SUB-COMMITTEE ON STABILITY AND LOAD LINES AND ON FISHING VESSELS SAFETY
53rd session
Agenda item 6

SLF 53/INF.2
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STANDARDS ON TIME-DEPENDENT SURVIVABILITY OF PASSENGER SHIPS IN DAMAGED CONDITION

Research project on internal flooding and management of stability and crises

Submitted by Finland

SUMMARY

Executive summary:	The document contains intermediate information on an ongoing research project FLOODSTAND, which stands for Integrated Flooding Control and Standard for Stability and Crises Management
Strategic direction:	5.1.
High-level action:	5.1.1
Planned output:	5.1.1.3
Action to be taken:	Paragraph 4
Related documents:	MSC.245(83); SLF 46/INF.3 and SLF 47/INF.6

General information

1 The European Commission has funded a research project (EC FP7) with focus on integrated flooding and stability and crises management. The project started in March 2009 and it will last for three years. A brief description of this project is presented in annex 1.

2 The project has reached mid-term and some working packages have been reported to the project co-ordinator. Experimental studies of factors affecting the Time-to-Flood, which is part of working package 2 "Flooding progression modelling", is presented in annex 2.

3 All reports of this project will be made available for this Sub-Committee upon completion. More information is available on the website http://floodstand.tkk.fi.

Action requested of the Sub-Committee

4 The Sub-Committee is invited to take note of the information provided.

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ANNEX 1:

FLOODSTAND – Research Project: Integrated Flooding Control and Standard for Stability and Crises Management

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1 Introduction

This paper is a short overview of the research project FLOODSTAND (218532), Integrated Flooding Control and Standard for Stability and Crises Management. FLOODSTAND is a 3-year project to be carried out within the European Community's Seventh Framework Programme. FLOODSTAND was started in March 2009 and it is coordinated by Aalto University[1].

FLOODSTAND sets out to derive missing data for flooding simulations, for the validation of time-domain numerical tools for the assessment of ship survivability, and to develop guidelines as well as a standard for a comprehensive measure of damaged ship stability, addressing the risk of flooding in passenger ships, cruise liners and ropax-vessels.

2 Objectives of the research project FLOODSTAND

The main objectives of FLOODSTAND are to increase the reliability of flooding simulation tools in design and onboard use by establishing modelling principles and uncertainty bounds, in particular by:

- establishing guidelines for modelling leaking through closed doors (e.g. non-WT doors) and the critical pressure head for their collapse under the pressure of floodwater;
- simplified modelling of pressure losses in flows through typical openings;
- feasible and realistic modelling of compartments with complex layouts (cabin areas) for flooding simulation tools;
- the use of flooding monitoring systems and simulation for assessing the damage and extent of flooding onboard the damaged ship.

The research efforts in FLOODSTAND, especially in Work Packages: WP1-WP3, aim at the above objectives, by representing a bottom-up approach, supported by experimental research (tests with real ship structures, such as doors, cabin wall panels etc., and model tests) and computational studies.

FLOODSTAND also aims to establish methods for instantaneous classification of the severity of ship flooding casualty, with the following objectives:

- establishing requirements and uncertainty bounds for methods for the prediction of the time it takes a ship to capsize or sink after damage.
- establishing requirements and uncertainty bounds for models of mustering. abandonment and rescue operations.
- deriving a standard for decision-making in crises.
- developing an implementation system and testing the effectiveness of the standard in rating different decisions for various casualty cases, as well as testing the approach in design.

The latter objectives are of special interest in WP4-WP7 with more focus on top-down approach.

[1] Aalto University started its operation at the beginning of 2010, when Helsinki University of Technology, the University of Art and Design Helsinki and the Helsinki School of Economics were merged together.

3 Structure of the Research Project and the Consortium

The research and development work is carried out in seven work packages (WP) (see Table 1).

Table 1: List of Work Packages and Tasks related to R&D

WP	Contents	Lead organisation*
WP1	**Design and application**	**STX Finland**
	Task 1.1 Development of basic design of passenger ships	STX Finland
	Task 1.2 Analysis of the real flooding effects on design	STX Finland
WP2	**Flooding Progression Modelling**	**AALTO**
	Task 2.1 Experiments with leaking and collapsing structures	CTO
	Task 2.2 Numerical modeling and criteria for leaking and collapsing structures	MEC
	Task 2.3 Experimental studies on pressure losses	AALTO
	Task 2.4 Computational studies & RANSE CFD	CNRS
	Task 2.5 Model tests for cabin areas	MARIN
	Task 2.6 Sensitivity of simulation model	AALTO
WP3	**Flooding Simulation and Measurement Onboard**	**NAPA**
	Task 3.1 Development of flood sensors data interpreter	NAPA
	Task 3.2 Impact of ship dynamics	AALTO
	Task 3.3 Design of flood sensor systems	NAPA
WP4	**Stochastic ship response modelling**	**SSRC**
	Task 4.1 Benchmark data on time to capsize, ttc	SSPA
	Task 4.2 Test/develop analytical time to capsize model	SSRC
	Task 4.3 Test/develop numerical time to capsize model	NTUA
	Task 4.4 Test/develop hybrid time to capsize model	SSRC
	Task 4.5 Establish uncertainty bound on ttc models	SSRC
WP5	**Rescue process modelling**	**BV**
	Task 5.1 Benchmark data on mustering/abandonment/rescue	BV
	Task 5.2 Test/develop mustering (M) model	BMT
	Task 5.3 Test/develop abandonment (A) model	BV
	Task 5.4 Test/develop rescue (R) model	BV
	Task 5.5 Establish uncertainty bounds on M-A-R models	SSRC
WP6	**Standard for decision making in crises**	**SSRC**
	Task 6.1 Develop loss function	SSRC
	Task 6.2 Develop likelihood function	SSRC
WP7	**Demonstration**	**NTUA**
	Task 7.1 Benchmark data on casualty mitigation cases	NTUA
	Task 7.2 Demonstration of a casualty mitigation standard	BMT
	Task 7.3 Demonstration for use as a design standard	NTUA

* The FLOODSTAND Consortium members' acronyms, full names and country are: **AALTO**: Aalto-korkeakoulusäätiö (=operating as Aalto University), Finland, **STX**: STX Finland Ltd (Finland), **CNRS**: Centre National de la Recherche Scientifique, France, **CTO**: Centrum Techniki Okretowej Spolka Akcyjna, Poland, **DNV**: Det Norske Veritas AS, Norway, **BMT**: BMT Group Limited, UK, **MARIN**: Stichting Maritiem Research Instituut Nederland, NL, **MEC**: MEC Insenerilahendused, EST, **MW**, MEYER WERFT GmbH, Germany, **NAPA**: Napa Ltd, Finland, **SSPA**: SSPA Sweden AB, Sweden, **SFC**: SF-Control Oy, Finland, **NTUA**: National Technical University of Athens - Ship Design Laboratory, Greece, **BV**: Bureau Veritas – Registre International de Classification de Navires et d Aeronefs SA, France, **SaS**: Safety At Sea Limited, UK, **MCA**: Maritime and Coastguard Agency, UK, **SSRC**: University of Strathclyde, UK. The project is based on the work of the whole consortium.

More detailed descriptions of the Tasks and Sub-Tasks are available at the project web-site (see sub-chapter 4.2 below). AALTO is responsible of administrative and overall technical coordination of the project FLOODSTAND, but the technical coordination for the Work Packages is further divided to AALTO/NAPA (for WP1-WP3) and to SSRC (for WP4-WP7)[2].

4 Results and Dissemination

4.1 Results

The intention of this research project is to offer a wide publicity for its results, in project deliverables, journal articles, papers and presentations. The results of the tests will also be used to further validate the time-domain flooding simulation tools of the project partners, but due to the publicity policy, the results of the project will be publicly available, thus widening the scope of utilisation.

A summary of some of the first results in FLOODSTAND WP2, Flooding Progression Modelling, are given in Annex 2.

4.2 Dissemination

Final reports (=deliverables) and more detailed information of the results of FLOODSTAND are publicly available at the project web page:

http://floodstand.tkk.fi

The intention of this research project is to offer a wide publicity for its results, in project deliverables, in journal articles, as well as in other papers and presentations. A list of recent publications is available in the end of this Annex.

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 218532. The financial support is gratefully appreciated.

5 Advisory Committee

The project FLOODSTAND has an Advisory Committee (AC). The purpose and function of the AC will include:

• offering a wider discussion forum for the continuous assessment of the project plan;

• being one channel for the dissemination of the project results;

• offering a wider discussion forum for the assessment of the project results.

[2] This division originates from the background of project FLOODSTAND as a merge of two project proposals FloodControl and Istand. After merge, the staff effort in project FLOODSTAND exceeded 350 man-months.

The Advisory Committee includes members from selected maritime authorities (TraFi (ex. FMA), STA (ex. SMA) and USCG), classification societies (DNV and GL), the largest cruise ship operators (CAR & RCCL) and representatives of the IMO and NMRI as well. Thus, important viewpoints from the administrations, classification societies and cruise ship operators, etc. can easily be brought up for the use of the consortium. The AC will also give better opportunities for the dissemination of the project results worldwide.

6 List of recent publications

Jakubowski, P. and Bieniek, N. (2010) Experiments with leaking and collapsing strucures, FLOODSTAND Deliverable D2.1b.

Jalonen, R. (2009) FLOODSTAND – Integrated Flooding Control and Standard for Stability and Crises Management, Maritime Research News, Vol. 24, 2009/1, Maritime Institute of Finland.

Jalonen, R., Jasionowski, A., Ruponen, P., Mery, N., Papanikolaou, A., Routi, A-L. (2010) FLOODSTAND – Integrated Flooding Control and Standard for Stability and Crises Management, Proceedings of the 11th International Ship Stability Workshop, Wageningen, The Netherlands, June 21-23, 2010.

Jasionowski, A. (2010) Decision Support for Crisis Management and Emergency Response, Proceedings of the 11th International Ship Stability Workshop, Wageningen, The Netherlands, June 21-23, 2010.

Kraskowski, M. (2010) Results of the computational study on the pressure losses in openings, air pipes and effects of ventilation, FLOODSTAND Deliverable D2.4b.

Penttilä, P. & Ruponen, P. (2010) Use of Level Sensors in Breach Estimation for a Damaged Ship", ICGS2010, June 2010.

Rask, I. (2010) Benchmark data on time to capsize, FLOODSTAND Deliverable D4.1a.

Rask, I. (2010) Benchmark data on time to capsize, FLOODSTAND Deliverable D4.1b.

Spanos, D. & Papanikolaou, A. (2010) On the Time dependent Survivability of ROPAX Ships, Proceedings of the 11th International Ship Stability Workshop, Wageningen, The Netherlands, June 21-23, 2010.

Stening, M. (2010) Pressure losses and flow velocities in flow through manholes and cross-ducts, FLOODSTAND Deliverable D2.3, 18 May 2010.

Stening, M., Järvelä, J., Ruponen, P., Jalonen, R. (2010) Determination of discharge coefficients for a cross-flooding duct, manuscript submitted to *Ocean Engineering*.

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ANNEX 2:

Experimental Studies on Factors Affecting the Time-to-Flood

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Risto Jalonen, Aalto University School of Science and Technology, Finland

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1 Introduction

This paper presents the first results of the Work Package 2 of the EC FP7 research project FLOODSTAND (Integrated Flooding Control and Standard for Stability and Crises Management, Grant Agreement No. 218532). This 3-year project was started in March 2009. Detailed description of the whole project is given in *Jalonen et al. (2010)*.

The objective of the WP2 is to provide further information on the input parameters and modelling practices for application in time-domain flooding simulation tools. In particular, data and guidelines for assessing the various coefficients are presented. The effects of these parameters on time-domain flooding simulation are studied.

2 Background

The use of time-domain flooding simulation tools has expanded as the computing capacity has increased. The applications vary from simple calculations of cross-flooding time to assessments of time-to-flood or time-to-capsize in damage scenarios with extensive progressive flooding.

It is an undisputable fact that the simulation results depend on the applied input data for the openings. Most notably, the leakage and collapsing of non-watertight structures, such as closed fire doors, can have a very remarkable effect on the time-to-flood. This issue was first raised in SLF 47/INF.6, pointing out the need for further research.

Typically, the simulation tools are based on Bernoulli's theorem and the pressure losses in the openings are taken into account by applying semi-empirical discharge coefficients. These coefficients can have a notable impact on the time-to-flood, especially in cross-flooding calculations.

In principle, the flooding through an opening can be calculated with the following equation:

$$Q = C_D A_{eff} \sqrt{2gH_{eff}}$$

where:

- C_D effective discharge coefficient (pressure losses in the opening)
- A_{eff} effective area of the opening (taking into account e.g. leakage)
- H_{eff} effective pressure head

3 Leakage and Collapse Pressure Heads

3.1 Test Arrangement

The full-scale tests were carried out at CTO in Gdansk, Poland. The participating shipyards, STX Finland and Meyer Werft, provided the test specimen, installed in the test frames by using the standard shipyard procedures. The frames with the test objects were fitted to a test mock-up, where the water pressure could be controlled. During the test, the water pressure level was gradually increased. The measurements included leakage rate and deflection of the test object in 6 points. Fresh water with a density of 999.2 kg/m^3 was used. The maximum pressure was 220 kPa and the maximum leakage rate was about 90 l/s.

In the following, some results analyses are briefly presented. A detailed description and results of each test case is given in the public report, *Jakubowski and Bieniek (2010)*.

3.2 Analysis of Leakage Area Ratio

In SLF47.INF6 a very simple approach was presented for assessing leakage through non-watertight closed doors in flooding simulation. The effective flooding area of the opening is obtained by multiplying the geometrical (submerged) area with a constant leakage area coefficient A_{ratio}.

In the test setup the water that flows through the test specimen discharges into air. Consequently, the flow rate through a vertical opening that has width *b* and height *h* is (see e.g. *Ruponen 2007*, Figure 1) can be calculated with the following equation:

$$Q = C_D A_{ratio} b \frac{2}{3} \sqrt{2g} \left[H_{eff}^{3/2} - \left(\max\left(H_{eff} - h, 0 \right) \right)^{3/2} \right]$$

where H_{eff} is the effective pressure head, measured from the bottom of the test specimen. The submerged area of the opening is:

$$A_{submerged} = b \cdot \left[H_{eff} - \max\left(H_{eff} - h, 0 \right) \right]$$

By assuming that the discharge coefficient is known, the following equation for the leakage area ratio is obtained:

$$A_{ratio} = \frac{Q}{C_D b \frac{2}{3} \sqrt{2g} \left[H_{eff}^{3/2} - \left(\max\left(H_{eff} - h, 0 \right) \right)^{3/2} \right]}$$

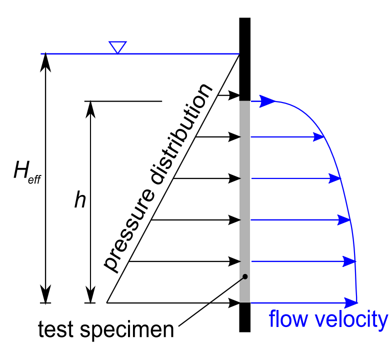

Figure 1: Distributions of pressure and assumed flow velocity for assessment of leakage area ratio

This approach is based on the following simplifications:

- Leakage area is equally distributed in longitudinal direction
- Leakage only through the door area (not through the surrounding wall panels)
- Discharge coefficient is constant and known (in this study C_D = 0.6 is assumed)

The first simplification is not fully valid since the pressure is larger at the bottom of the door and hence also the deformation is likely much larger there. The tests also showed that the second assumption is not valid for B-class cabin walls. Furthermore, it should be noted that the test arrangement did not allow testing of leakage flow that discharges to water.

3.3 Tested Structures

3.3.1 Overview

The list of tested items, as well as some initial results and observations are listed in Table 1. Most of the tests with the doors were conducted in both directions, i.e. pressure into and out from the doorframe.

Table 1: List of tested structures and the most notable observations

Type[1]	Item	H_{coll}	dir.[2]	Notes
A2	SWT door, sliding	~8 m	out	Minimal leaking before structural failure Area ratio linearly increasing
B2	A-class fire door sliding	~1 m	in	Area ratio about 0.025
		~1 m	out	Test direction had only a small effect on the critical pressure head
B2	A-class fire door hinged	~2.4 m	in	Linearly increasing area ratio.
		~2.4 m	out	very different leakage rates, depending on the gap between the sill and the door
B2	A-class fire door hinged with a hose port	–	in	Area ratio increases until H_{eff} ≈ 1 m and a constant A_{ratio} ≈ 0.03 is reached structural damage at H_{eff} ≈ 2 m
B2	A class fire door, double leaf	–	out	Large leakage, constant A_{ratio} ≈ 0.025 collapsing not be reached (H_{coll} > 1 m)
B3	B-class joiner door, hinged	–	in	Wall panels around the door fail first, resulting in large leakage
		–	out	Leakage through door frame (A_{ratio} ≈ 0.03)
B3	B-class walls	–	in	Leakage through the bottom of the wall
			out	Larger leakage ratio in this direction
–	Cold room sliding door and panels	>2.4 m	in	Linearly increasing area ratio. Test had to be stopped due to too large leakage rate
–	Window	>17 m	–	No leakage

[1] The type refers to water tightness category (A, B or C) and subtypes as described in SLF 47/INF.6

[2] The direction of the pressure is either into or out from the doorframe

3.3.2 Semi-Watertight (SWT) Door

The tested door type is typically used on the bulkhead deck. It is a sliding "Light Watertight door" (LWT), that actually fills the requirements for a watertight door (category A1 in SLF 47/INF.6), but only for a smaller maximum pressure.

Leakage through the tested door started at pressure height of about 2.0 m and it was very minimal (less than 1.0 l/s) until structural damage occurred at a pressure head of about 8.0 m. Thus it seems to be justified to ignore this kind of minimal leakage in time-domain flooding simulations.

Even after significant structural failure (Figure 2), the leakage through the door is only about 40 l/s, corresponding leakage area ratio of 0.017.

Just one test was performed; the direction of the pressure was out from the doorframe. It is assumed that for the opposite direction the door could have withstood even higher pressures.

Figure 2: Flooding through damaged SWT door (p = 82 kPa)

3.3.3 A-Class Fire Doors

Hinged Doors (Single Leaf)

Two different single leaf A-class fire doors were tested for both pressure directions. The doors were practically identical and from the same manufacturer. However, the gab size between the sill and the bottom of the door was different. Consequently, there is a significant difference in the leakage under the water pressure. The second door (Tests 2.3 and 2.4) was leaking so much that the maximum leakage rate of 90 l/s was achieved at very low pressure head of about 1.2 m. For this door, the direction of the pressure had only a minimal effect on the leakage rate. For the first door type (Tests 2.1 and 2.2), significant structural damage occurred at pressure height of about 2.4 m (Figure 3). Leakage was much smaller than for the second door type. Also, when pressure acted into the doorframe, leakage was even smaller. For all four test cases the calculated area ratio for leaking increased linearly as a function of pressure height.

Figure 3: A-class hinged door leaking (left, *p* = 26 kPa) and damage

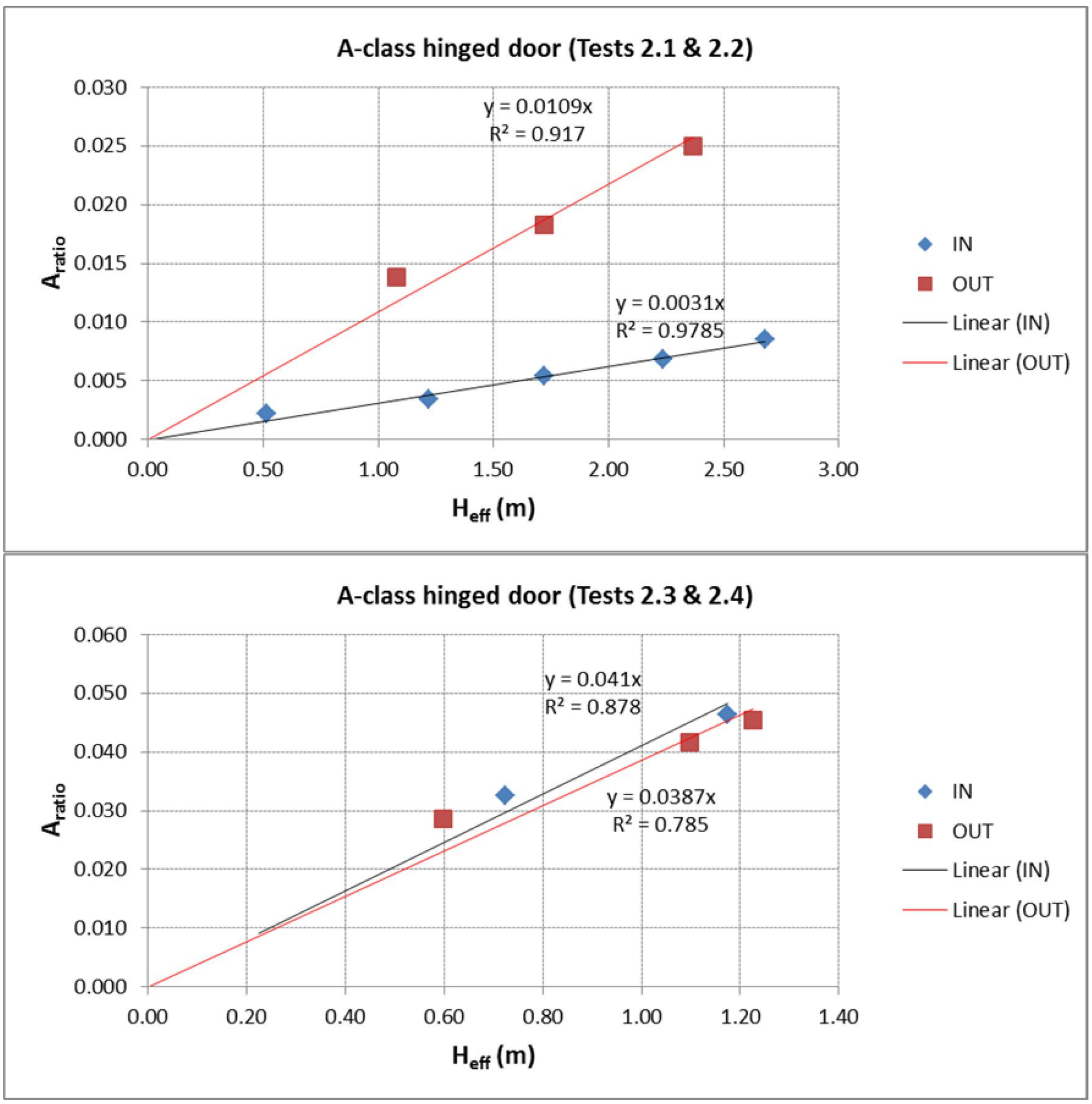

Figure 4: Calculated area ratio as a function of pressure height and a linear regression for two different A-class hinged door arrangements

Figure 5: Leaking through different A-class hinged doors (left 16 kPa and right 11.3 kPa), pressure into the doorframe

Hinged Doors with Hose Port

A single leaf door with a hose port was tested so that the pressure acted into the doorframe. The maximum flow rate of 90 l/s was reached at a pressure height of about 2.2 m, Figure 6. For tested pressure heights above 1.0 m, the leakage area ratio was constant, about 0.03.

Figure 6: Leaking A-class door with hose port (p = 21.9 kPa)

Hinged Doors (Double Leaf)

One test was performed for A-class double leaf hinged door in a condition, where the pressure acted out from the doorframe. Due to the large area of the doors, the critical flow of 90 l/s was reached at low pressure height of about 1 m. The calculated area ratio for leakage is about 0.025. The leaking took place mainly underneath the doors (Figure 7).

Figure 7: Leakage through A-class double leaf hinged door (*p* = 5.1 kPa)

Sliding Doors

Large leakage through the door was observed in both test directions at low pressure heights. The calculated area ratio was about 0.025. Significant damage occurred also at rather low pressure of 12.8 kPa into the doorframe or 10.8 kPa out from the doorframe. That is just about a pressure head of 1.0 m, and less than the rough approximation in SLF47/INF.6. Photos from the tests are shown in Figure 8.

Figure 8: Leakage (*p* = 6 kPa) and damage to sliding A-class fire door (*p* = 12.8 kPa)

3.3.4 B-Class Joiner Doors

Two different kinds of B-class joiner doors were tested, both water pressure into and out from the doorframe. Most notably, the direction of the pressure had a significant effect on the structural failure (Figure 9). When the water pressure acted into the doorframe, the wall panels around the door were the weakest point.

The behaviour of the two different doors was very similar. The calculated area ratios for all tested cases (two different doors, two directions) are presented in Figure 10.

Figure 9: Leakage of a B-class joiner door under 11.9 kPa pressure into the doorframe (left) and damage to the wall panels when the pressure direction was the opposite (right)

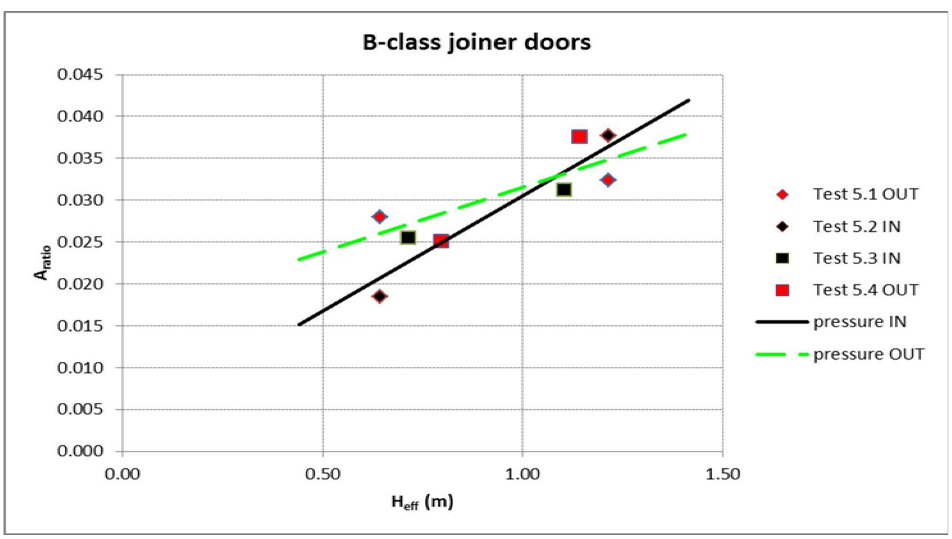

Figure 10: Calculated area ratio for all tested B-class joiner doors and linear regressions for the two pressure directions

3.3.5 B-Class Walls

B-class cabin wall with steel frames was tested for two pressure directions. In both cases, there was notable leakage through the bottom of the wall already at moderate pressure height of about 1.0 m. Unfortunately, higher pressures were not tested. However, since the deformation of the wall is large even under a moderate water pressure, it seems likely that this kind of structures might be ignored in time-domain flooding analyses.

Figure 11: Leaking through B-class wall with steel frames

3.3.6 Cold Room Sliding Door

Cold room walls and doors are considered to be a notable restriction for the progress of the floodwater. The doors are usually closed and cold rooms are often large and asymmetric rooms on the lower decks of passenger ships.

A typical sliding cold room door, installed in a small piece of cold room panel wall, was tested (Figure 12). With a pressure height of about 2.4 m, the leakage rate was 84 l/s. If only the door area is taken into account, the corresponding calculated area ratio is 0.036. With lower pressures also the area ratio was smaller. Most of the leaking was underneath the door. Collapsing could not be achieved due to the high leakage.

Figure 12: Cold room sliding door in test setup (left) and leaking (p = 22 kPa)

3.3.7 Window

A typical window was also tested (Figure 13). No collapsing took place under the maximum pressure head of about 17 m. The maximum measured deflection was about 20 mm. This result is in good agreement with the values presented in IMO SLF47/INF.6.

Figure 13: Tested window, no damage

4 Pressure Losses in Openings and Cross-Flooding Ducts

4.1 Test Arrangement

The experiments were carried out in a 50 m long, 1.09 m wide and 1.40 m deep flume with a horizontal bed at the laboratory of Water Engineering Group, Aalto University School of Science and Technology in Finland. Detailed descriptions of the test arrangement and results are given in the public deliverable, *Stening (2010)*. In the following, some significant findings are briefly presented.

4.2 Manhole Tests

Several tests were performed with a full-scale (400 mm × 600 mm) manhole in different flow conditions, Figure 14. In addition, scale 1:2 model manhole was tested.

The often applied discharge coefficient 0.6 was found to be a good approximation for the manhole in free flow conditions. The discharge coefficient of a full-scale manhole was mostly in the range 0.58 .. 0.59. The scale model manholes had 3-5% higher discharge coefficients than the full-scale manhole in free flow. An inclination of the manhole at an angle of 20° towards the flow caused an approximately 5% decrease in the C_D value in free flow, but did not have any considerable effect in submerged flow conditions.

In submerged flow, the discharge coefficient was found to be higher than in free flow. The difference between the C_D values in free and submerged flow conditions was greater for the full-scale manhole than for the scale models. In fully submerged flow, the discharge coefficients of the full-scale manhole were in the range of 0.67-0.7. The scale model manholes had up to 8% smaller C_D values than the full-scale manhole in submerged flow.

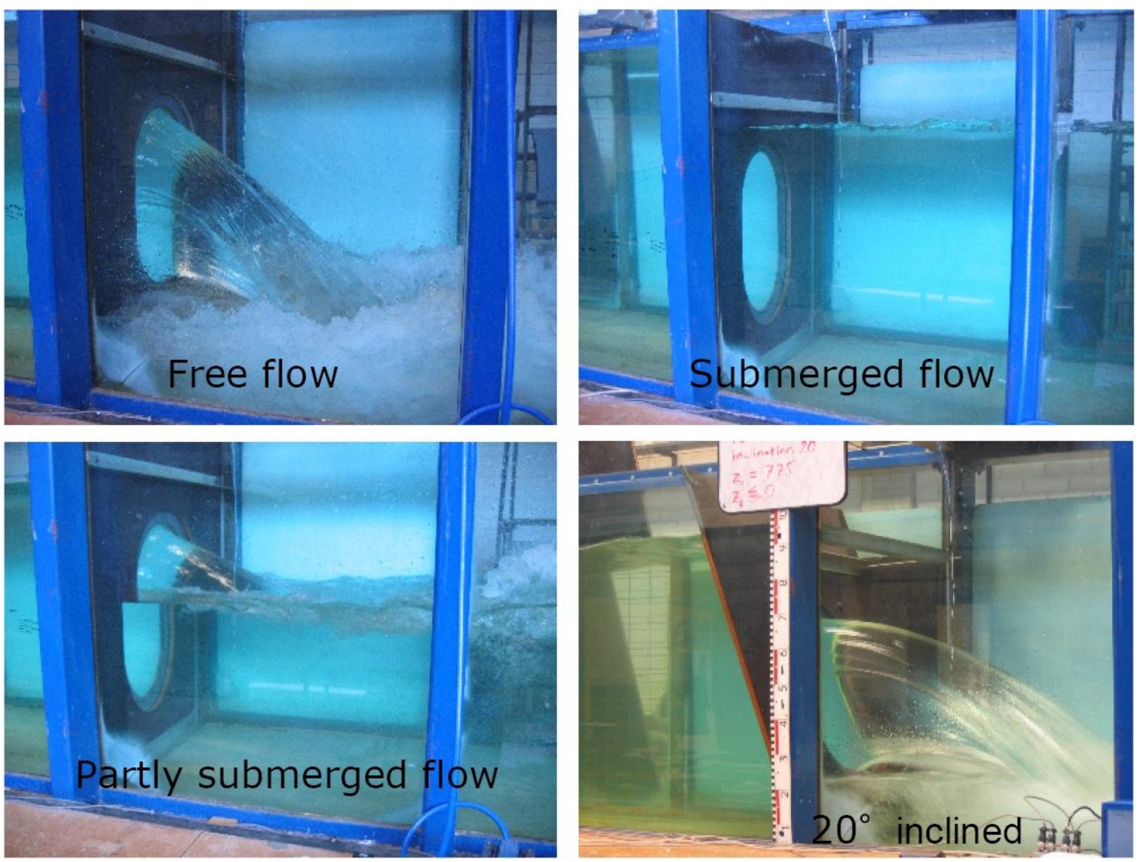

Figure 14: Examples of manhole tests in the flume, photos: Aalto University

4.3 Tests with Cross-Flooding Ducts

Tests were carried out with several variations of a cross-flooding duct design with two manholes in the girders and constant distance of 2.0 m between the girders. The scale was 1:3. One cross-duct element with all dimensions is shown in Figure 15.

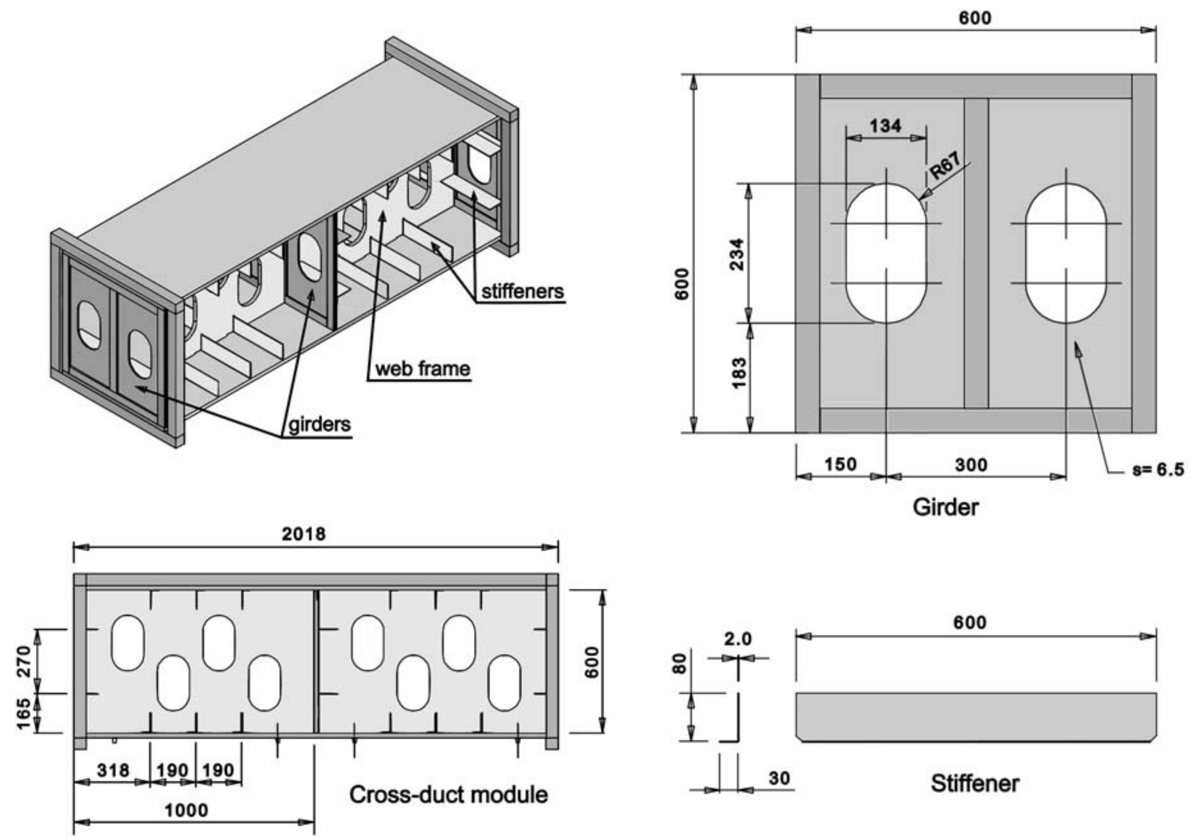

Figure 15: One cross-duct module with the investigated structural components. All dimensions of the 1:3 scale model are in mm

The IMO Resolution MSC.245(83) for assessing cross-flooding time contains an Appendix, where various pressure loss coefficients for water flow through pipes and valves are presented. In addition the Appendix contains simplified regression formulae for pressure losses in cross-flooding ducts. These are based on systematic CFD calculations. The following equation is recommended for the determination of the pressure loss coefficient k_i for a space between two girders with two manholes:

$$k_i = 0.0424L_i^3 - 0.3593L_i^2 + 1.1401L_i - 0.356, \quad 1 \le L_i \le 4 \tag{1}$$

where L_i is the distance between the girders in meters.

The discharge coefficient of the cross-duct is obtained from the following equation:

$$C_{D,C} = \frac{1}{\sqrt{1+\sum_{1}^{n} k_i}} \tag{2}$$

The constant 1 in the square root represent the pressure losses due to the outlet of the duct.

The obtained experimental results are compared to these formulae in Figure 16. The computational method recommended by the Appendix of the IMO Resolution MSC.245(83) for the estimation of a discharge coefficient for a cross-duct yielded higher C_D values than obtained from the experiments. The difference was at its greatest when the pressure loss coefficient k_i was estimated with the regression equation in Appendix 2 of MSC.245(83). There is a risk that the discharge coefficients of cross-ducts are overestimated if the guidelines of the resolution are applied without properly considering the geometrical properties of the girders in the cross-ducts.

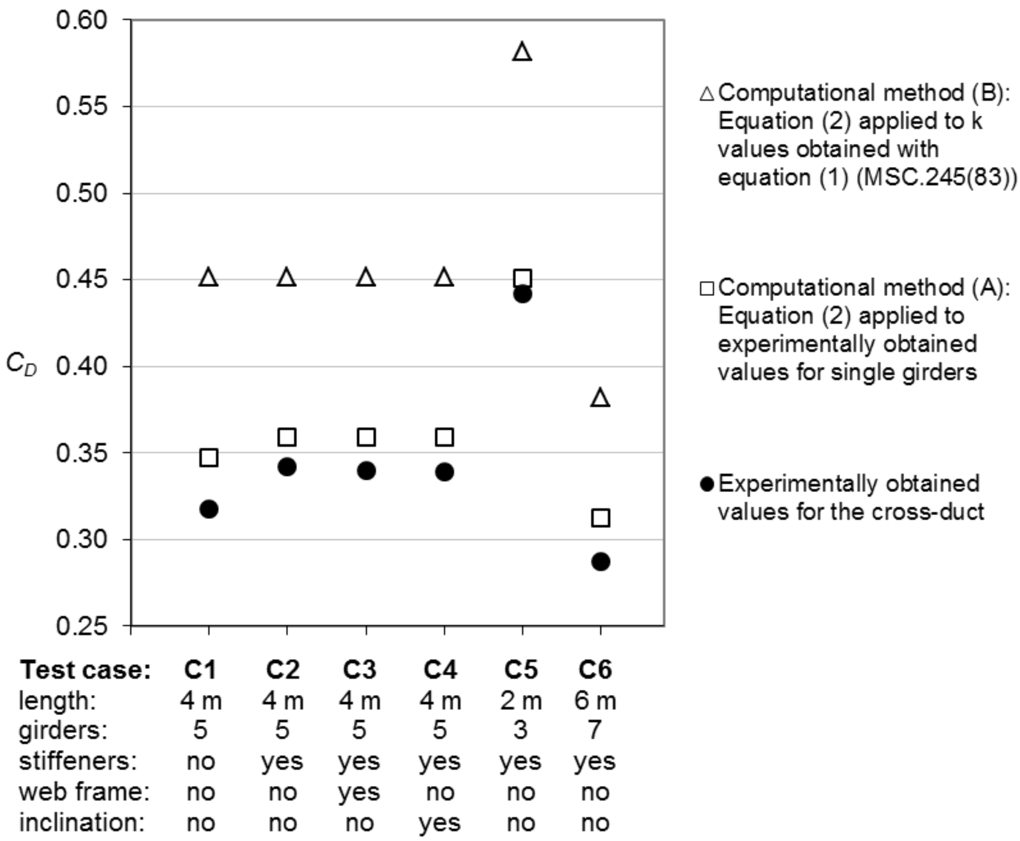

Figure 16: Comparison of experimental results and formulae in MSC.245(83)

4.4 CFD Calculations for Cross-Flooding Ducts

Several cases will also be calculated with CFD tools at CNRS in France. The aim is to first validate the applied software with the experimental results. In addition, the application of CFD allows studies with much higher pressure heads than in the experiments. The CFD simulation of the mode-scale cross-duct is in good agreement with the experimental results. Furthermore, calculations for full-scale duct with high pressure heads at the inlet (5 m and 10 m) resulted in very similar discharge coefficients, Table 2. More details are presented in the public report, *Visonneau, et al. (2010)*.

Table 2: Comparison of experimental and numerical results for cross-flooding duct arrangement C2, *Visonneau et al. (2010)*

Case	*H (m)*[3]	*discharge (m^3/s)*	*C_D*
model (experimental)	1.75	0.043	0.338
model scale (CFD)	1.67	0.042	0.333
full scale (CFD)	5.00	0.638	0.325
full scale (CFD)	10.00	3.140	0.335

4.5 Pressure Losses in Air Pipes

Air compression inside the equalizing tank can significantly delay the cross-flooding time. This important issue has been included in the IMO Resolution MSC.245 (83). Time-domain flooding simulation is a powerful tool for assessing the cross-flooding time with air compression and airflows taken into account. However, this procedure requires effective discharge coefficients or pressure losses for the airflow in the air pipes. Traditionally, the formulae in the Appendix of the Resolution have been used also for airflow.

In the FLOODSTAND project, the validity of these formulae was tested by performing detailed CFD calculations for two different typical air pipe configurations:

1. Pipe with two double mitre bends, no air cap
2. Straight pipe with air cap

The calculations were done by CTO. The flow was considered to be quasi-stationary. Three different over-pressures in the flooded tank were studied (1 kPa, 10 kPa and 20 kPa). Based on the results, also the losses in the air cap of the second pipe could be examined. The results are presented in Figure 17. The dependency on the pressure difference seems to be marginal, and consequently it is reasonable to apply constant factor in cross-flooding time calculations.

A comparison between the CFD calculations and the simple calculation method in the Appendix of the Resolution MSC.245(83) is presented in Table 3. The difference in the total pressure loss is very significant. This can be due to the fact that the IMO resolution is elaborated for water flows, for which the Reynolds number is usually smaller, which means higher pressure losses in general, *Kraskowski (2010).* Further research may be needed for establishing more appropriate formulae for rough estimation of the pressure losses in air pipes.

[3] Water height at duct inlet in full-scale

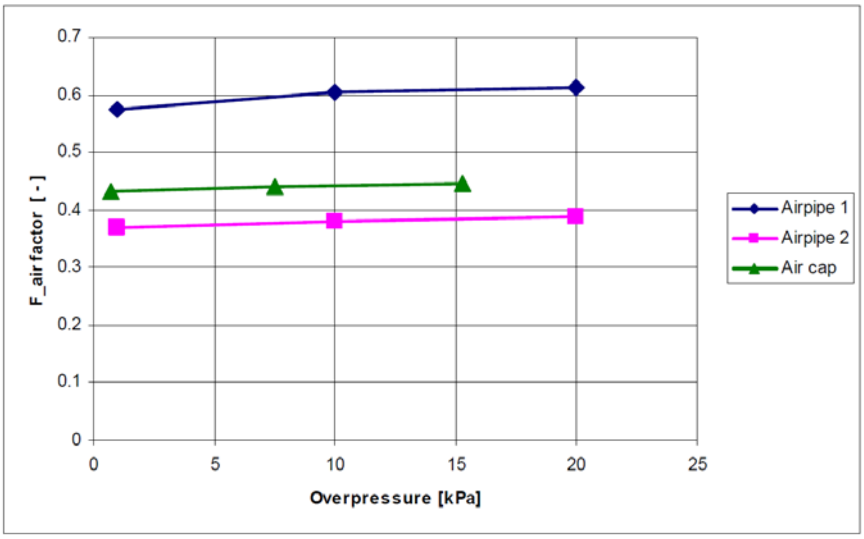

Figure 17: Speed reduction factor (discharge coefficient) as a function of over-pressure, *Kraskowski (2010)*

Table 3: Comparison of MSC.245 and CFD results for the air pipe case 1, *Kraskowski (2010)*

Pressure loss coefficient	*MSC.245(83)*	*CFD*
Inlet	k = 0.43	
Outlet	k = 1.00	
2 × 90° double mitre bend	k = 2 × 0.44	
Pipe friction	k = 0.02 × L / D = 2.10	
Total	**∑k = 4.41**	**∑k = 2.75**

5 Further Research

5.1 FEM Calculations

In parallel with the tests, also a numerical study on critical pressure heads for non-watertight structures was carried out at MEC in Estonia. Four types of structures were studied: cold-room structure (including wall and door), cabin wall, A-60 hinged door and A-60 semi-watertight (SWT) sliding door. All these structures were analysed with non-linear finite element method. The results will be published at the project web site http://floodstand.tkk.fi.

5.2 Detail Level of Modelling

The effect of modelling details is studied through dedicated model tests at Marin in the Netherlands, by using two models of the same ship with different level of detail. In addition, tests will be carried out in a depressurized towing tank in order to study also the effect of air compressibility in a realistic way. The results of the tests will also be used to further validate the various time-domain flooding simulation tools of the project partners.

5.3 Sensitivity Analysis

Most notably, a dedicated sensitivity analysis will be carried out, using the developed sample ship designs. The previous research, such as *van't Veer et al. (2004)*, indicates that there are certain critical openings, such as fire doors to staircases. The applied input parameters for pressure losses and leaking for these openings can have a very notable effect on the simulation results. This is the starting point for this research that will be carried out at AALTO University in co-operation with Napa Ltd.

6 Conclusions

6.1 Leaking and Collapsing of Non-Watertight Structures

Measurement of very large leakage rates through damage structures is very difficult. In this test arrangement flow rates up to 90 l/s could be achieved. With higher leakage the pump system could not maintain the pressure level. In practice very high pressure heads in a flooded ship are very rare, and this limitation was not considered to be significant.

It is also recognized that due to the limited resources in general only one test was performed for each test case. Thus any possible statistical variation is ignored. In addition, different manufactures can have different construction of the doors. Based on the repetition tests with the A-class hinged door, it is obvious that the size of the gap between the lower edge of the door and the sill has a significant effect on the leakage rate.

However, some notable conclusions based on the experiments can still be derived:

- Tested sliding SWT (or LWT) door is practically watertight up to very large pressure heights (about 8 m), very small leakage (less than 1.0 l/s) was observed with pressure heights above 2 m.
- A-Class fire doors will likely delay the flooding and they should be included in the numerical model. There is notable leakage even at small pressure heights. The calculated area ratio is often (almost) linearly increasing. There was notable deviation in the leakage rates for the tested A-class doors, mainly caused by the different size of the gap between the door and the sill.
- B-Class boundaries do restrict the flow of floodwater but the structural failure can happen in many different ways, usually with rather low pressure heights. Thus the leakage through the damaged structures is very large. It was also shown that the wall panels around the doors can be the weakest part. Consequently, these structures could likely be ignored in time-domain flooding simulations.
- Cold room doors and walls can stand high pressures but leaking is very significant.
- Windows on lower decks may be excluded from flooding simulation since they are likely watertight to pressure heights of 17 m or above.
- The tests proved that the approximations for leakage area ratios in SLF47/INF.6 were much over-estimated. Maximum area ratio in the analysis of the test results was less than 0.06. In many cases, the effective leakage area ratio increases linearly as the pressure height is raised.

The experimental data, supported by the FEM calculations, forms a solid basis for systematic sensitivity analysis and guidelines for modelling and coefficients in time-domain flooding simulations.

6.2 Pressure Losses in Openings

The generally applied rough estimation C_D = 0.6 is rather close to the measurements for the tested manholes in different flow conditions. Within the planned sensitivity analysis the effects of small variations in the applied coefficients will be examined in detail.

For cross-flooding ducts, the regression formulae in MSC.245(83) are likely oversimplified. For example, the stiffeners in the duct have a notable effect on the pressure losses. Also different configurations, such as the manhole shape and size are not taken into account in these formulae. Performed CFD computations match well with the experimental results, pointing out that the applied model was large enough. Further research may be needed, although the Resolution allows use of both CFD tools and model experiments as alternative methods.

The simplified method in Resolution MSC.245(83) seems to over-estimate the pressure losses in air pipes very significantly. Further analysis and research is needed for establishing better formulae for pressure losses in airflow in pipes.

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The final reports of the research project FLOODSTAND are publicly available at the project web page: http://floodstand.tkk.fi

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