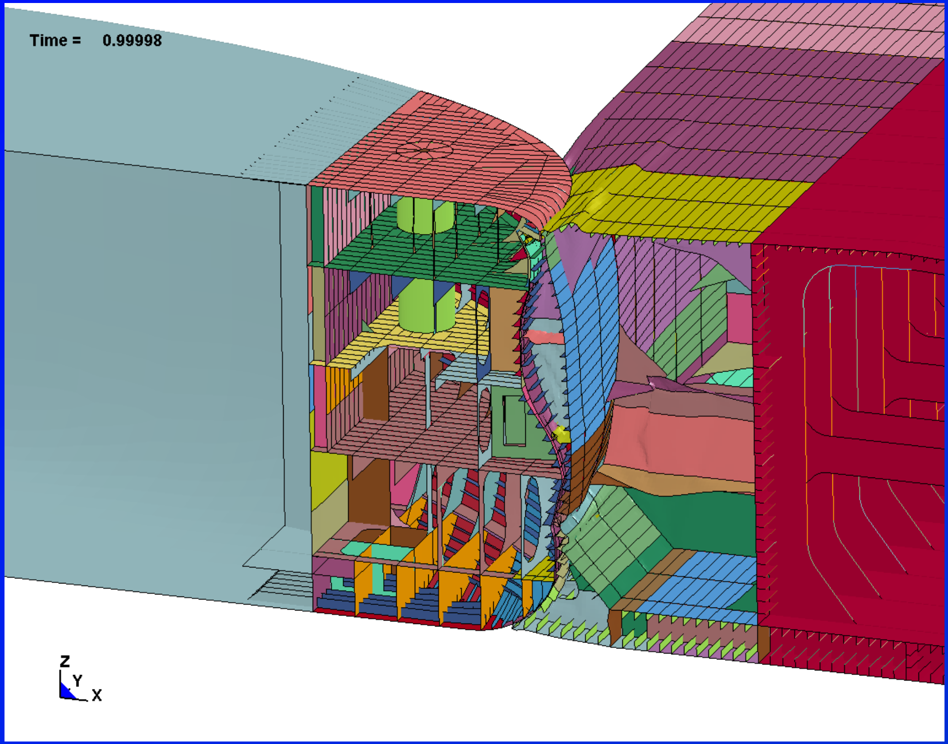
衝突時の被害低減のための船体構造への高延性鋼(HDS＊)適用に関する研究



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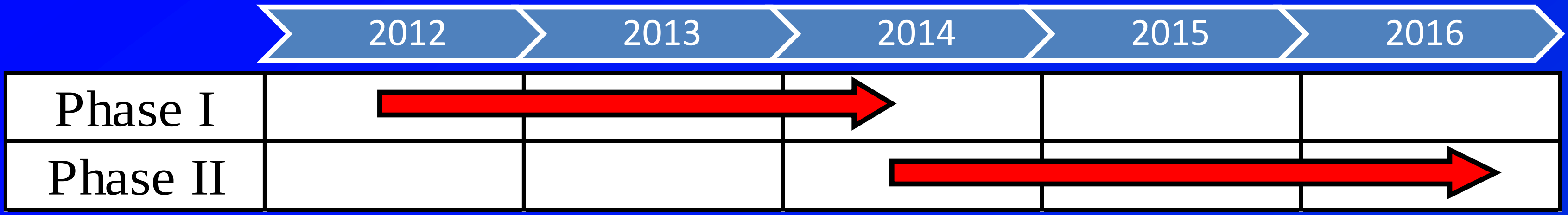
＊HESから名称変更

HDS Project



Nippon Steel & Sumitomo Metal

Imabari Shipbuilding Co., Ltd.

ClassNK

National Institute of Maritime, Port and Aviation Technology

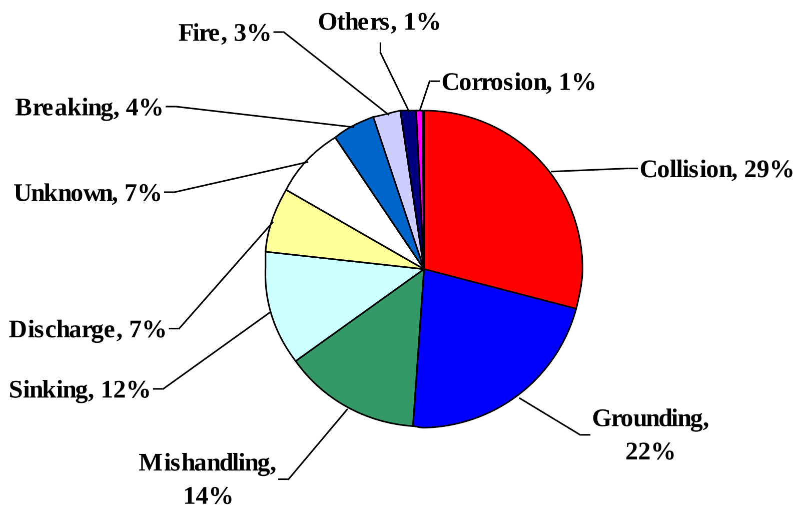
- HDS Project has started since 2012
- The project consists of Phase I and II

Contents

Background

1. Background

- Collision & Grounding most probable cause
- D/H system is effective, but not sufficient as shown in accidents such as Baltic carrier (2001).
- Important to further reduce risk of oil spill from ship collision.
- IMO discussion about environmental FSA.

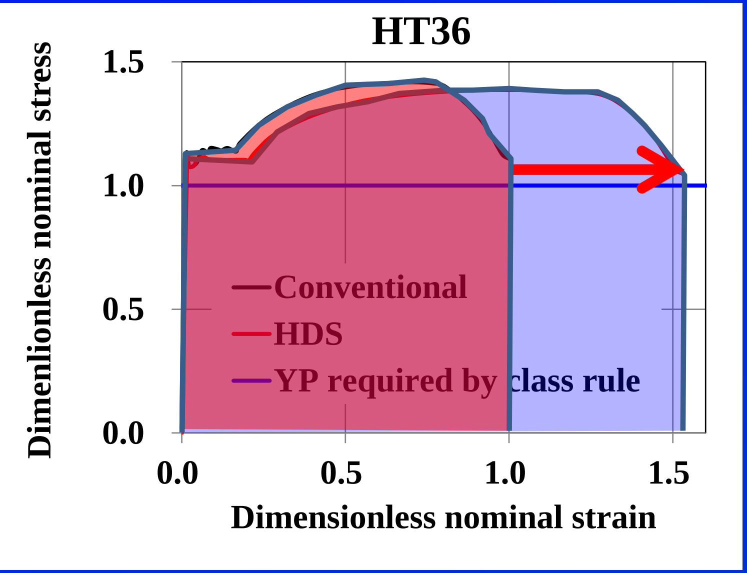


Cause of oil spills from tankers in 1970-2008
IOPCF (2008)

- Recently new material is developed and is applicable to ships.
- Highly Ductile Steel (HDS)

2. Concept of Highly Ductile Steel (HDS)

(1)Elongation of HDS is assumed to be about 1.5 times larger than minimum requirement of conventional steel considering current material technology



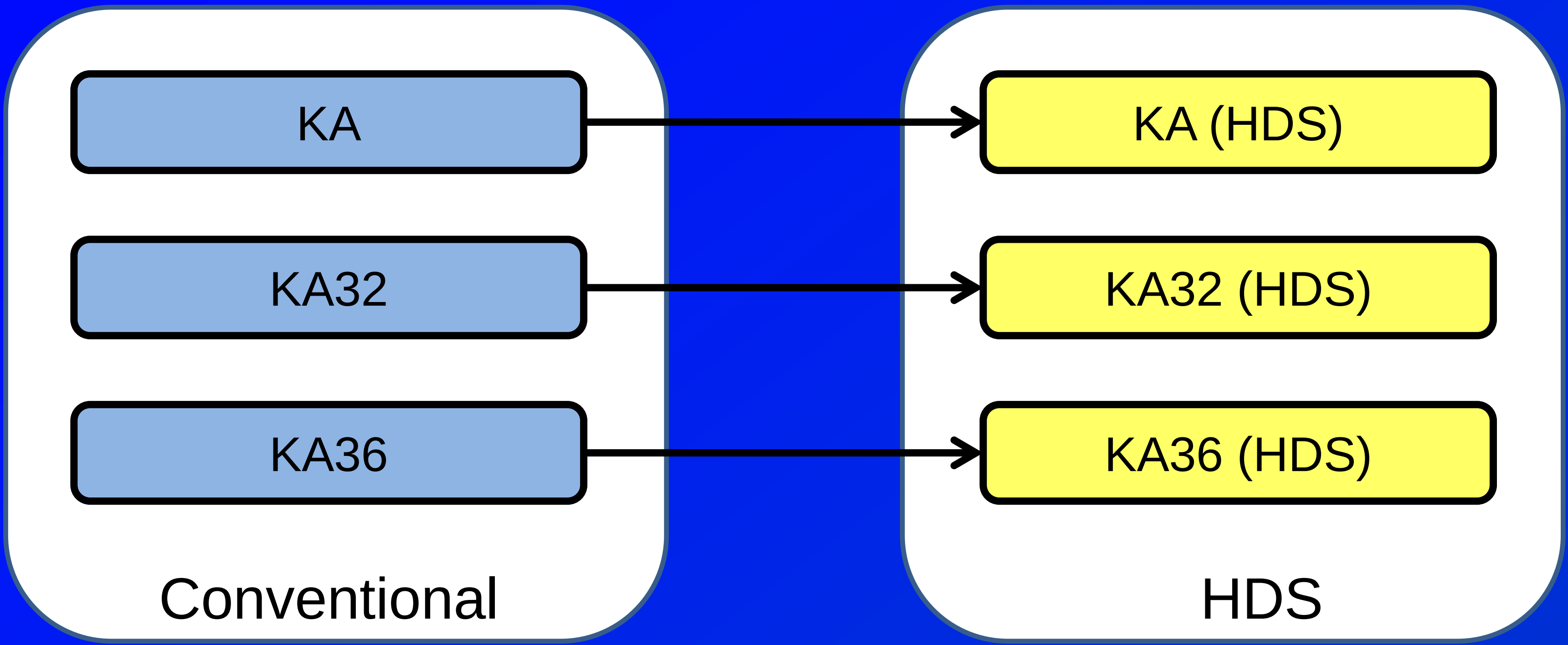
(2)while keeping yield, tensile and fatigue strength as well as weldability.

(3)comply with class rule
(already approved by NK +Notation given)

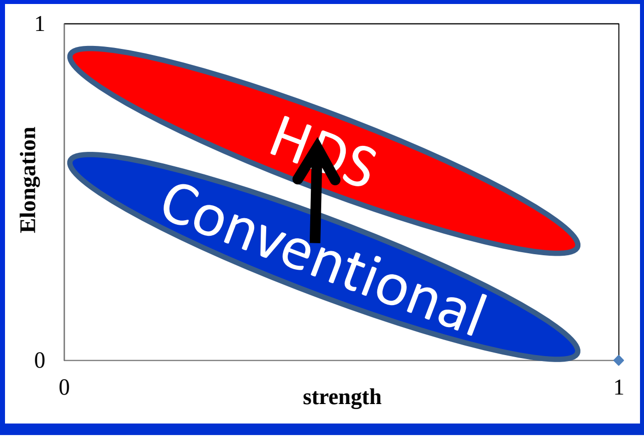
(4) can be applied without changing conventional structural design

Point : HDS can be used just by substituting plate only !!

3 Types of HDS developed by NSSMC



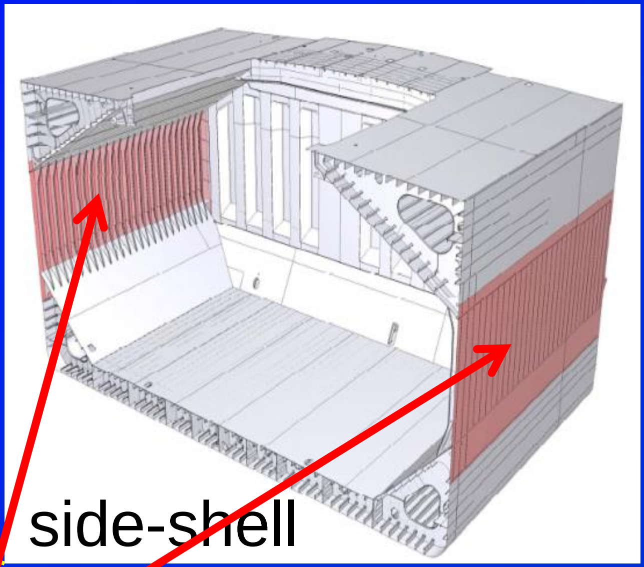
- Generally, Elongation is inversely proportional to strength.
- It is difficult to manufacture HDS for High strength steel

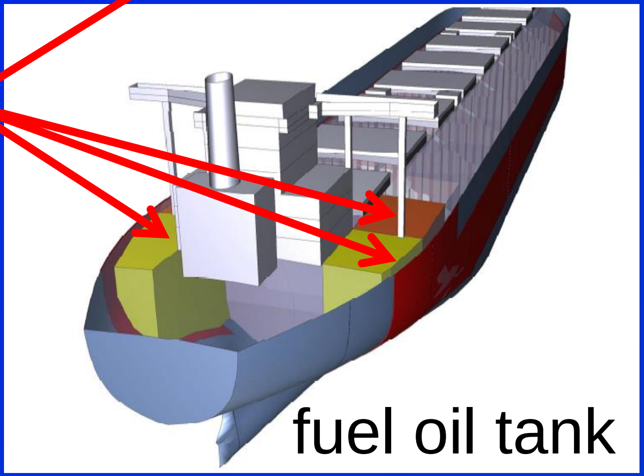


World First Application of HDS on actual ship

Loa	299.94 m
B	50m
D	24.7 m
DWT	206, 600 ton

Highly ductile steel (HDS)





HDS applied to side shell and fuel oil tank of the BC, 3000 ton of HDS used in total.
Since then 6 ships already delivered, 10 ships adopted (as of 1st Oct, 2016).

Class Notation : HP-HDS

ClassNK Notation

"Hull Protection by Highly Ductile Steel" (HP-HDS)

Notation is assigned to ships using ClassNK approved HDS effectively to increase the energy absorbed by the hull in the case of collision or grounding.

Descriptive Note

Specifies the grades and application areas of the HDS used.

e.g. : KA32-HD XX applied to side shell plate and side longitudinal within Fr. XX-XX(or No. X-X WBT)

Material grade of HDS

Approved HDS is indicated by "HD XX"

"XX" shows the increased percentage of elongation of HDS against the rule required minimum specified elongation of the corresponding normal steel.

e.g. : KA32-HD50 for 15＜t≦20

KA32-HD50 is Highly Ductile Steel with minimum specified elongation 27%, where the minimum specified elongation of KA32 is 18%. (18 x 1.5 = 27)

3. Objectives of the Project

- To investigate effects of HDS on crashworthiness of the struck ship using a large-scale ship-ship collision analysis with Nonlinear FEA (NLFEA)

- Assessment index
  - ▪Energy absorption capability
  - ▪Critical striking velocity (minimum speed of causing rupture of cargo oil tank)

- Comparative study : Conventional vs HDS

  Several application pattern of HDS investigated

Analysis condition

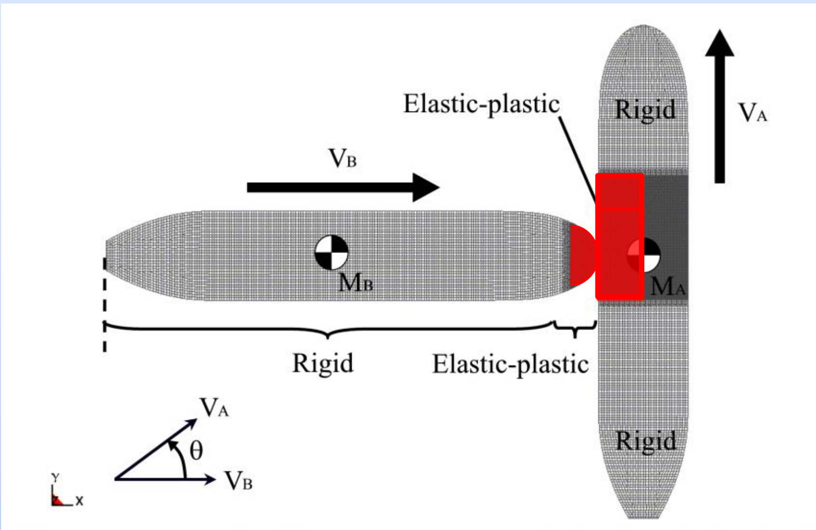
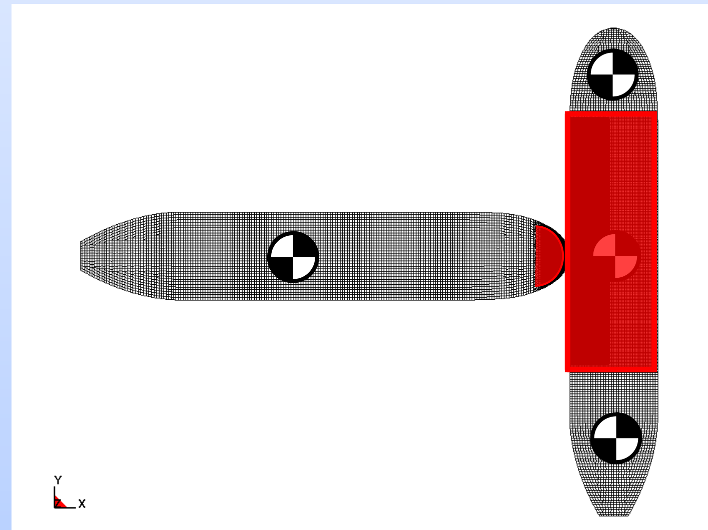
Overview of Analysis

The project consists of 3 sets of simulations

Simulation No.	Phase	Struck ship model	Struck ship motion	Collision Angle	HDS Application Pattern	Outer shell	Outer shell longi.	Inner shell	Inner shell longi.	Outer shell bilge	Other members	Number of cases
Simulation 1	I	Model 1 (1 tank)	Considered	90	Conventional							44
					Partial Application I	○		○				
Simulation 2	II	Model 2 (9 tanks)		30-150 (oblique)	Conventional							53
					Partial Application I	○		○				
					Partial Application II	○	○	○				
					Full Application	○	○	○	○	○	○	
Simulation 3			Fixed (Conservative)	90	Conventional							45
					Partial Application OS	○	○					
					Partial Application IS			○	○			
					Partial Application OS+IS+B	○	○	○	○	○		
											Total	142

- Simulation 1: θ=90, preliminary, 2 patterns
- Simulation 2: θ=30-150, Oblique collision, 3 patterns
- Simulation 3: Effect of HDS on Deformation, 4 patterns

Finite Element Model

Model 1 (Phase I)	Model 2 (Phase II)
Simulation 1	**Simulation 2 and 3**
	
1 tank elasto-plastic model	9 tanks elasto-plastic model Horizontal hull girder bending considered Effect of boundary condition reduced

Analysis Condition

Solver : LS-DYNA ver.971

explicit analysis

FE model (Model II)	Node	Element	Part
Struck Ship (A13)	669,110	825,299	2166
Striking Ship (B10)	157,546	168,110	357
Total	826,656	993,409	2,523

VLCC vs VLCC

Striking, struck ship : elasto-plastic + rigid

Material Model: piecewise linear model (MAT24)

Failure (Barba's law + stress-tri-axiality)

Strain rate effect (Cowper-Symonds Model)

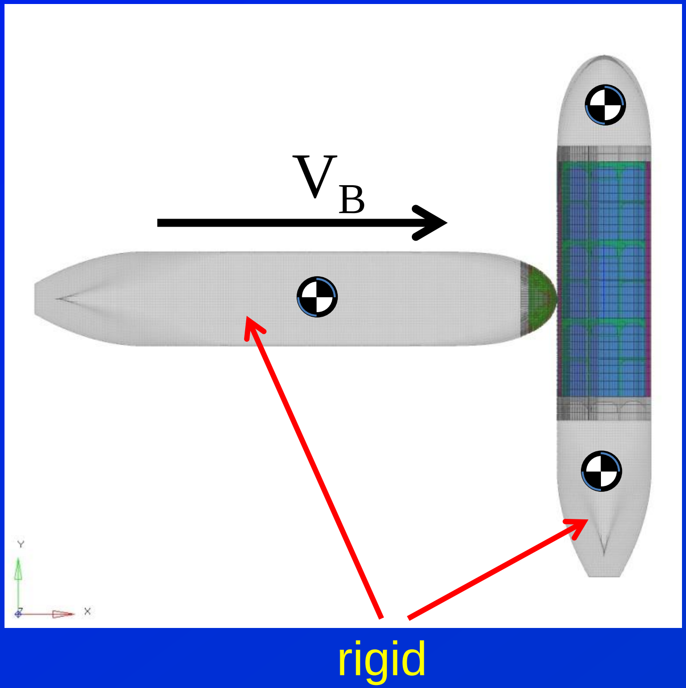
Contact (Penalty method including self-contact)

9 tanks of cargo oil: mass element

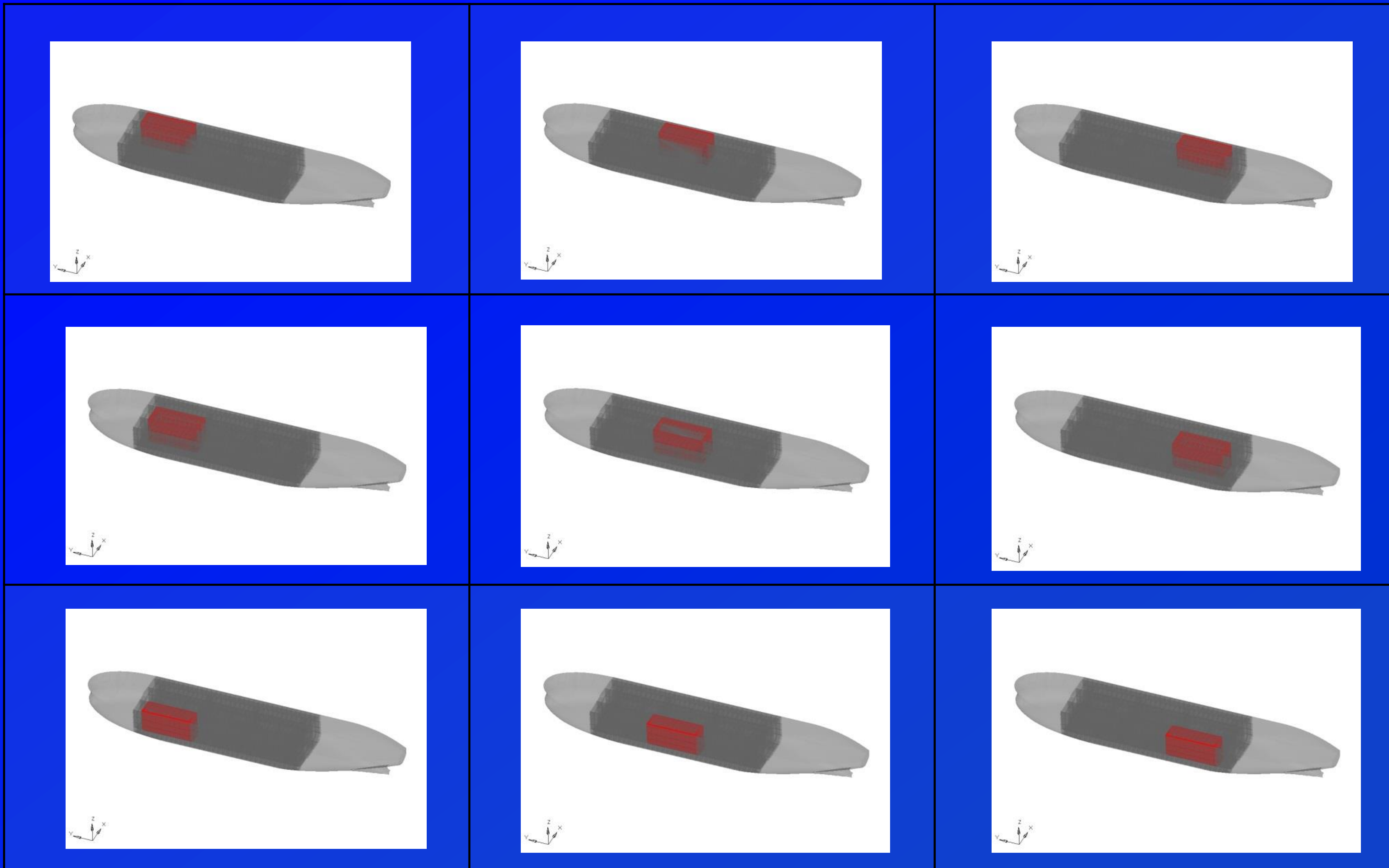
6 DOF for both ships (mass matrix)

sea water : added mass (Sway, Surge)

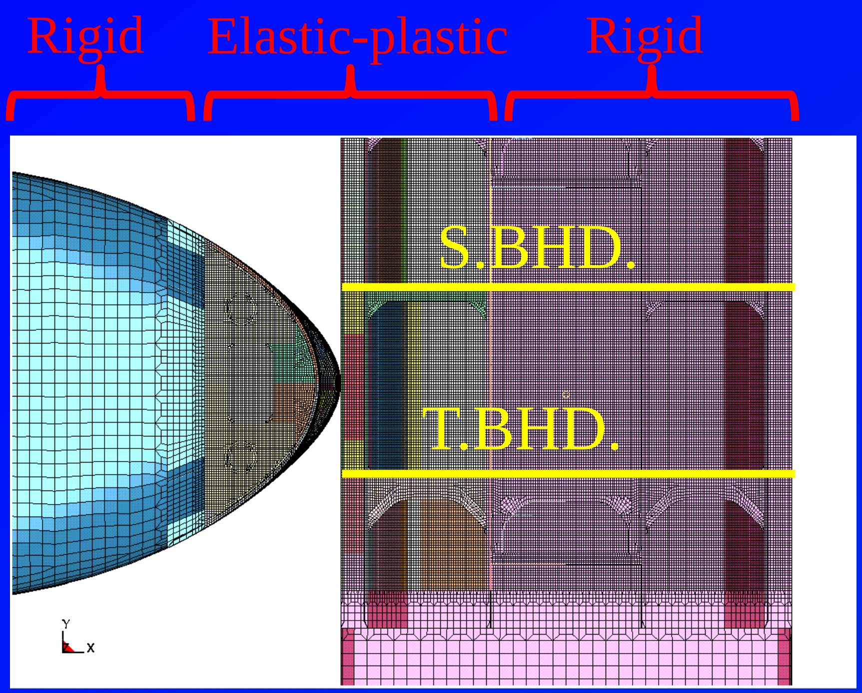
Restoring force (Roll, Pitch, Heave) : spring element



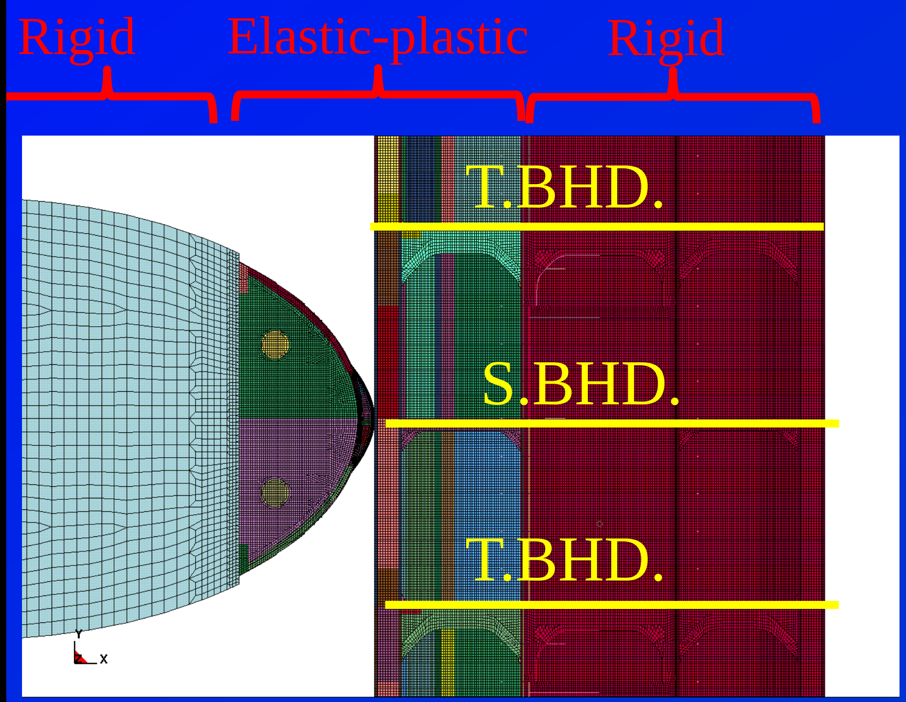
Modeling of mass of cargo oil tanks



Collision Scenario - collision point -



Collision Point 1
(Bet. BHD)



Collision Point 2
(On S.BHD)

Collision Point 1 is assumed in Phase II (severe for the struck ship)

Critical Striking Velocity ($V_{B,cr}$)

Definition: Minimum striking ship speed to penetrate cargo oil tank in case of collision, below which oil spill does not take place in collision (can be navigational index for ship master).

Simplified formula (SF)

If θ=90, V_A=0

Momentum Conservation

Energy Conservation

$$V_{B,cr} = \sqrt{2E_{s,cr} \times \frac{M_A + M_B}{M_A M_B}}$$

M_A、M_B : displacement of ships including added mass.

$E_{s,cr}$: Absorbed Energy by the time of cargo oil tank rupture.

- By using the above formula, VB,cr can be effectively estimated by one simulation analysis (without carrying out a lot of analysis).

Analysis results
(Simulation 1)

Overview of Analysis

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					Full Application	○	○	○	○	○	○	
Simulation 3			Fixed (Conservative)	90	Conventional							45
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						Total						142

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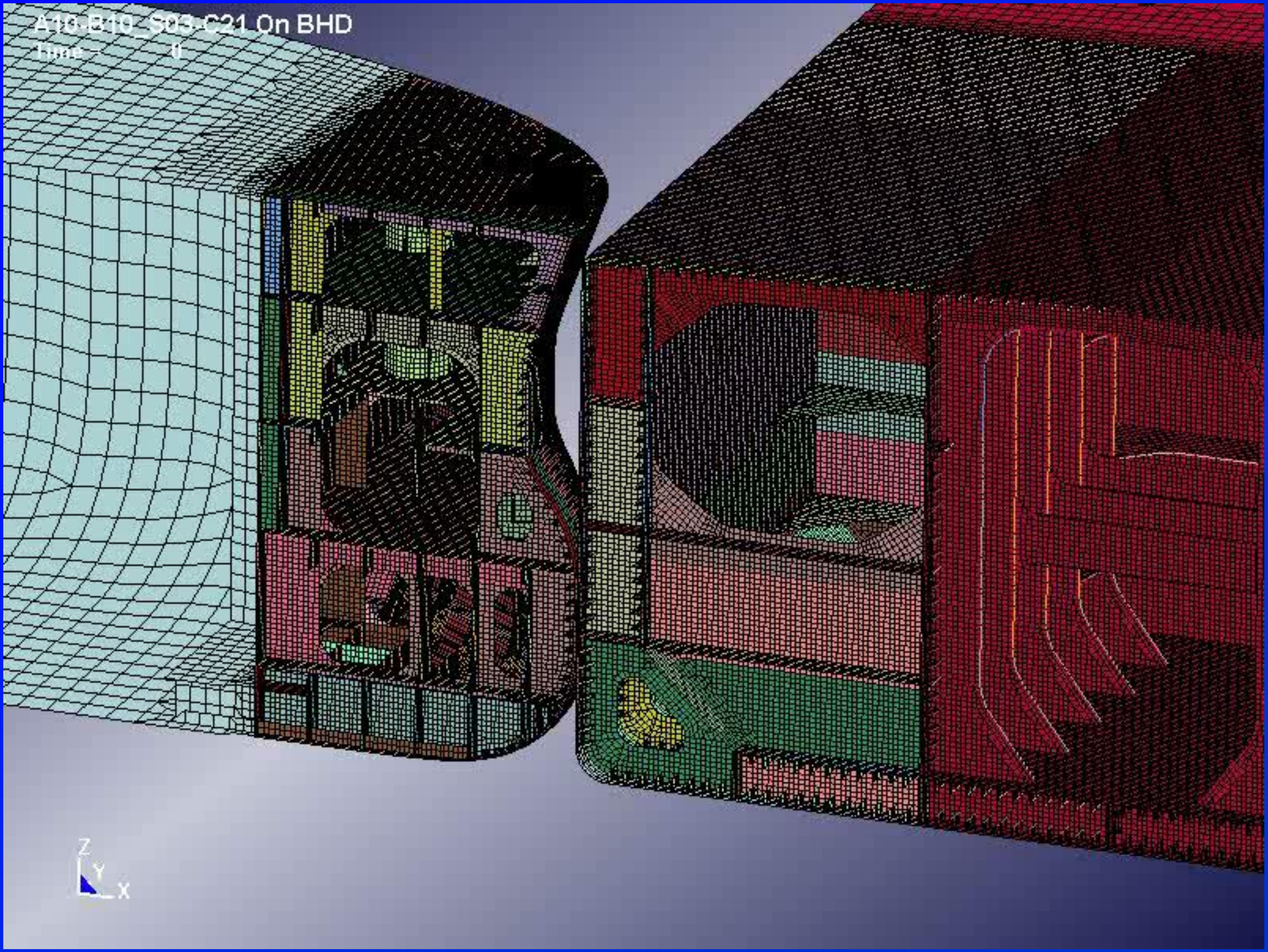
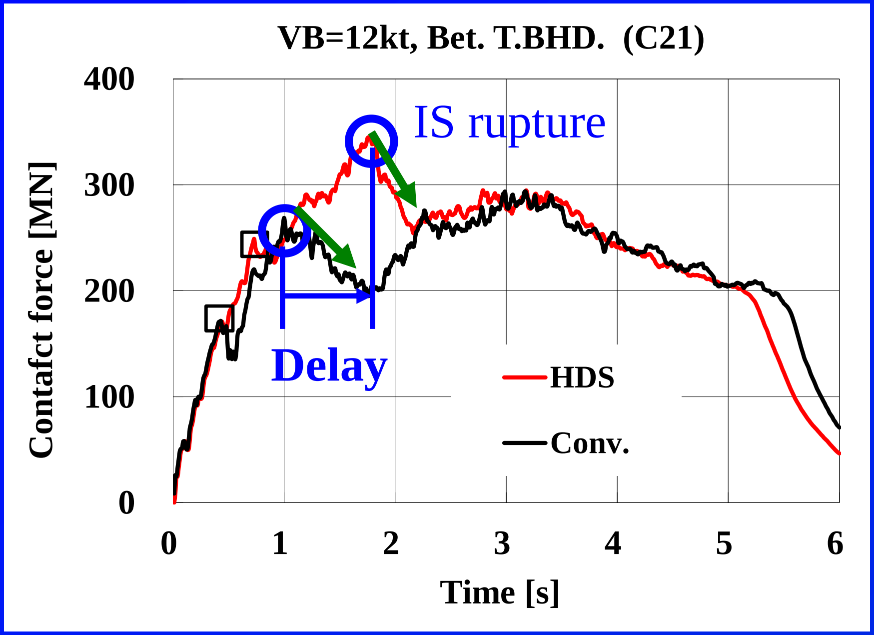
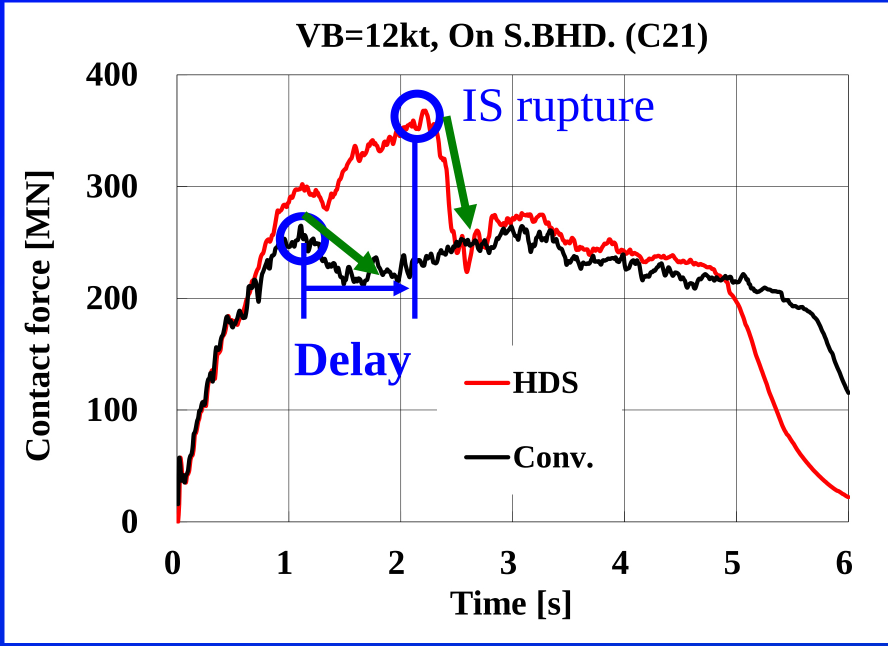
FEA Results (Phase I, Simulation 1, V=12kt, θ=90)



Comparison of histories of contact force



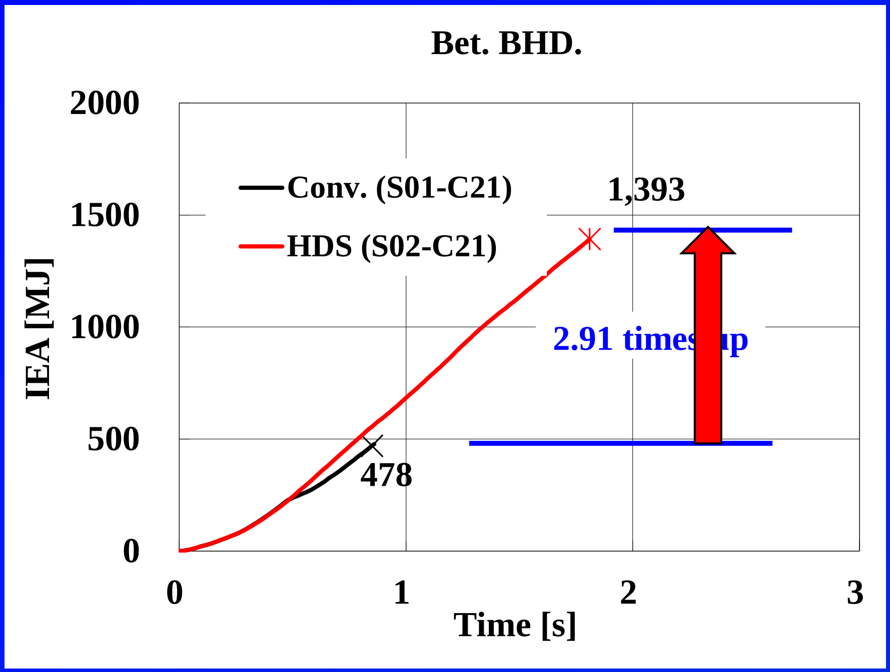


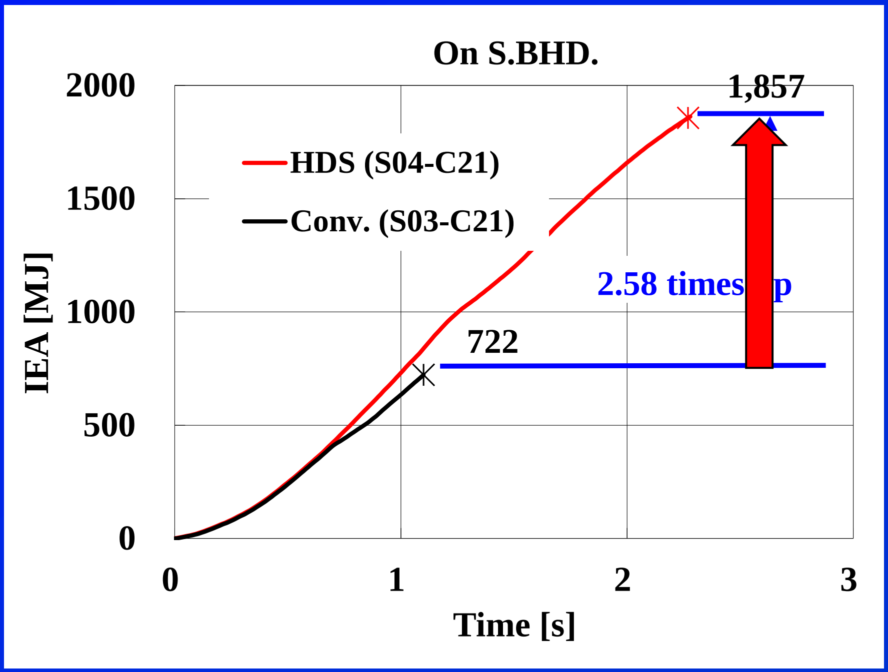
Between T.BHD On S.BHD

Black: Conventional, Red: HDS

- Contact force decrease significantly after IS rupture.
- Due to application of HDS, delay of IS rupture can be seen
- ($T_{rupture}$; 0.87s →1.81s, 1.11s→2.28s, 2 times later).

Effect of HDS on Energy absoprtion

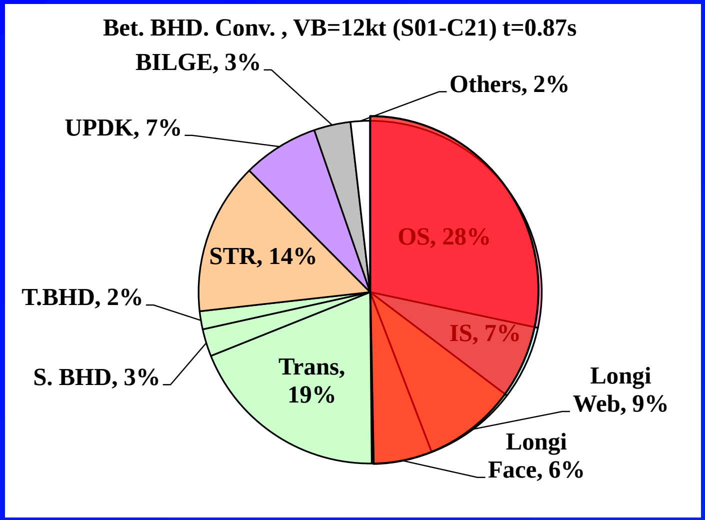




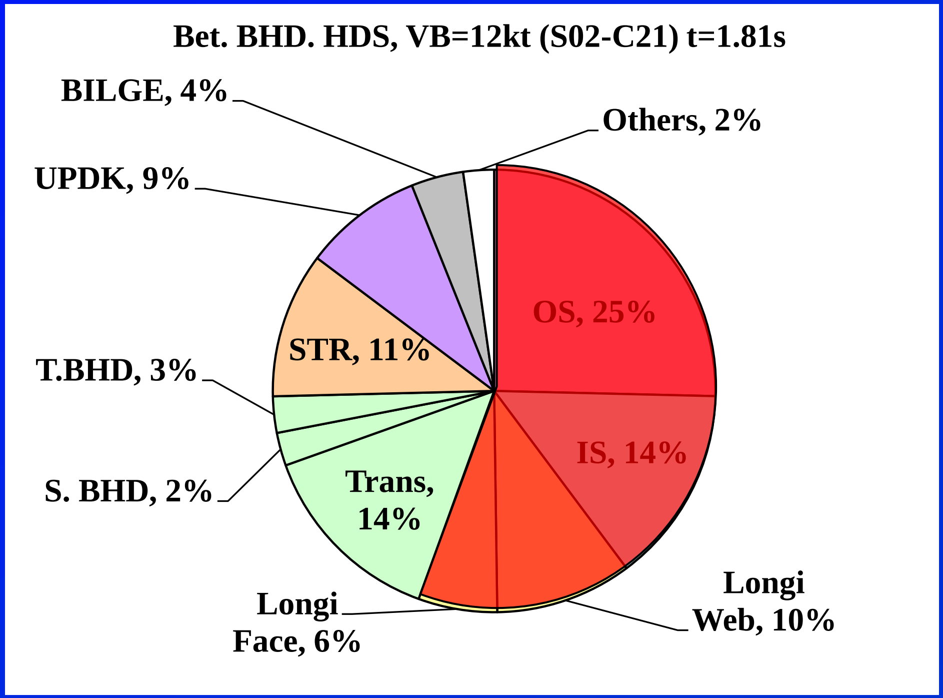
Energy absoprtion by the struck ship until oil tank rupture becomes about 2.6-2.9 times larger than conv.

Simulation 1: Share ratio of energy absorption by structural members

Between T.BHD (Analysis of 756 parts for the struck ship)



Conventional **478**[MJ]



HDS **1393**[MJ]

- Absolute value of energy absorption by HDS is about 3 times larger than Conv.
- Energy absorption by OS is the largest mainly due to membrane effect.
- Interesting to note more than 50% energy by OS+IS+Longitudinal

Validation of SA

Validation for Simplified Formula (SF)

44 cases of FEA simulation carried out

	VB [kt]													
	2	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**15**	**16**	**18**	**20**
Case	C34	C31	C29	C23	C33	C25	C27	C26	C28	C21	C30	C36	C35	C32
S01	○	○	○	×	×	×	×	×	×	×	×	-	×	×
S02				○		○	×	×	×	×	×	×	×	×
S03				○	×	×	×	×	×	×	×	-	×	×
S04	○			○		○	○	○	○	×	×	×	×	×

No rupture

Rupture

Critical point
(VB,cr = 5.5kt)

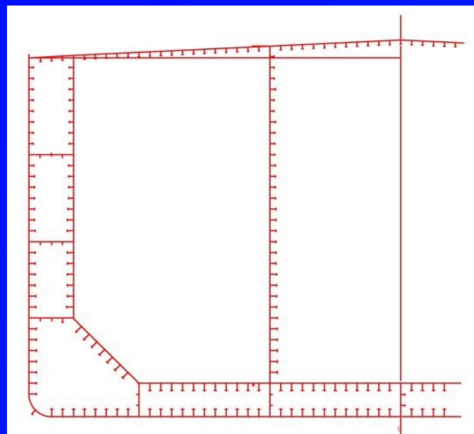
Case	VB,cr [kt]		Error [%]
	SF+FEA (1case)	FEA (44cases)	
1	5.1	5.5	7.3
2	8.7	8.5	-2.4
3	6.3	6.5	3.1
4	10.0	11.5	13.0

- 1 cell represents 1 simulation analysis (1 week)
- Simplified formula gives fairly good estimation of VB,cr, considering its computational efficiency although small discrepancies can be seen.

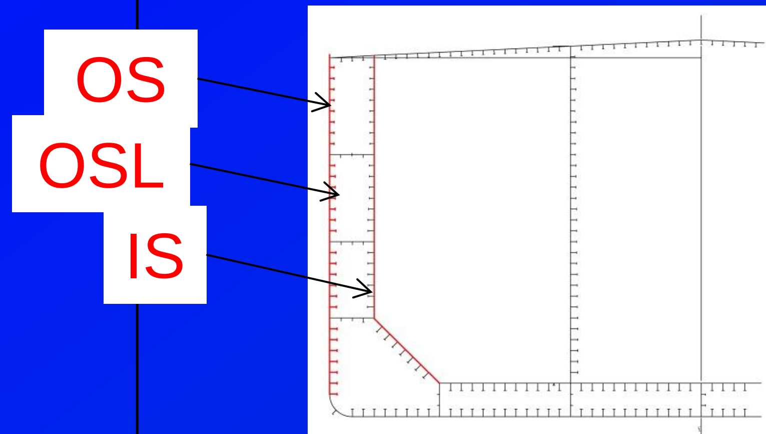
Analysis results (Simulation 2)

2a : θ=90, 4 patterns of HDS application
2b: Oblique collision -> rupture limit curve

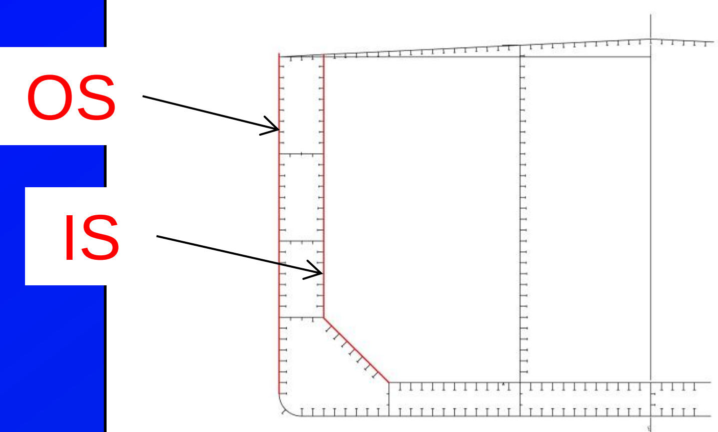
Simulation 2: Application Patterns of HDS (4 patterns)



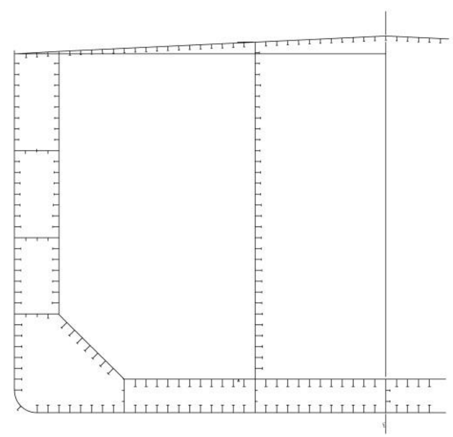
4. HDS-Full (All members HDS)



3. HDS-Partial II (OS+IS+OSL)



2. HDS-Partial I (OS+IS)



1. Conventional（No HDS）

4.2 HDS application pattern

HDS Application Pattern		Outer sell	Inner shell	Outer shell longi.	Inner shell longi.	Other members
1	Conventional					
2	HDS-Partial I	●	●			
3	HDS-Partial II	●	●	●		
4	HDS-Full	●	●	●	●	●

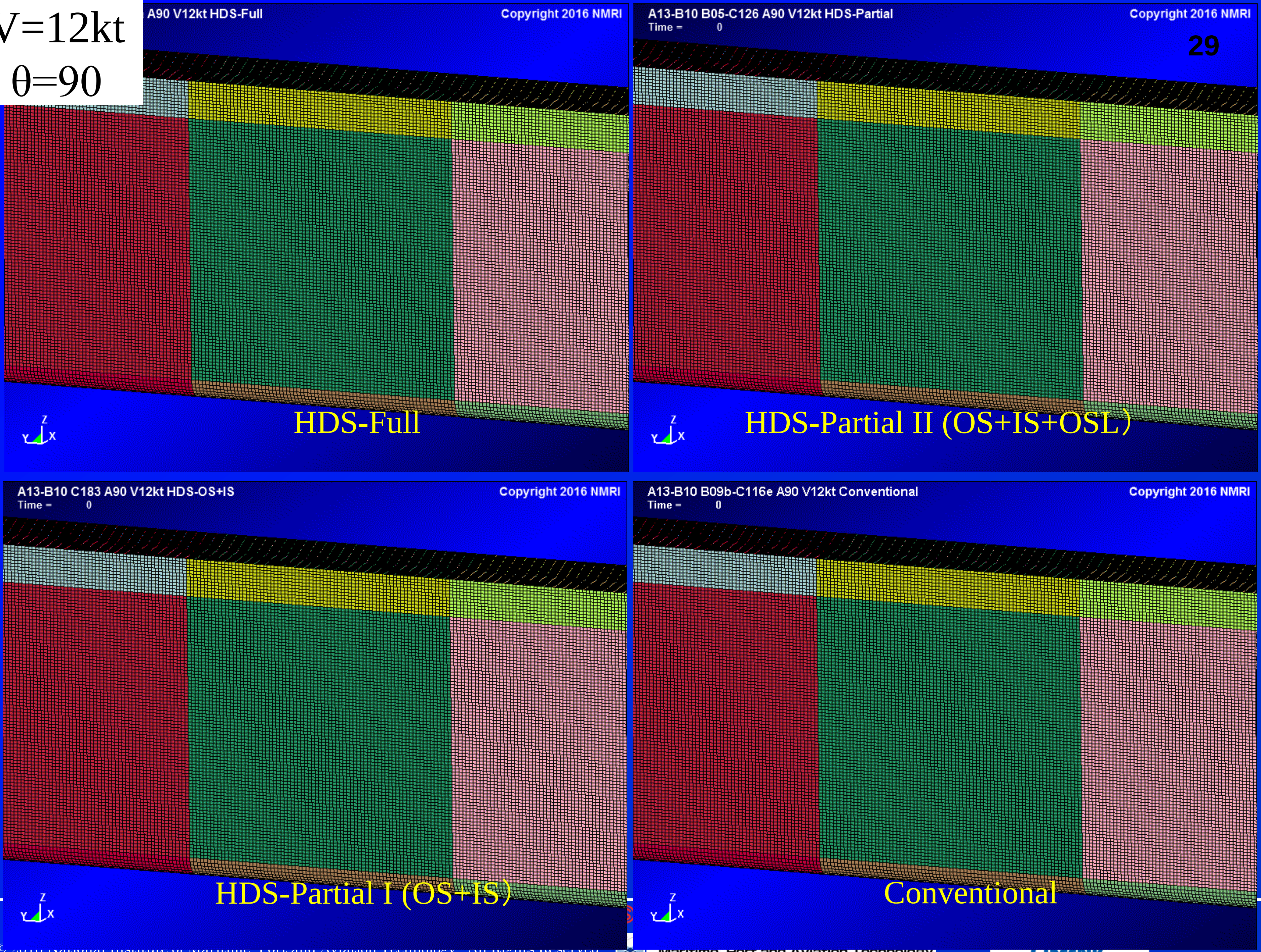
amount of HDS applied

less

more

- Amount of applied HDS increases as 1→2→3→4

V=12kt
θ=90


A90 V12kt HDS-Full
Copyright 2016 NMRI
HDS-Full
A13-B10 B05-C126 A90 V12kt HDS-Partial
Time = 0
Copyright 2016 NMRI
HDS-Partial II (OS+IS+OSL)
A13-B10 C183 A90 V12kt HDS-OS+IS
Time = 0
Copyright 2016 NMRI
HDS-Partial I (OS+IS)
A13-B10 B09b-C116e A90 V12kt Conventional
Time = 0
Copyright 2016 NMRI
Conventional

Simulation 2: Analysis cases (53 cases)

HDS-Full

	Velocity [knot]										
Angle	12	10	9	8	7	6	5	4	3	2	1
60	–	–	–	–	–	–	–	–	–	–	–
75	○	–	–	–	–	–	–	–	–	–	–
90	○	–	–	–	–	–	–	–	–	–	–
105	○	–	–	–	–	–	–	–	–	–	–
120	–	–	–	–	–	–	–	–	–	–	–
135	–	–	–	–	–	–	–	–	–	–	–
150	–	–	–	–	–	–	–	–	–	–	–

HDS-Partial II

	Velocity [knot]										
Angle	12	10	9	8	7	6	5	4	3	2	1
60	–	–	–	–	–	–	–	–	–	–	–
75	○	–	–	–	–	–	–	–	–	–	–
90	○	–	–	–	–	–	–	–	–	–	–
105	○	–	–	–	–	–	–	–	–	–	–
120	–	–	–	–	–	–	–	–	–	–	–
135	–	–	–	–	–	–	–	–	–	–	–
150	–	–	–	–	–	–	–	–	–	–	–

Conventional

	Velocity [knot]										
Angle	12	10	9	8	7	6	5	4	3	2	1
30	○	–	–	–	–	–	–	–	–	–	–
45	×	×	–	○	○	○	–	–	–	–	–
60	×	–	–	–	×	○	○	○	–	–	–
75	×	×	–	×	–	○	○	○	–	–	–
90	×	–	–	–	–	×	×	○	○	○	○
105	×	–	–	–	×	×	×	○	–	○	–
120	×	–	–	–	×	○	○	○	–	–	–
135	×	×	○	○	–	○	○	○	–	–	–
150	○	–	–	–	○	○	○	–	–	–	–

- 3+3+46=52 cases, 1 case only for Partial I (θ=90deg)
- × : IS rupture、○IS not rupture

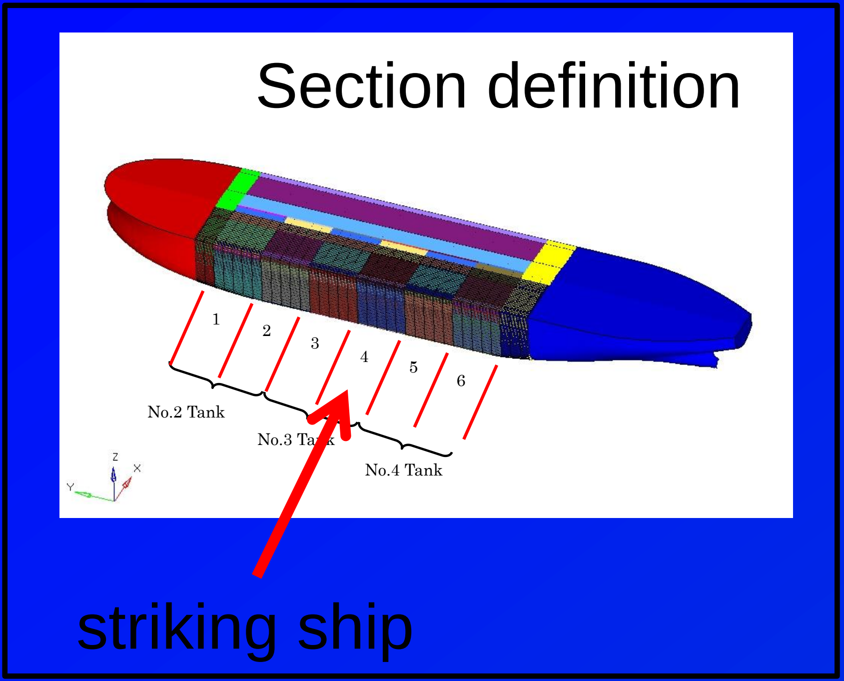
Application pattern of HDS

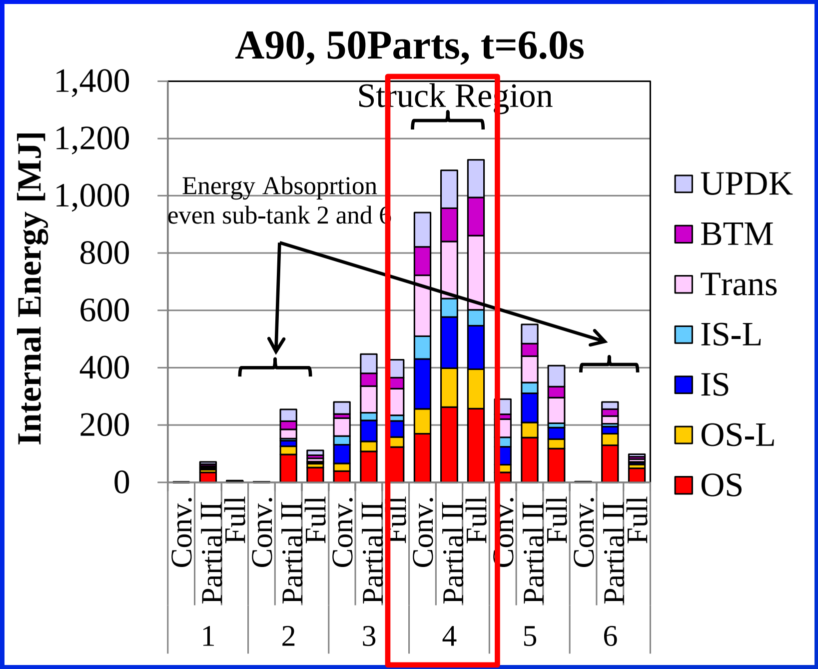
	HDS Application Pattern (● applied)	Outer shell	Inner shell	Outer shell longi.	Inner shell longi.	Other members	OS Rupture	IS Rupture
1	Conventional						×	×
2	HDS-Partial I	●	●				×	×
3	HDS-Partial II	●	●	●			○	○
4	Full	●	●	●	●	●	○	○

× rupture
○ not rupture

・Effectve to apply to longitudinal of OS to prevent rupture of cargo oil tank.

Spatial distribution of energy absorption (in longitudinal direction) - which region absorbs how much energy ? -





- Section No.4 absorb largest energy
- Initial stage: Next to OS, Trans absorbed much energy
- In Partial II, Full, energy absorption not only at No.4 but also at No.2 and No.6 → presumably due to membrane effect of OS

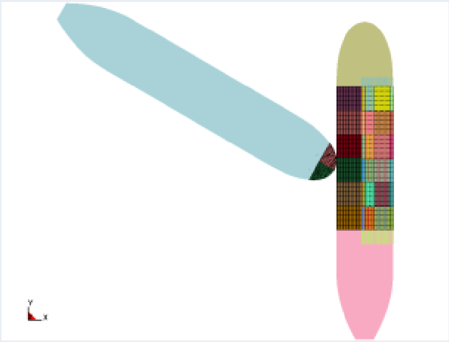
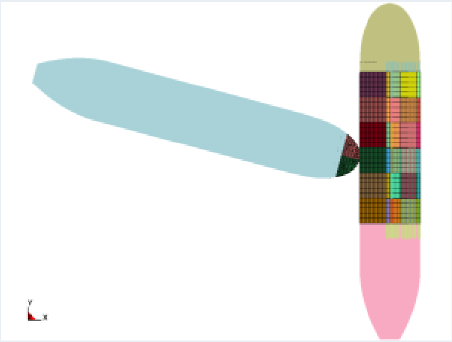
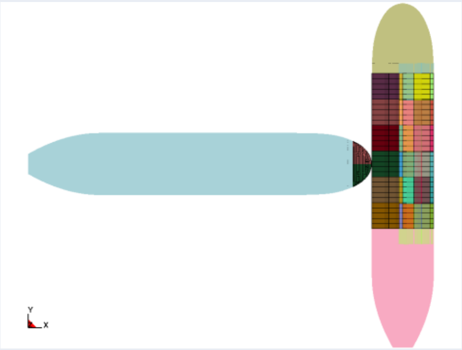
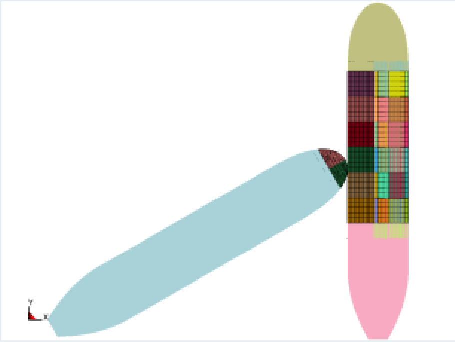
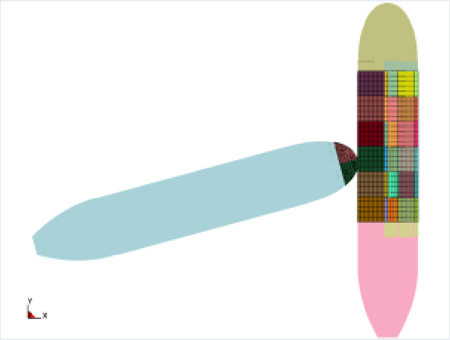
Mechanism of increase of energy absorption in using HDS

1. Delay of rupture due to larger elongation capability

2. Increase of energy absorption in space due to delay of rupture (especially increase in longitudinal direction)

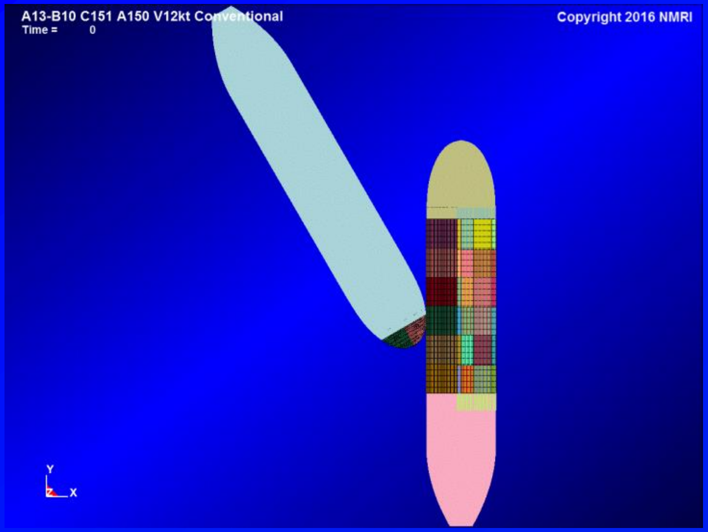
Synergetic effects of above 1. and 2. is presumed to cause the increase of energy absorption by the point of IS rupture

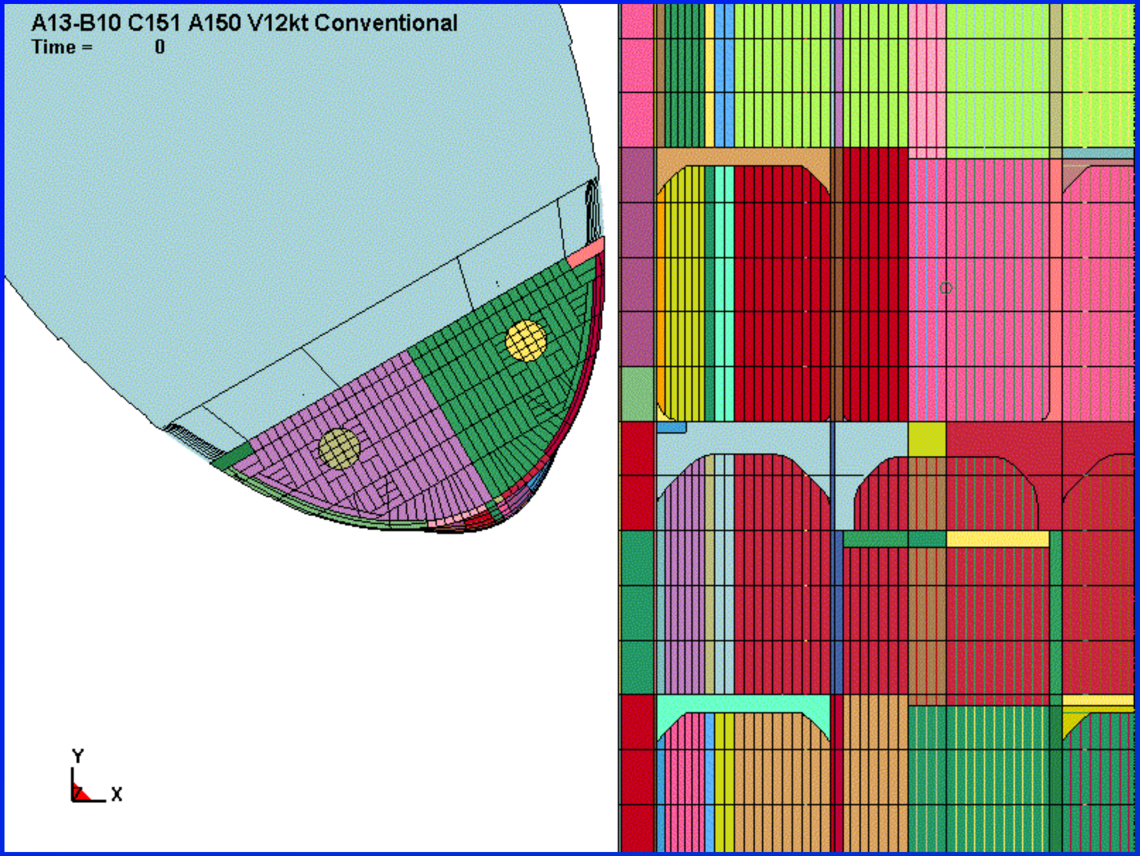
4.1 Initial setup of oblique collision analysis

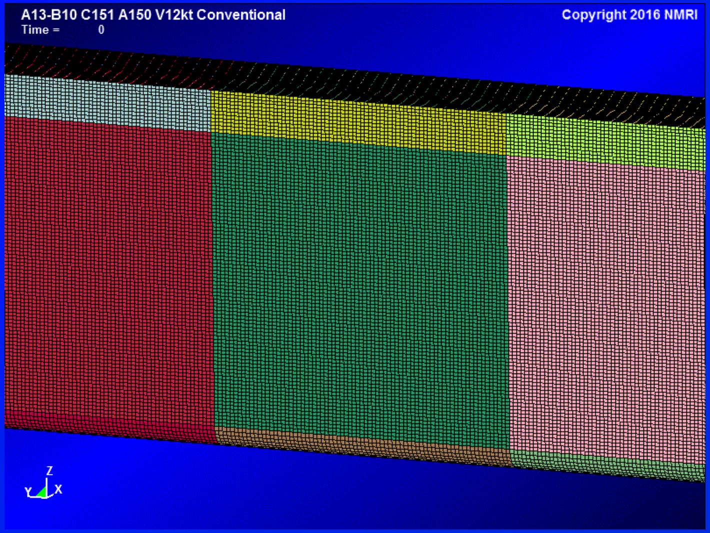
		
θ=120	θ=115	θ=90
		
θ=60	θ=75	

- No forward speed of striking ship assumed
- θ＝30, 45, 60, 75, 90(right angle), 105, 120, 135, 150 (9 angles)

Example results of oblique collision (θ=150deg)

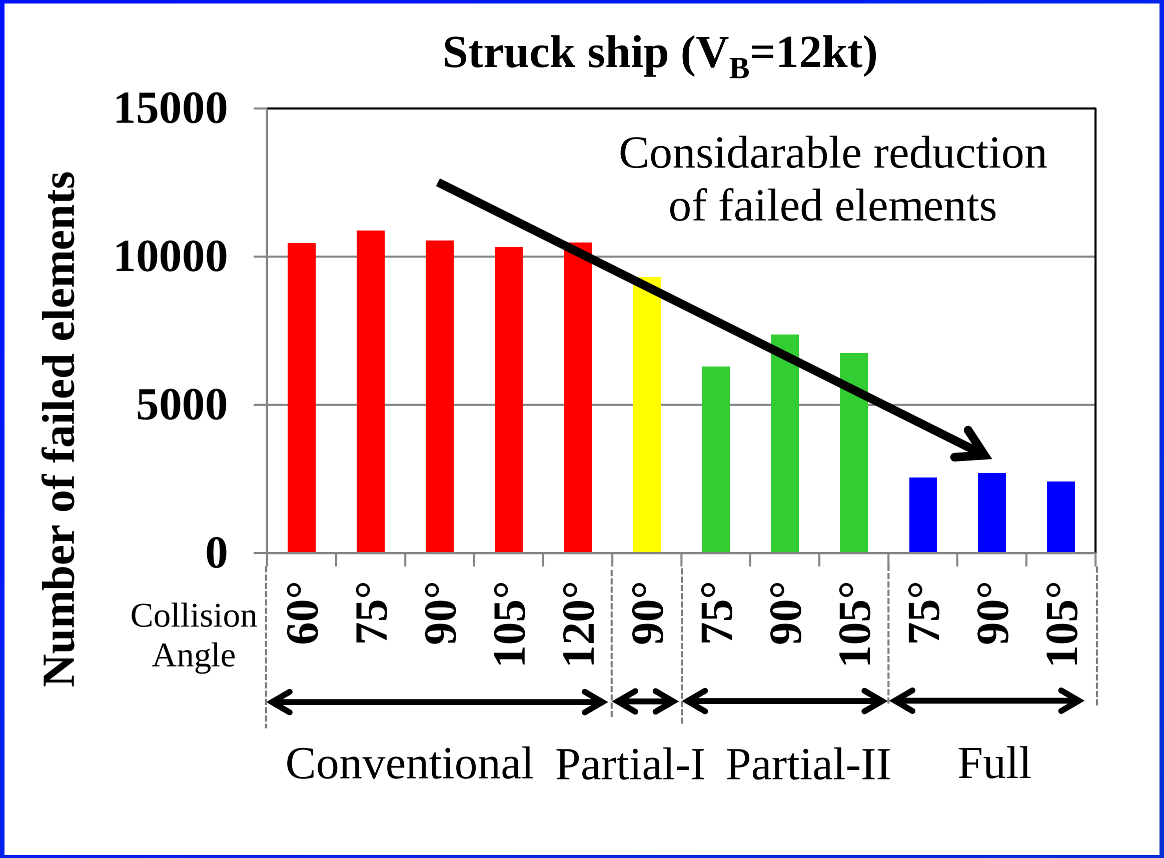






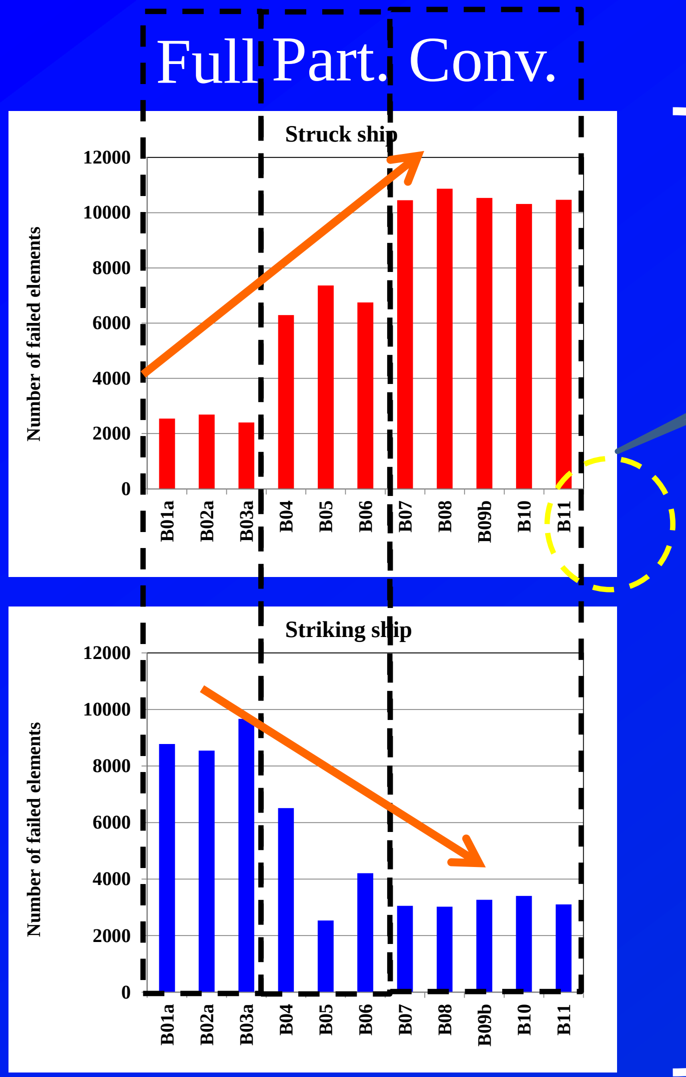
In θ=30、150deg, slip condition take place. Out-of-plane deformation of OS take place without rupture is observed.

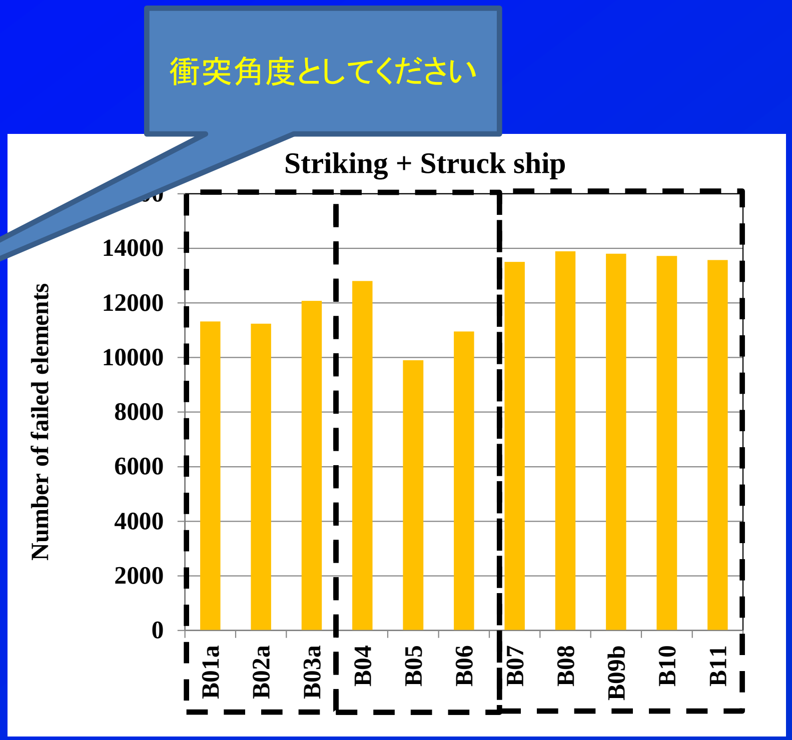
Comparison of failed elements in struck ship



- Number of failed elements decreases as HDS increases → reasonable
- Ratio of failed elements ($N_{HDS}/N_{Conventional}$): Partial-II→ 2/3, Full→ 1/4

Failed elements

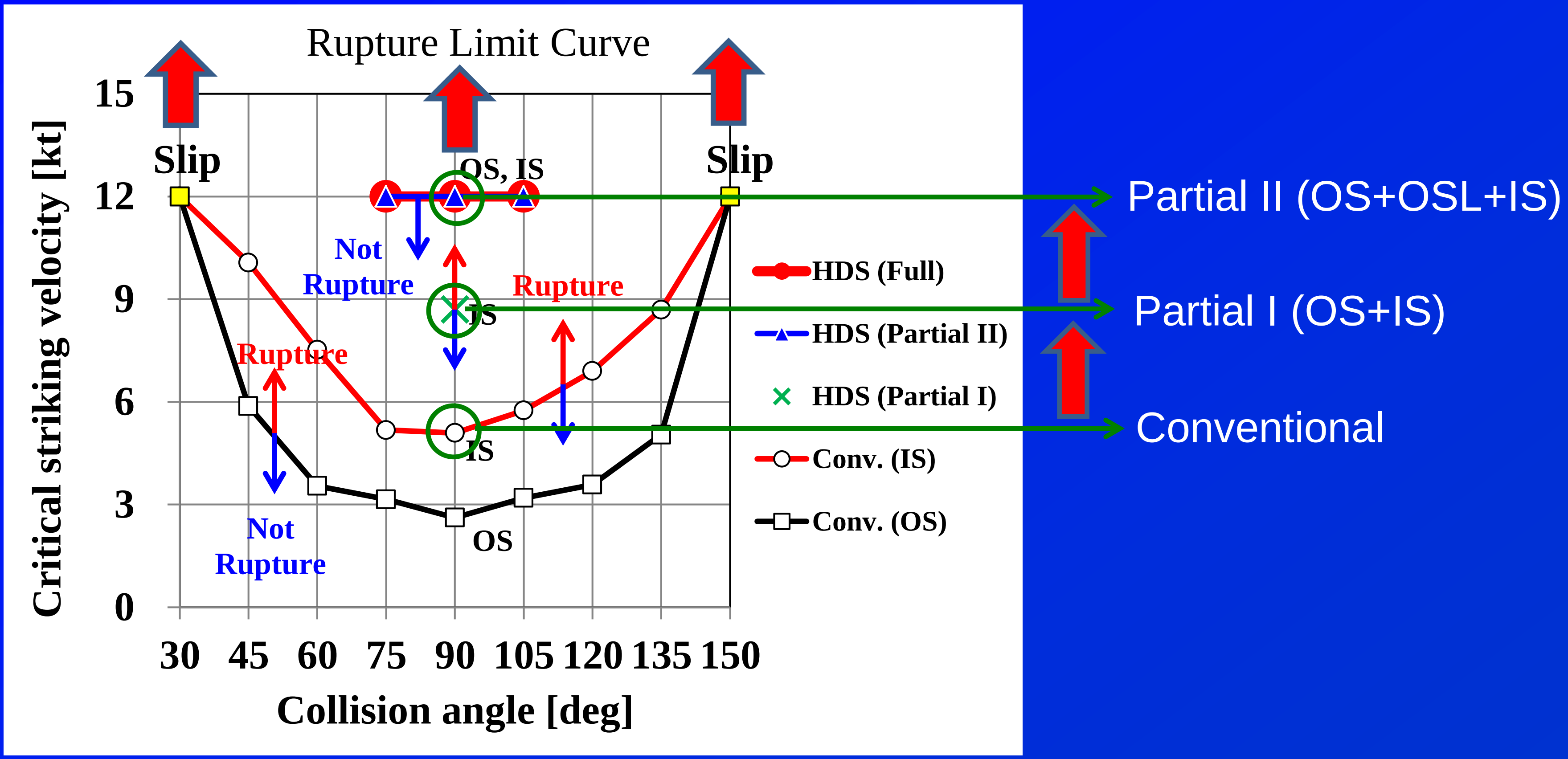




被衝突船の破壊用素数はFull→Partial Ⅱ→Conv.の順に増加し、衝突船のそれはその順に従って減少する。両船の和ではFullおよびPartial Ⅱで少なくなっている。

- Conv.になると、被衝突船破壊要素数増加。衝突船では減少。
- 両船の和では、部分適用の場合がやや少ない。Partialがバランスが良い。

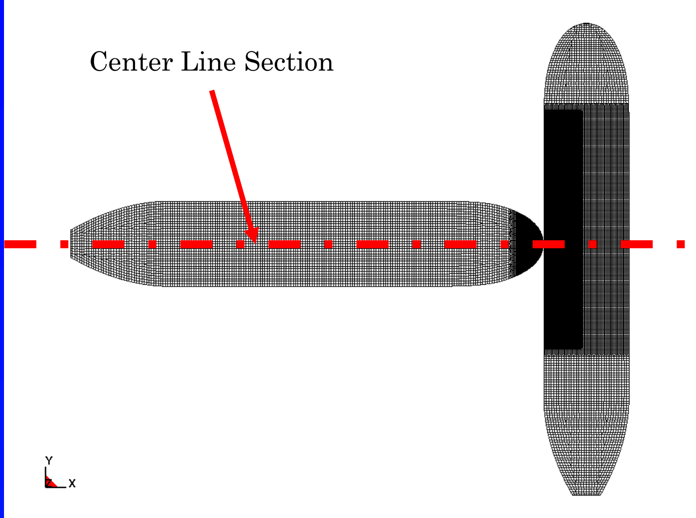
Rupture Limit Curve (RLC) of critical striking speed

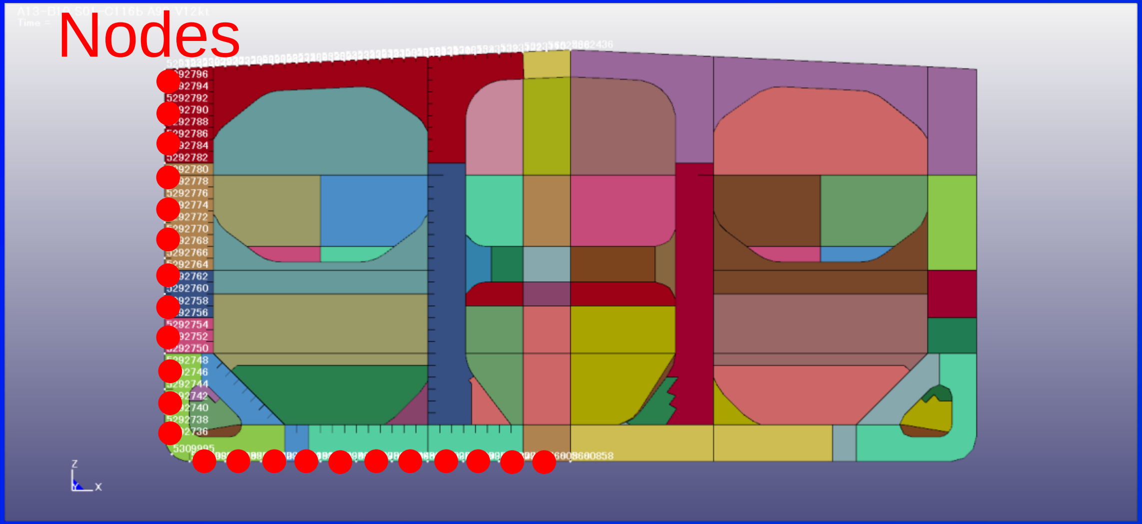


- In case of HDS-Full, HDS-Partial II：Rupture of cargo oil tank does not take place in striking speed of 12kt

Analysis results (Simulation 3)

Analysis Methods for deformation

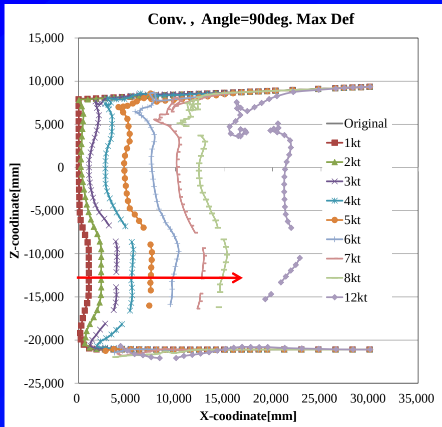


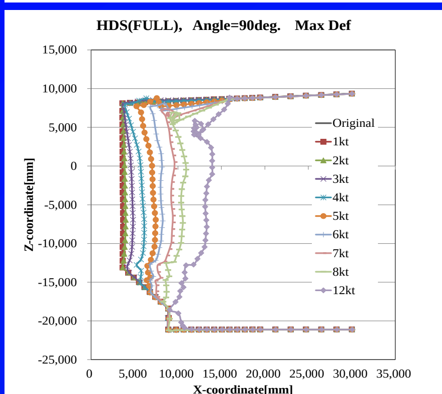


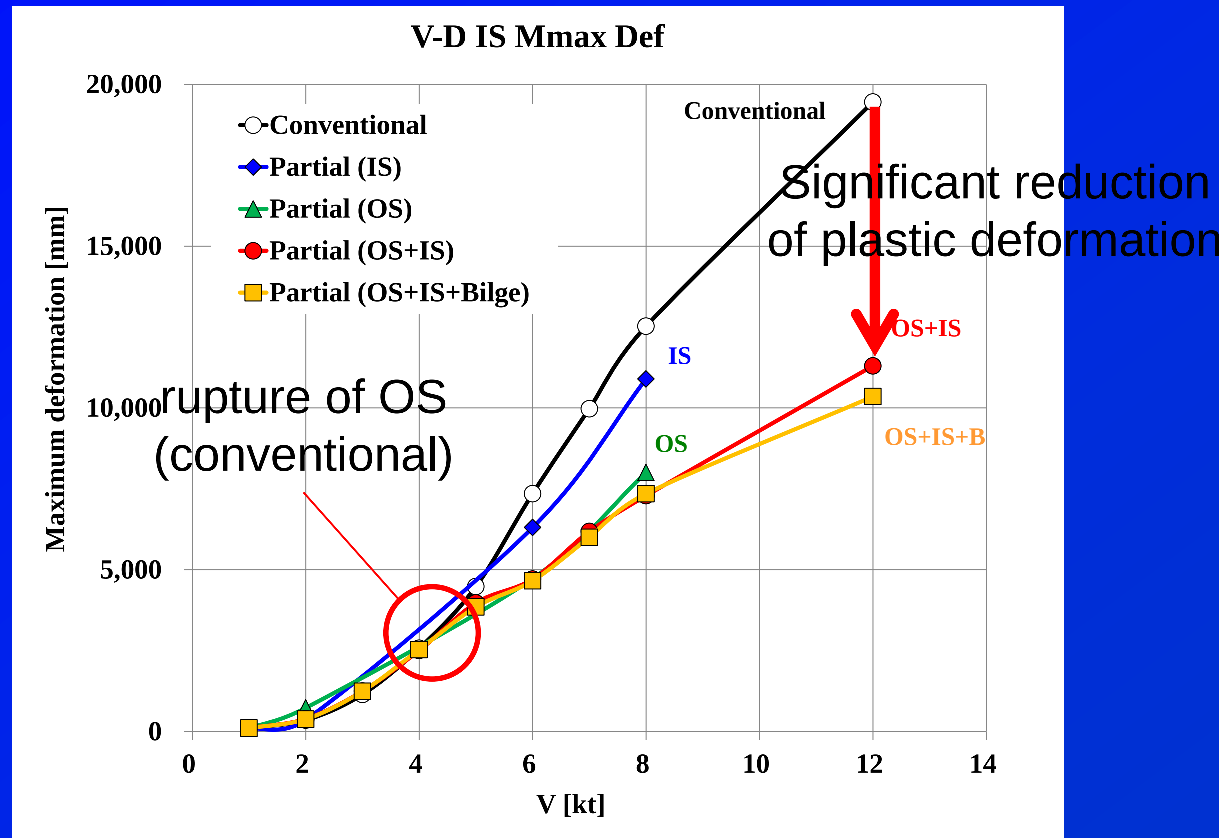
Center Line Section

- Motion of the struck ship is fixed (conservative)
- Output positions of nodes on outer sell/inner shell at center line
- Plot deformed shape and extract maximum indentation of side shell

Comparison of deformation







- Max. Deformation increases as collision speed gets larger
- If V=12kt, maximum deformation in case of HDS (for OS+IS+B) is estimated to be about half of that in case of conventional.
- Effect of HDS on reduction of deformation is small for minor collision, but can be significant for major collision.

7. Concluding remarks

A series of nonlinear finite element simulations carried out in order to investigate effect of HDS on ship-ship collision including oblique collision. Following conclusions can be achieved.

(1) HDSを外板及び内板に適用することにより、荷油タンク破壊までのエネルギー吸収量が従来鋼に比べ2.6-2.9倍となる。

(2) HDS適用によるエネルギー吸収量の増大が確認できた。その原因として主に下記2点が考えられる。

(i) 高延性効果による各要素のエネルギー増大（各要素のE吸収量が最大1.5倍）

(ii)(i)による破断遅延効果（時間軸でのエネルギー吸収量増大） 言い換えれば 空間方向のエネルギー吸収量増大（特に、船長方向）

(3) 従来鋼及び部分適用I(OS and IS)時の限界衝突速度は、それぞれ約5kt及び9ktとなる。部分適用II (OS+ OSL+IS)及び全適用時の限界衝突速度は12kt以上となることが分かった。12ktは、我が国の主要航路の最大制限速度であり、油流出リスクの大幅な低減を期待することができる。

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7. Concluding remarks

(4) HDSの適用パターン比較検証により、HDSを外板のロンジに適用することが効果が大きいことが分かった。これは主に、被衝突船ではmembraneによるエネルギー吸収が支配的であることによる。

(5) HDS適応による最大変形量抑制効果は、低速衝突（minor collision）では小さく, しかしながら比較的高速衝突で大きいことが分かった。

(6) 破壊要素数について、被衝突船においては従来鋼適用が最も多い結果となり、新材料の中ではHDS(IS)、HDS(OS)、HDS(Full)の順に破壊要素数が減少したため、合理的な結果を得ることができた。特に新材料適用パターンの破壊要素数は、従来鋼と比べて半分程度に減少した。

(7) 新材料(HDS)を船体に適用させた結果、検討したすべての衝突速度において、破壊までの時間が従来鋼適用に比べて長くなり、HDSによる変形量の抑制効果も確認することができた。これは新材料が優れた延性を持つためと考えられ、特に衝突による船側外板及び内板の面外変形量抑制のためには、船側外板(OS)に新材料を集中的に適用することが効果的であると考える。→効果的である。

7. Concluding remarks

(8) 新材料適用により、破断タイミング遅延が生じ、船側外板膜力（membrane force）が船長方向遠方まで伝わり、船体全体のエネルギー吸収量が増加する。このことより、従来綱では被衝突船の衝突部近傍で局所的に破壊が集中し、塑性要素数少・外板破壊要素数大となる。一方で、新材料では、外板破断が生じず塑性要素数大・破壊要素数少となる。

(9) 荷油タンクより油流出を生じない限界衝突角度として、少なくとも角度が30度以下もしくは150度以上になれば、衝突船と被衝突船がスリップし、荷油タンク破断に至らないと推定することができる。

7. Concluding remarks

(10) 被衝突船のエネルギー吸収はFull（全面適用）で最大となるが、コストを考えると、Partial II（OS+IS+OSL）の適用も効率的である。Partial IIは相対的により広範囲に塑性変形を生ずる可能性はあるが、本研究の目的の1つは海洋環境汚染防止であり、油流出被害の甚大性を考慮すれば、Partial IIは非常に効果的である。

今時結論は、特定の船舶に対する特定の衝突シナリオによって導かれた結果であり、より普遍的な結果を導くためには、更なる検討が必要である。しかしながら、今回の一連のシリーズ解析により、HDSを適用することによる大幅な油流出提言が見込めることが定量的に検証され、HDSの将来性ある効果を確認できたと考えられる。海洋環境の保全のため、HDSの普及促進に向けた更なる研究・開発が望まれる。

Thank you for your attention

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