis & Safety Case
Technical assistance
Personnel qualification
Site inspection, supervision
Non-destructive testing (NDT)
Classification of Offshore unit
Risk Assessment
Strategy optimisation
Occupational health & safety
Technical Due Diligence


MARINE & OFFSHORE DIVISION
Scope of activities
Ships, Offshore units & equipment Classification
Design review, survey of construction, inspection of equipment, supervision of installation to assess compliance with classification rules.
Maintenance of class in service through periodical inspections
Classification covers hull, mooring, topsides connection and topsides (PROC).
Ships, Offshore units & equipment Certification
Inspection and certification on behalf of 140 Flag States for the implementation of international conventions
Certification of offshore floating units and equipment according to international and national standards
Assessment of compliance of marine safety equipment with Marine Equipment Directives (MED) on board EU Flag vessels
Offshore units Independent Verification
Risk based safety assessment scheme required by a national authority.
IVB can be combined with classification and certification
Consulting & Outsourcing ("C&O")
Project management
Front End Engineering Design (FEED) for Offshore units
Technical assistance services: risk analysis, hydrodynamics, mooring, structural strength and fatigue, vibrations and noise
Services to operators, ship owners, navies, port facilities…
BUREAU VERITAS

Znanstveni skup: SUVREMENE METODE U PROJEKTIRANJU I ANALIZI INŽENJERSKIH KONSTRUKCIJA
Bilt. Razreda teh. znan., god. 17: br. 1 (2024), str. 9-171

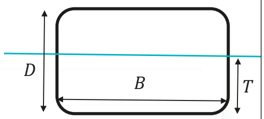
BUREAU VERITAS 1828

CLASSIFICATION SOCIETIES

EVOLUTION OF THE RULES

EVOLUTION OF THE RULES & PROCEDURES
80 Years ago

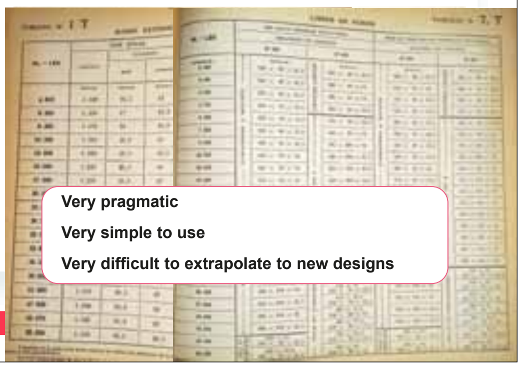
PURE EMPIRICISM



Rule prescriptions only based on regressions on existing ships

Example : BV rules 1940

- **Ship length** L } **Coefficient** K
- **Ratio** T/D
- **Longitudinal number** $NL = LBTK$
- **It gives the different required scantlings**
  - Bottom plate
  - Side shell
  - Stiffeners
  - …



Very pragmatic
Very simple to use
Very difficult to extrapolate to new designs

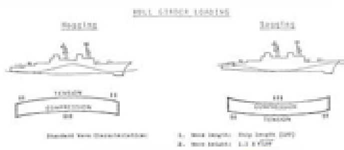
1940

EVOLUTION OF THE CLASSIFICATION SOCIETIES RULES
2nd half of 20th century

HULL GIRDER STRENGTH

Cross section properties

- Inertia $I = \iint y^2 dS$
- Neutral axis $\int (y - y_0) dy = 0$
- Section modulus $W = \frac{I}{y - y_0}$



Bending and stress

- M: applied bending moment
- R: radius of curvature
- E: Young's modulus
- σ: stress

$$R = \frac{EI}{M}$$

$$\sigma = \frac{M}{W} = E\frac{y - y_0}{R}$$

1940

EVOLUTION OF THE CLASSIFICATION SOCIETIES RULES
2nd half of 20th century

HULL GIRDER STRENGTH

1968: foundation of IACS

1973: UR S4

- Material factor k
- Minimum inertia
  $I > 3CL^3B(C_B + 0.7)$

1973: UR S7

- Minimum section modulus
  $W > CL^2B(C_B + 0.7)k$

1989: UR S11

- Vertical wave bending moment and shear force
  $M_{wH} = 0.19\, CL^2BC_B$
  $M_{wS} = 0.11\, CL^2B(C_B + 0.7)$
- Minimum section modulus
  $W > 1000\frac{|M_s + M_w|}{175/k}$

IACS UR S4 & S7 UR S11

1940 1968 1973 1989

EVOLUTION OF THE CLASSIFICATION SOCIETIES RULES

Goal Based Standards

RULES FOR RULES (2010)

INTERNATIONAL MARITIME ORGANIZATION

"Ships shall be designed and constructed for a specified design life to be safe and environmentally friendly, when properly operated and maintained under the specified operating and environmental conditions, in intact and specified damage conditions, throughout their life"

- **Design life: 25 years**
- **Environmental conditions: North Atlantic**
- **The structural strength shall be assessed against excessive deflection and failure modes, including but not limited to buckling, yielding and fatigue.**

1992: Rec.34

- **North Atlantic scatter diagram**

IACS UR S4 & S7 UR S11 Rec.34 GBS

1940 1968 1973 1989 1992 2010

EVOLUTION OF THE CLASSIFICATION SOCIETIES RULES

Today

LOAD FORMULATIONS & DIRECT STRUCTURAL ANALYSIS

2014: Common Structural Rules

Extreme or fatigue hydrodynamic loads 25 years in North Atlantic

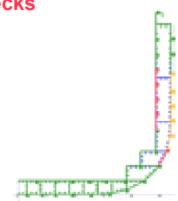
- **Hull girder loads**
- **Motions and accelerations**
- **Sea pressure**
- **Equivalent Design Waves**
- **Load combination factors**

Various structural checks

- **Longitudinal strength**
- **3D FE analysis**

Different limit states

- **Yielding**
- **Buckling**
- **Ultimate strength**
- **Fatigue**



IACS UR S4 & S7 UR S11 Rec.34 GBS CSR

1940 1968 1973 1989 1992 2010 2014 2022

DIRECT CALCULATION APPROACH

DIRECT CALCULATION APPROACH
Relevant BV documents

Deterministic tools

ENVIRONMENTAL CONDITIONS, LOADS AND INDUCED RESPONSES OF MARINE UNITS

NI691 - DECEMBER 2022

&

NI638 GUIDANCE FOR LONG-TERM HYDRO-STRUCTURE CALCULATIONS

Methodologies

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DIRECT CALCULATIONS APPROACH

➢Basic idea
- Simulate the entire life of the unit and check the failure modes directly
  - *Extreme*
  - *Fatigue*

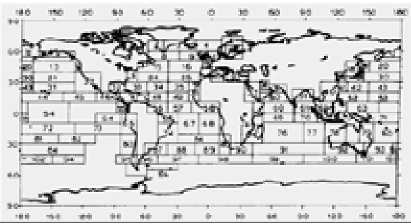
➢Main difficulties
- Accuracy of the deterministic tools
  - *Numerical*
  - *Experimental*
  - *Full scale*

S \ *H*	*Linear*	*Weakly nonlinear*	*Strongly nonlinear*
Static	✓	✓	✓
Dynamic	✓	✓	✓

- Methodologies
  - *Stochastic nature of the environment needs to be taken into account*

DESIGN METHODOLOGIES
Long term analysis

➢Context
- Within the direct calculation approach (or first principle approach) the structural response needs to be evaluated for the lifetime of the floating unit.
- The environmental conditions (wind, waves, current) are highly unsteady and stochastic in nature and it is fundamental to take into account these aspects within the design process.
- The statistical description of the environment should cover both its short term and the long term variations in order to properly asses the response in terms of extremes as well as in terms of the accumulated fatigue.
- Once the design environment defined the determination of the design responses for extreme and fatigue conditions, needs to be performed following the dedicated methodology.

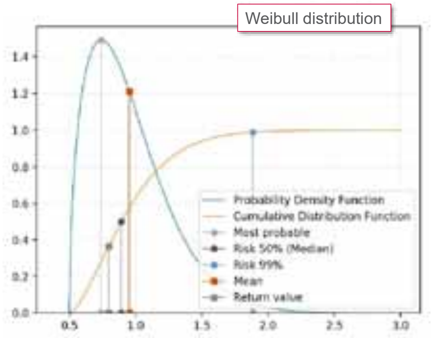


DESIGN METHODOLOGIES
Short-term and long-term variability

➢Definitions
- •Short and long term variability and associated distributions

➢Short term variability
- •Short-term distribution of events
- •Maximum response over a short duration T (few hours)
- •Response spectrum
  - *Spectral analysis*

➢Long term variability
- •Long-term distribution of events
- •Maximum response over a life time T



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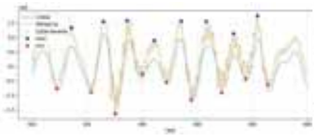
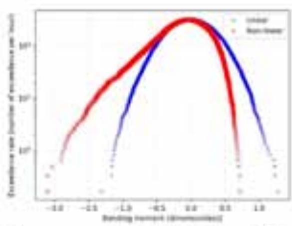
DESIGN METHODOLOGIES
Short-term statistics

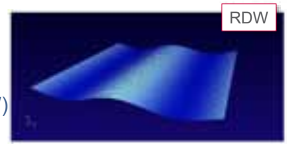
➢Purpose
- •Characterize the statistical distribution of the response cycles

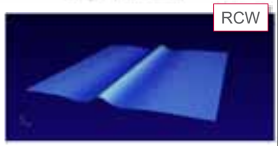




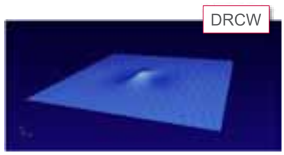
➢Frequency domain
- •Linear

➢Time domain
- •Nonlinear





➢Equivalent design wave approach (EDW)
- •Goal
  - *Reduce the short-term simulations to a limited number of very short duration wave events*
- •Regular design wave (RDW)
- •Response conditioned wave (RCW)
- •Directional response conditioned wave (DRCW)



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DESIGN METHODOLOGIES
Long term approaches

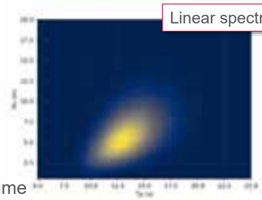
➢Purpose
- •Characterize the statistical long-term distribution of the response cycles
- •Balance between the accuracy and the CPU time

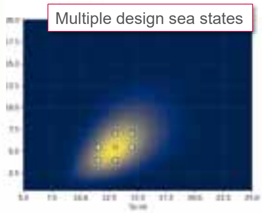
➢Linear spectral approach

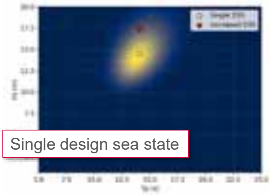
➢Multiple design sea-states

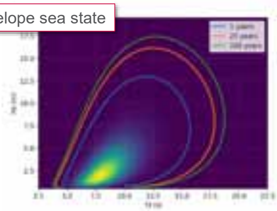
➢Single design sea-state

➢Envelope sea-states


Linear spectral analysis


Multiple design sea states


Single design sea state


Envelope sea state

DESIGN STRATEGIES
Extreme response

➢Different possibilities
1. Linear long term extreme
2. Linear long-term extreme + non-linear correction based on design wave
3. Linear long-term extreme + non-linear correction based on a single design sea-state
4. Short-term approach based on envelope sea-states
5. Linear long-term extreme + non-linear correction based on multiple design sea-states
6. Linear long-term extreme + non-linear correction based on multiple design sea-states using EDWs
7. Prescriptive approach

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state		③Stress
Multiple design sea-states	②Non-linear loads	
Entire scatter diagram	①Linear loads	

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DESIGN STRATEGIES
Fatigue life

➢Different possibilities

1. Linear spectral fatigue damage
2. Linear spectral fatigue damage + non-linear correction based on a single design sea-state
3. Linear spectral fatigue damage + non-linear corrections based on multiple design sea-states
4. Linear spectral fatigue damage corrected by several stress based design waves
5. Fatigue damage from load based design waves at several probability levels
6. Fatigue damage from load based design waves at one probability level
7. Prescriptive approach

	Sea-state short-term	Equivalent Design Wave
Envelop sea-state		
Single design sea-state	②Non-linear stress	
Multiple design sea-states		
Entire scatter diagram	①Linear stress	

BUREAU VERITAS

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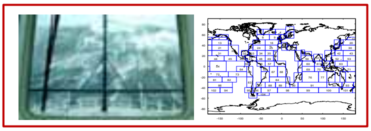
DESIGN STRATEGIES
Specific problems (slamming, green water …)

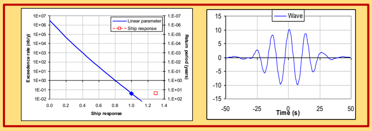
1. Definition of the operational profile

1 Operational profile



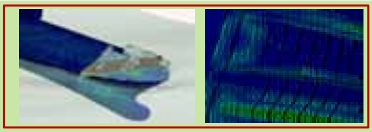
2. Long term analysis and definition of the short duration design conditions

Potential flow
2 Design conditions



3. Hydro structure interactions simulations on selected design conditions

CFD
3 H-S interactions



BUREAU VERITAS

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CONCLUSIONS

- Classification societies represent an essential link between the owners (operators) of engineering constructions and the insurance companies
- They guarantee the sufficient safety level of the units by applying the state of the art tools and methodologies
- Marine structure are specific and quite some uncertainties still exist
  - Deterministic numerical tools of different levels of accuracy
    - *Potential flow, CFD, FEM …*
  - Design methodologies
    - *Uncertainties in the definition of the representative operational profile*
    - *Stochastic nature of the environment requires extensive number of numerical simulation*
    - *Combined use of low and high level accuracy numerical tools*
      - Low accuracy tools (potential flow) for detrmination of the design conditions
      - High accuracy numerical tools (CFD-FEM) for evaluation of the response at design conditions
  - Safety factors are still required
- Rules and procedures are continuously updated in order to account for the most recent advances in the development of the numerical tools

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Thanks for your attention

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