Tanker Structure and Hull Failure Strength

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3. Failure strength of aging tanker hull
   3 - 1. Basic mechanism of large-scale hull failure
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Large-scale oil spill accident by tankers

<table>
<thead>
<tr>
<th>year</th>
<th>ship name</th>
<th>flag state</th>
<th>volume (10³ kL)</th>
<th>causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967</td>
<td>“Torrey Canyon”</td>
<td>Liberia</td>
<td>119</td>
<td>grounding</td>
</tr>
<tr>
<td>1972</td>
<td>“Sea Star”</td>
<td>Korea</td>
<td>120</td>
<td>collision &amp; fire</td>
</tr>
<tr>
<td>1976</td>
<td>“Urquiola”</td>
<td>Spain</td>
<td>100</td>
<td>grounding</td>
</tr>
<tr>
<td>1977</td>
<td>“Hawaiian Patriot”</td>
<td>Liberia</td>
<td>95</td>
<td>founded at 12yrs</td>
</tr>
<tr>
<td>1978</td>
<td>“Amoco Cadiz”</td>
<td>Liberia</td>
<td>223</td>
<td>grounding</td>
</tr>
<tr>
<td>1979</td>
<td>“Atlantic Empress”</td>
<td>Greece</td>
<td>287</td>
<td>collision &amp; fire</td>
</tr>
<tr>
<td>1979</td>
<td>“Independenta”</td>
<td>Rumania</td>
<td>95</td>
<td>collision &amp; fire</td>
</tr>
<tr>
<td>1983</td>
<td>“Castillo de Bellver”</td>
<td>Spain</td>
<td>252</td>
<td>fire</td>
</tr>
<tr>
<td>1988</td>
<td>“Odyssey”</td>
<td>Greece</td>
<td>132</td>
<td>founded at 17yrs</td>
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<tr>
<td>1989</td>
<td>“Exxon Valdez”</td>
<td>USA.</td>
<td>37</td>
<td>grounding</td>
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<tr>
<td>1991</td>
<td>“ABT Summer”</td>
<td>Liberia</td>
<td>260</td>
<td>Fire</td>
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<tr>
<td>1993</td>
<td>“Braer”</td>
<td>Liberia</td>
<td>85</td>
<td>grounding</td>
</tr>
<tr>
<td>1996</td>
<td>“Sea Empress”</td>
<td>Liberia</td>
<td>72</td>
<td>grounding</td>
</tr>
<tr>
<td>1997</td>
<td>“Nakhodka”</td>
<td>Russia</td>
<td>6.2</td>
<td>founded at 26yrs</td>
</tr>
<tr>
<td>1999</td>
<td>“Erika”</td>
<td>Malta</td>
<td>10 + α</td>
<td>founded at 25yrs</td>
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<tr>
<td>2001</td>
<td>“Baltic Carrier”</td>
<td>Marshall Is.</td>
<td>2.5</td>
<td>collision &amp; fire</td>
</tr>
<tr>
<td>2002</td>
<td>“Prestige”</td>
<td>Bahama</td>
<td>(4)??</td>
<td>founded at 26yrs</td>
</tr>
</tbody>
</table>
1-2. IMO rule movement on tanker structure
History in VLCC structural changes (1)

1st generation VLCC;
Mass-transportation

* Idemitsu Maru (209kDWT) in 1966.
* Gigantic tankers & Mammoth docks.

2nd generation VLCC;
Environment friendly and energy-saving era

* Torrey canyon casualty accompanied MARPOL 73/78.
* SBT, limited tank volume, protective location, IGS/COW
* Automatized machines and tools, maintenance-free,
turbo to diesel conversion, long-stroke diesel,
increase of HT-steels use.

3rd generation VLCC;
Life-cycle cost, economical & safety oriented

* Exxon Valdez brought about Double-hull tanker.
* Structural safety against oil leakage, ESP, access for inspection, re-cycling & scrapping.
1-2. IMO rule movement on tanker structure
History in VLCC structural changes (2)

Tanker structural regulation by IMO

1954: OILPOL adopted (海洋汚濁防止条約)
1969: Load on top (LOT) system
1971: Tank size limitation
1973: Segregated ballast tank (SBT)
         Damage stability
1978: MARPOL 73/78 13E. SBT protective location (PL)
         IGS / COW requirement
1992: MARPOL 73/78 13F. Double-hull tanker for new ship
       ditto 13G. Existing ship phase out schedule
1-2. IMO rule movement on tanker structure
Enhanced Survey Program on tanker structure

**Guideline on “Enhanced Survey Program”**

IMO resolution A.744 (18)
SOLAS chapter XI, regulation 2

1) Survey program worked out in advance
2) Dry-dock survey
3) Overall survey
4) Close-up survey
5) Thickness measurement
   *incl. belt gauging*
6) Corrosion preventive system (coating)
7) survey report file on board
1-2. IMO rule movement on tanker structure
Phase out of single hull tankers

**MEPC46 revision to MARPOL regulation 13G.**

<table>
<thead>
<tr>
<th>Category of tanker (crude and dirty oil)</th>
<th>New phase out schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category-1</td>
<td></td>
</tr>
<tr>
<td>Non-double hull (Pre-PL/SBT) oil tankers</td>
<td>Withdrawn between 2003 - 2007</td>
</tr>
<tr>
<td>Built before 1982</td>
<td>Beyond 2005, CAS requirement</td>
</tr>
<tr>
<td>20,000 DWT and above</td>
<td></td>
</tr>
<tr>
<td>Category-2</td>
<td></td>
</tr>
<tr>
<td>Non-double hull (PL/SBT) oil tankers</td>
<td>Withdrawn between 2003 - 2015 by arriving at 25 years of age</td>
</tr>
<tr>
<td>Built during 1982 ~ 1996</td>
<td>Final use 2015</td>
</tr>
<tr>
<td>20,000 DWT and above</td>
<td>Beyond 2010, CAS requirement</td>
</tr>
<tr>
<td>Category-3</td>
<td></td>
</tr>
<tr>
<td>Non-double hull oil tankers</td>
<td>Withdrawn between 2003 - 2015</td>
</tr>
<tr>
<td>5,000～20,000 DWT</td>
<td>Final use 2015</td>
</tr>
</tbody>
</table>

(Note) CAS; Condition Assessment Scheme
2. Aging effect on ship hull
2-1. Typical strength degradation by aging

(1) Corrosion
   a. Corrosion in frame member
   b. Corrosion in plating
   c. Local corrosion

(2) Fatigue crack

(3) Degradation of paint coating
2-1. Typical strength degradation by aging (1)

(1) Corrosion
   a. Frame corrosion
   b. Plating corrosion
   c. Local corrosion
(2) Fatigue crack
(3) Coating degradation

Corrosion wastage in deck longitudinal of WBT, with poor fillet weld and sharp edge at depth end. (aged 15 years)
2-1. Typical strength degradation by aging (2)

(1) Corrosion
   a. Frame corrosion
   b. Plating corrosion
   c. Local corrosion
(2) Fatigue crack
(3) Coating degradation

Corrosion in bottom plating;
   1) horizontal/vertical plating
   2) splashed zone or not
   3) effect of fluid velocity
   4) effect of high temperature, etc
2-1. Typical strength degradation by aging (3)

(1) Corrosion
   a. Frame corrosion
   b. Plating corrosion
   c. Local corrosion
(2) Fatigue crack
(3) Coating degradation

Typical local corrosion on stringer: below

- pitting corrosion
- raised by high stresses
- grooving corrosion, etc.

grooving corrosion along fillet weld of deck longl.
2-1. Typical strength degradation by aging (4)

(1) Corrosion
   a. Frame corrosion
   b. Plating corrosion
   c. Local corrosion
(2) Fatigue crack
(3) Coating degradation

Fatigue crack at side longitudinal, in 2nd generation VLCC damages.

Fatigue crack growth at fillet welded corner.
2-1. Typical strength degradation by aging(5)

Stress vs. strain curve of aging plate;

a) Cut-out and flushed specimen shows no less ability to virgin plate.

b) Apparent drop in S-S curve for aging plate is by surface roughness due to corrosion.
2-1. Typical strength degradation by aging
Degradation tendency with increase of ship age

(a) Trend in degradation mode  (b) Trend in number of failures
2. Aging effect of ship hull  
2-2. Hull plate corrosion data properties

Corrosion rate analysis by using class NK database

<table>
<thead>
<tr>
<th>Structural Member</th>
<th>50% level</th>
<th>95% level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tk. 5yrs. 10yrs. 15yrs. 20yrs.</td>
<td>Tk. 5yrs. 10yrs. 15yrs. 20yrs.</td>
</tr>
<tr>
<td>Upper Deck Plate</td>
<td>COT 0.00 0.52 1.03 1.33</td>
<td>0.82 1.93 2.63 3.14</td>
</tr>
<tr>
<td></td>
<td>WBT 0.00 0.00 0.79 1.06</td>
<td>0.51 1.15 1.59 1.92</td>
</tr>
<tr>
<td>Deck Longitudinals</td>
<td>COT 0.00 0.34 0.82 1.06</td>
<td>0.51 1.21 1.64 1.95</td>
</tr>
<tr>
<td></td>
<td>WBT 0.00 0.00 0.63 0.96</td>
<td>0.00 0.99 1.46 1.82</td>
</tr>
<tr>
<td>Bottom Plate</td>
<td>COT 0.00 0.74 1.16 1.43</td>
<td>1.02 2.11 2.78 3.27</td>
</tr>
<tr>
<td></td>
<td>WBT 0.00 0.00 0.88 1.28</td>
<td>0.30 1.53 2.35 2.96</td>
</tr>
<tr>
<td>Bottom Long.</td>
<td>Web COT 0.00 0.00 0.68 1.00</td>
<td>0.27 1.04 1.50 1.85</td>
</tr>
<tr>
<td></td>
<td>WBT 0.00 0.00 0.68 1.00</td>
<td>0.00 1.03 1.50 1.85</td>
</tr>
<tr>
<td></td>
<td>Flange COT 0.00 0.00 0.77 1.01</td>
<td>0.59 1.24 1.64 1.94</td>
</tr>
<tr>
<td></td>
<td>WBT 0.00 0.00 0.53 0.91</td>
<td>0.00 0.93 1.40 1.77</td>
</tr>
<tr>
<td>Side Shell Plate</td>
<td>COT 0.00 0.00 0.78 1.03</td>
<td>0.44 1.16 1.60 1.92</td>
</tr>
<tr>
<td></td>
<td>WBT 0.00 0.00 0.69 1.20</td>
<td>0.00 1.11 1.66 2.09</td>
</tr>
<tr>
<td>Side Longi.</td>
<td>Web COT 0.00 0.00 0.59 0.94</td>
<td>0.29 1.02 1.46 1.81</td>
</tr>
<tr>
<td></td>
<td>WBT 0.00 0.00 0.44 0.87</td>
<td>0.00 0.97 1.41 1.76</td>
</tr>
<tr>
<td></td>
<td>Flange COT 0.00 0.00 0.58 0.94</td>
<td>0.00 0.98 1.44 1.80</td>
</tr>
<tr>
<td></td>
<td>WBT 0.00 0.00 0.48 0.89</td>
<td>0.00 0.92 1.39 1.75</td>
</tr>
<tr>
<td>Longitudinal Bhd.Plate</td>
<td>COT 0.00 0.00 0.84 1.10</td>
<td>0.55 1.19 1.63 1.96</td>
</tr>
<tr>
<td></td>
<td>WBT 0.00 0.33 0.81 1.04</td>
<td>0.56 1.24 1.65 1.95</td>
</tr>
<tr>
<td>Longi.Bhd.Longi.</td>
<td>Web COT 0.00 0.00 0.54 0.92</td>
<td>0.27 1.01 1.45 1.79</td>
</tr>
<tr>
<td></td>
<td>WBT 0.00 0.00 0.54 0.92</td>
<td>0.25 1.01 1.44 1.79</td>
</tr>
<tr>
<td></td>
<td>Flange COT 0.00 0.00 0.62 0.96</td>
<td>0.34 1.04 1.48 1.82</td>
</tr>
<tr>
<td></td>
<td>WBT 0.00 0.00 0.44 0.94</td>
<td>0.00 0.97 1.75 2.45</td>
</tr>
</tbody>
</table>
2-2. Hull plate corrosion data properties (2) - example for deck structure -
## Allowable diminution Level by Class Society spec.

<table>
<thead>
<tr>
<th>Structural Member</th>
<th>Allowable Diminution Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Shell plates</td>
<td>20% of original thickness + 1 mm</td>
</tr>
<tr>
<td>- Strength deck plates</td>
<td></td>
</tr>
<tr>
<td>- Slab longs on shear strake and stringer plate of strength deck</td>
<td></td>
</tr>
<tr>
<td>- Tight bulkheads in deep tanks</td>
<td></td>
</tr>
<tr>
<td>- Inner bottom plates</td>
<td></td>
</tr>
<tr>
<td>- Floors and girders in double bottom</td>
<td>25% of original thickness</td>
</tr>
<tr>
<td>- Primary members (web &amp; face)</td>
<td></td>
</tr>
<tr>
<td>- Web, face and bracket of hold frames</td>
<td></td>
</tr>
<tr>
<td>- Watertight bulkhead plates</td>
<td></td>
</tr>
<tr>
<td>- Web, face and bracket of frames (excluding hold frames), longitudinal beams and</td>
<td>30% of original thickness</td>
</tr>
<tr>
<td>stiffeners</td>
<td></td>
</tr>
<tr>
<td>- Effective deck plates</td>
<td></td>
</tr>
<tr>
<td>- Hatch cover and hatch beam</td>
<td></td>
</tr>
</tbody>
</table>
2-2. Hull plate corrosion data properties
Schematic diagram on aging ship strength
2. Aging effect of ship hull
2-3. Reduction in mid-ship section modulus

Estimated results on average tendency of the VLCC mid-ship section modulus;

(1) IMO requirement: within 10% loss of Z

(2) Average corrosion damage is within IMO requirement.

Note:
- analyzed
- ---- imaginary scatter
3. Failure strength of aging tanker hull

3-1. Basic mechanism of large-scale hull failure

- Corrosion
- Corrosion progress
- Crack/buckling in stringer/frame
- Crack progress in outer shell/bulkhead plate
- Leakage at outer shell → Flooding/founder
- Environmental pollution, loss of cargo/human lives

Diagram:
- Intact state
- E2/H1
- E1/H1, H3
- H2
- Corrosion progress
- Crack/buckling in stringer/frame
- H2
- Crack progress in outer shell/bulkhead plate
- Leakage at outer shell → Flooding/founder
- Environmental pollution, loss of cargo/human lives

Legend:
- ◯: Failure or sequential event
- ◦: Factor making failure occur or propagate

Environment Factor:
- E1: Excessive load/impact load
- E2: Corrosive circumstance

Human Factor:
- H1: Insufficient strength or defects
- H2: Poor maintenance
- H3: Miss-operation
3-1. Basic mechanism of large-scale hull failure
As to hull break-up mode

Trigger element for tanker hull break-up;

(1) Buckling/collapse at Deck structure in Sagging

(2) Crack propagation at Bottom structure in Sagging

(3) Crack propagation at Deck structure in Hogging

(4) Buckling/collapse at Bottom structure in Hogging

• (multi-site damage)

• i) break-up occurs in high wave; Sagging M. > Hogging M.

• ii) deck back surface is the most severe corrosive space
  in hull circumstances, and so forth.
3-2. Case study
Outline of the Nakhodka casualty

Date: 1977.1.02, 02:40am
Location: Okino-shima NNE 106km
wave condition: $H_{1/3} \geq 8m$, $T_{ave} \geq 9$ sec

General Arrangement of the MS Nakhodka

Fr.137 Fr.153
Failed and broke in two

Fractured cross-section of hull girder at sea bottom
3-2. Case study
Loading pattern at the Nakhodka casualty

<table>
<thead>
<tr>
<th>No.5 P.W.T.</th>
<th>No.4 P.W.T.</th>
<th>No.3 P.W.T.</th>
<th>No.2 P.W.T.</th>
<th>No.1 P.W.T.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (0)</td>
<td>1,300 (618.5)</td>
<td>1,307 (1,420)</td>
<td>1,263 (0)</td>
<td>440 (408.5)</td>
</tr>
<tr>
<td>No.9 C.T.</td>
<td>No.8 C.T.</td>
<td>No.7 C.T.</td>
<td>No.6 C.T.</td>
<td>No.4 C.T.</td>
</tr>
<tr>
<td>590 (1,543)</td>
<td>1,417 (1,543)</td>
<td>1,432 (1,543)</td>
<td>1,418 (1,543)</td>
<td>1,372 (1,543)</td>
</tr>
<tr>
<td>No.5 S.W.T.</td>
<td>No.4 S.W.T.</td>
<td>No.3 S.W.T.</td>
<td>No.2 S.W.T.</td>
<td>No.1 S.W.T.</td>
</tr>
<tr>
<td>0 (0)</td>
<td>1,302 (618.5)</td>
<td>1,301 (1,420)</td>
<td>1,257 (0)</td>
<td>601 (408.5)</td>
</tr>
</tbody>
</table>

Loading Patterns

values: Load (in kl) at the casualty
( ) indicates a standard condition.
### 3-2. Case study
Corrosion wastage at the Nakhodka casualty

**Measurement result:**
20-35% of plate thickness reduced due to corrosion

<table>
<thead>
<tr>
<th>Structural member</th>
<th>Original thickness</th>
<th>Thickness reduction</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom plate</td>
<td>20 mm</td>
<td>6 mm</td>
<td>based on the average of measured data around Fr. 157</td>
</tr>
<tr>
<td>Side shell</td>
<td>17 mm</td>
<td>6 mm</td>
<td>measured data are limited, and considered to be the same as bottom plating</td>
</tr>
<tr>
<td>Deck plate of center tank</td>
<td>20-24 mm</td>
<td>4 mm</td>
<td>based on the measured data in 1993</td>
</tr>
<tr>
<td>Deck plate of side tank</td>
<td>20-24 mm</td>
<td>7.5 mm</td>
<td>based on the average of measured data</td>
</tr>
<tr>
<td>Deck longitudinal</td>
<td>14 mm</td>
<td>5.5 mm</td>
<td>based on the average of measured data</td>
</tr>
<tr>
<td>Other members</td>
<td>11-14 mm</td>
<td>3 mm</td>
<td>measured data are scattering between 2 mm and 4 mm</td>
</tr>
</tbody>
</table>
3-2. Case study
Applied force at the Nakhodka casualty

VBM and VSF were obtained by using non-linear ship motion and response simulation software.

Still water shearing force and bending moment for the Nakhodka
(solid line: at the accident, dotted line: standard condition)
3-2. Case study
Simulation cal. on ultimate collapse of Nakhodka

Simulation result showed;
the break-up started at the deck structure on about Fr.153.

(a) collapse mode at deck
(b) stress at deck vs. time in simulation
3-2. Case study
Estimated results on load and strength

Causes of the Nakhodka casualty;
(1) Excessive corrosion made the Nakhodka’s vertical bending strength about one half to that of as built.
(2) So, the most severe wave load in a year at Japan sea, let her broke up.
(3) In addition to the above, the non-standard loading pattern at the accident had enlarged the wave load.
4. Conclusions

(1) Large-scale oil spill from tankers were not yet exterminated. And one critical factor must be hull excessive corrosion that might be overlooked, so that it should be strongly required strict implementation of the ESP and excluding sub-standard tankers.

(2) From the analysis of corrosion measurement data at the classNK inspections, not only average wastage rate but also increase of standard deviation of the rate are key factors to understand the ship ageing and the influence.

(3) As to hull breaking up, it seems that excessive corrosion and severe wave condition are two main players and a possible trigger failure might be a buckling/ collapse of deck structure at the time of high wave of sagging.

In anyway more actions are necessitated, not only to prevent casualties but also to mitigate the oil outflow and the damage of the ocean, to keep our global environment clean.