Investigation into the effects of petalling on coefficient of discharge during compartment flooding

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Abstract

Ships or risers, among many other marine structures, incur damage even with the best precautions. Whilst these damages can be catastrophic they often lead to scenarios whereby the damaged structure is ailing but not failed. In these scenarios the structure will flood and it is vital that the rate of flooding can be estimated, from a limited knowledge of the damage, so that safety and the environment can be best considered and an economical and effective recovery or repair of the vessel occurs. In an effort to improve the modelling and hence improve the advice available, research has been performed into how petalling, folding of the structure at the edge of the damage, effects the flooding of the structure. Experiments have been conducted on petalled structures and the results are compared to the coefficient of discharge for flat edged damages. The results show that petalling makes a substantial difference to the coefficient of discharge of the orifice flow which is largely dependent on the petalling angle which can both reduce or increase the flow rate dependent on the orientation. However, this difference can be predicted if the type of petalling is known.

Keywords: Compartment flooding, Coefficient of Discharge, Damaged Structures

1. Introduction

Marine structures can be seriously damaged by, or lost because of, many different causes such as fire, explosion, flooding, structural failure and loss of propulsive power (Tupper, 2004). During these incidents, there is a high likelihood of structural damage with Konopelko (1990) showing that 53% of accidents caused damage to the hull. Each of these damages comes from a different scenario resulting in a large

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variation of, position and size of damage. Eghtesad et al. (2012) provided a review of a number of cases where damage has been investigated for a range of applications using different fluid modelling methods. Calyron et al. (2013) summarised the problems associated with modelling leakage through cracks in thin walled structures.

If the damage is below the waterline, it will lead to flooding of the structure. The flooding can have two important consequences: change of buoyancy and stability and reduction in structural strength. This is because when flooding occurs, the reduction in underwater volume will lead to the loss of buoyancy force. The structure will reach a new balanced condition through sinkage, which will affect the stability by changing the position of the centre of buoyancy and also affect the structural strength by deteriorating the loading distribution. During decision making of emergency response, coefficient of discharge, C_d , is commonly used to assess the impact of damage to the stability and structural integrity and therefore it is vital that this value can be accurately determined after damage. Bazso and Hos (2013) highlighted the difficulties in estimating this coefficient of discharge finding that the current estimates were not suitable for their calculations for direct spring loaded poppet relief valves.

The time period from the start of flooding to the final equilibrium condition is defined as time-to-flood. In general, the flooding process from the creation of the damage hole can be divided into three main phases (IMO SLF46/INF.3, 2003). Figure 1.1 provides a brief description of these phases.

The first phase of transient flooding starts as soon as the creation of the damage when the water rushes into the compartment through the opening. It is then followed by the second phase of progressive flooding where the water floods into the undamaged compartments through any openings. If the ship finds an equilibrium condition, the ship will reach a steady state which is the final phase. When evaluating the flooding process Ruponen (2007) showed that flooding ships will

experience intermediate stages which can be more dangerous than the final condition, if equilibrium can be found at the final condition. Moreover, in the case of damaged ships, the simulation of the compartment flooding process will provide an estimation of the possible time for abandonment and evacuation.

To explore flooding, Ruponen (2006) performed a series of tests on the progressive flooding of a box-shaped barge. The model contained eight compartments and all of the openings, which represented broken pipes, leaking doors, manholes, and staircases, are simplified to ideal rectangular or circular shapes. All the compartments in the model were open to the external air in order to avoid the air compression. The resulting mean coefficients of discharge, namely, the ratio of actual discharge to the theoretical discharge, are shown in Table 1.1.

Table 1.1 Coefficient of discharges for different openings (Ruponen, 2006)

Opening	Mean C_d
Large damage (40 mm×60 mm)	0.78
Small damage (25 mm×25 mm)	0.83
Broken pipe (Ø20 mm)	0.80
Partly open door (20 mm×20 mm)	0.75
Staircase (100 mm×100 mm)	0.72

Smith (2009) used hydraulic models to measure the coefficient of discharge of an orifice. The experiments were conducted using a model forced with vertical velocity to generate a quasi-steady flow; the assumption made in orifice flow theory. The results showed that with an increase in the orifice size, the coefficient of discharge reduced and the velocity of the water jet also decreased. As the orifice size increased, the effect of model velocity became more significant on the coefficient of discharge.

Prohaska et al. (2010) investigated the coefficient of discharge for different orifice sizes in two different sizes of riser pipe. They found the coefficient of discharge to be a function of head height over the orifice, location of the orifice above the floor of the tank and the ratio of the orifice diameter to riser pipe diameter. The coefficient of discharge increases as the ratio between the head height over the orifice and the orifice diameter reduces. For a given size of riser pipe the coefficient of discharge decreased with an increase in the ratio between the heights of the internal and external fluid, if the orifice was above the floor. The coefficient of discharge also reduced as the ratio between orifice diameter and riser pipe diameter increased. Moreover, if the orifice diameter was small compared with the head above the orifice and the height of the orifice above the tank floor, the coefficient of discharge would be constant. Finally it can be shown that, with all of the other variables fixed, the coefficient of discharge was lower for riser pipes of a larger size.

Jan and Nguyen (2010) examined the coefficient of discharge for water flow passing through a circular orifice at the bottom of a conical hopper. The results indicated that the larger orifice diameter or higher water head would lead to a smaller coefficient of discharge and the orifice diameter was more important to the coefficient of discharge than the water head. Moreover, the coefficient of discharge for a bottom orifice was larger than for a sidewall orifice under the same test condition.

Wood (2010) estimated the coefficient of discharge of orifices with different shapes and areas. The coefficients of discharges were found to vary from 0.452 to 0.725 as a result of different orifice shapes: circles, squares and rectangles; and areas: 12.6-50.3 cm². The coefficient of discharge decreased as the orifice area reduced and it also had a large difference between different orifice shapes.

Wang (2011a) designed a number of orifice plates which contained different regular shapes; different positions of the orifice; and the different edge shapes of the orifice. The results show the damage area and shape strongly influenced the coefficient of discharge furthermore the orifice position also had a strong effect on the coefficient of discharge which increased closer to the centre of the bottom plate.

Wang (2011b) used three circular orifice plates, with different damaged areas, to investigate the

coefficient of discharge for different wave properties. During these tests the model was immersed to 4 different depths and exposed to 4 different wave periods at each immersion condition. The flow rate was clearly affected by wave properties and an increase in wave period and wave amplitude decreased the flow rate.

In literature, there is a limited amount of research on how damaged size, shape and type affect the coefficient of discharge and none on how petalling will affect the flow rate. This paper focuses on the local properties of the damaged orifice and the novelty comes from investigating the effect of petalling on the flow rate in the transient flooding condition where petalling of the damaged hole is defined as the part of the hole which bends and contorts after penetration by a striking object such as depicted in Figure 1.2. This study will experimentally investigate the effects of different petal properties on the flow rate and the coefficients of discharge of orifices with petals are compared to those without.

2. Orifice Flow Theory

It is known that the majority of ships larger than 100 m in length are made from steel plate where the hull thickness typically varies from 10 mm to 30 mm with risers and other structures having a similar profile (Smith, 2009). As the thickness is small compared to the size of the compartment, orifice flow theory is valid for the investigation of ingress and egress of flooding water so it can be used to determine the instantaneous rate of the flow in a damaged compartment.

Torricelli found the relationship between the orifice flow velocity and the relevant hydrostatic pressure by measuring the velocity of water through an orifice and comparing the results to the instantaneous hydrostatic head of water above the orifice. This outcome was later supported by Bernoulli's equation. The relationship between the orifice flow velocity v , the hydrostatic head h and the gravity acceleration g can be given in Torricelli's equation, 2.1, as:

$$v = \sqrt{2gh}. \quad (2.1)$$

Smith (2009) described an example of the flow through an orifice with the application of the steady form of Bernoulli's equation as shown in Figure 2.1. Assuming that the flow is inviscid and irrotational along a streamline then equation 2.2 can be applied:

$$p_1 + \rho g z_1 + \frac{1}{2} \rho v_1^2 = p_2 + \rho g z_2 + \frac{1}{2} \rho v_2^2; \quad (2.2)$$

if the flow is assumed to be steady, then pressure $p_1 = p_2 = p_a$ and if $v_1 \ll v_2$ equation 2.3 can be derived:

$$v_2 = \sqrt{2g(h_1 - h_2)}. \quad (2.3)$$

However, there are differences between the basic ideal orifice flow theory and practical applications to marine structures. The coefficient of discharge was introduced by Massey (1968) in order to take into consideration of friction, viscosity and turbulence. As the fluid leaves the orifice the flow would remain parallel however, in practice, frictional effects produce parallel flow only at a short distance from the orifice. The jet may diverge which leads to the section of minimum area A termed the vena contracta. If the area of the orifice is A_d , the coefficient of contraction, C_c , can be expressed by the ratio of the orifice area to the vena contracta area given in equation 2.4:

$$C_c = \frac{A}{A_d}. \quad (2.4)$$

For a sharp-edged, or ideal, circular orifice, the coefficient of contraction usually increases with an increase in coefficient of discharge and as the head above the orifice decreases. In the case of Smith and Walker (1923) the coefficient of discharge varies from 0.67 for a 2 cm orifice to 0.614 for a 6 cm orifice with heads above 1.2 m. The velocity actually attained at the vena contracta is also less than the ideal velocity at the orifice. In the same way, the coefficient of velocity, C_v , is defined as the ratio of the actual mean velocity to the ideal velocity. Assuming the actual average velocity is V and the ideal velocity is V_i , the C_v can be written as in

equation 2.5:

$$C_v = \frac{V}{V_i}. \quad (2.5)$$

This coefficient varied from 0.95 to 0.99 for diameters of orifice between 2 and 6 cm with heads up to 30 m and is relatively insensitive to head change (Smith and Walker, 1923). Massey (1968) uses the definition of the coefficient of discharge that it is the ratio of the actual discharge to the ideal value, this is reflected in the following derivation given in equation 2.5:

$$C_d = C_c \times C_v. \quad (2.5)$$

Massey (1968) stated that the value of C_d does not change for a free jet or a jet of much higher fluid density than the fluid into which it is emerging. However, the Bernoulli equation is used for steady flow but the flow in a damage scenario will constantly vary with the height of the internal water surface, under the assumption that the external water surface is constant, and therefore the velocity of the flow will change with time. As a result, the assumption of quasi-steady flow is introduced as an approximation to the calculation of compartment flooding. Massey (1968) emphasized that “an assumption of quasi-steady flow should always be checked to see whether the rate of change of h is negligible in comparison with the velocity of the jet”. Based on the assumption of quasi-steady flow and the Bernoulli equation of ideal orifice flow, along with the coefficient of discharge, the flooding models are now referred to as hydraulic models.

3. Experimental design

3.1 General description

A cylindrical tube is used in these flooding experiments where it is assumed that it is consistent with the hydraulic model. The experimental set-up consists of three parts: a gas and a Schrader valve placed on a top plate; an opening in the centre of the bottom plate and a tube connecting the top and bottom plates. The junctions

between the tube and the plates are filled with silicon sealant in order to keep the whole tube both airtight and watertight. Different orifice plates can be fitted to the bottom plate through bolts so that the opening on the bottom can represent different damaged scenarios. Two wave probes are vertically installed along the internal sidewall of the tube. The average value from these two wave probes is taken as the internal water height, at a recording frequency of 50Hz, in order to reduce the dynamic effects and avoid the water jet in the centre of the cylinder. Using multiple wave probes allows an average value for the water height to be evaluated allowing a more accurate measurement in the cases where the water was not flat.

The whole model is partially submerged in the tank and it can be inflated through the Schrader valve until the water inside is evacuated. Later, the gas valve is suddenly opened to make the internal air pressure equal to the external air pressure in a short time period allowing water to flood the tube. The water will stop flowing when the internal water surface reaches the external free surface and the flooding process can be recorded through using the wave probes. The tank particulars related to the experiments are shown in Table 3.1:

Table 3.1 Testing facilities of tank

Length	30 m
Breadth	2.4 m
Water depth	1.2 m
Water temperature	18.5°C

Figure 3.1 shows the experimental set-up and the principal dimensions of the hydraulic model are given in Table 3.2.

Table 3.2 Principal dimensions of the hydraulic model

Cylinder height	694 mm	Bottom plate thickness	3 mm
Internal diameter of the cylinder	180 mm	Orifice plate diameter	148 mm
Cross beam length	2700 mm	Bottom plate diameter	240 mm
Longitudinal beam Length	255 mm	Immersion depth	400 mm
Orifice plate thickness	1 mm		

3.2 Orifice design

The orifice plates are made of aluminium alloy with a thickness of 1 mm in order to ensure a sharp edged orifice. A theoretical petal shape is used to represent all of the petals with a square hole and 1 petal on each side of the square similar to Zhang (1999) which suggests this is an idealised damage shape for a ship collision accident as shown in figure 3.2.

11 orifice plates were used and 21 groups of experiments carried out. For each group, the experiment was repeated 3 times and the average value is taken in order to reduce the effect of the experimental error. Two factors are considered during the design process: (1) The bending angle of the petal and (2) the damage integrity ratio of the petal.

3.3 Petal Design

An important feature to be investigated is the effect of the bending angle of the petal on the coefficient of discharge. For this study, three different angles, i.e. 40, 60, and 80 degrees, are tested.

Not only can material be bent during a damage scenario but there can also be loss of material. This can range from just distortion without material being lost to the entire area being removed. The damage integrity ratio of the petal is therefore defined by

the authors as the remaining petal's height in comparison to the full petal's height. Due to this definition the change in area to damage integrity ratio is different, for example, when the height is reduced from 100% to 50%, the decrease in area is only 25% but when the height decreases from 25% to 0%, the area is reduced from 43.75% to 0. However, in the first case the change in coefficient of discharge is large but in the second it is small.

Three damage integrity ratios are used in the experiments: 25%, 50%, and 100%. The integrity ratio of 50% is chosen as the standard parameter which is applied to the bending angle tests, while the bending angle of 60 degrees is regarded as the standard parameter which is applied to the integrity tests. The 3D drawings of the petals with different integrity ratios are shown in Figures 3.3-5.

There are two groups of experiments where the petals either face inwards or outwards. The different experimental sets are summarised in table 3.3 with the designation of each set.

Table 3.3 Experiments plan

Inward Facing Experimental Set	Outward Facing Experimental Set	Inward Facing		
		Petal Uniformity	Bending Angle (°)	Integrity (%)
1	11	Uniform	60	50
2	12	Uniform	40	50
3	13	Uniform	80	50
4	14	Uniform	60	100
5	15	Uniform	60	25
6	16	Combination	60	50
7	17	Combination	40	50
8	18	Combination	80	50
9	19	Combination	60	25

10	20	Combination	0	0
21	No Petalling			

3.3 Experimental procedure

Each set of experiments is conducted following the steps described below:

Step 1: To calibrate the wave probes by raising the cross beam to different known heights;

Step 2: To equalise the internal air pressure to the atmospheric pressure as well as the internal water surface to the external free surface by opening of the gas valve;

Step 3: To close the gas valve and to evacuate the water from the cylinder with an electric pump through the Schrader valve. In this step, it is necessary to wait for about one minute in order to check the airtight condition of the cylinder.

Step 4: To start data recording just before the gas valve is quickly opened. Since the internal air pressure will suddenly reduce to the atmospheric pressure, the water will flow into the cylinder and the internal water height will continue to increase until there is no water head between the external and internal water. The recording will be kept on for about 15 seconds after the flooding process is finished in order to provide enough data to capture the complete flooding process.

Step 5: To replace the orifice plate on the bottom plate for the next set of tests and then repeat the experiment from step 2.

4 Experimental results

4.1 Verification of experimental set-up

To ensure that the experimental set-up was correctly determining the coefficient of discharge the rig was verified against experiments and CFD simulations previously performed by Wood (2010 and 2012). Table 4.1 shows the comparison between the

results from experiment and CFD. The verification performed with this set of test data varied from the comparison set where the current results used a damaged area of $4.9 \times 10^{-3} \text{ m}^2$ and those performed previously had a damaged area of $5.03 \times 10^{-3} \text{ m}^2$. The results show a good correlation and there is a high confidence that the results performed were giving accurate data.

Table 4.1 Coefficient of discharges for varying damage geometries

Damage Area ($\times 10^{-3} \text{ m}^2$)	Shape	Mean C_d (Wood (2010) Experiment)	Mean C_d (Wood (2012) CFD)	Mean C_d (Current)
5	Square	0.700	0.643	0.7058

4.2 Data for different Petalling parameters

The observed data from the tests are presented in a series of tables according to their petal properties (See Tables 4.1-4.4). The two main factors are the bending angle and damage integrity ratio. Different rows are for differing bending angles whereas the columns are for differing integrity ratios. When the integrity is 0, both of the coefficients of discharge and the flooding periods do not vary with the bending angle and therefore there is a constant value. The four tables contain the flooding period and the coefficient of discharge values for both the orifice plates with uniform petals and those where petals were in combination with two petals kept at 60° angle and full integrity and two petals were varied as shown by tables 4.3 and 4.4.

Table 4.2 Flooding period using uniform petals

Inward Facing					Outward Facing				
	0%	25%	50%	100%		0	25%	50%	100%
40°	2.3167		4.4800		40°	2.3167		5.6067	
60°	2.3167	2.6133	2.8400	3.2133	60°	2.3167	3.3533	3.7133	4.0733

80°	2.3167		1.7467		80°	2.3167		2.4200	
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Table 4.3 C_d values for uniform petals

Inward Facing					Outward Facing				
	0%	25%	50%	100%		0	25%	50%	100%
40°	0.7058		0.3663		40°	0.7058		0.3038	
60°	0.7058	0.6105	0.5694	0.5048	60°	0.7058	0.4807	0.4320	0.3935
80°	0.7058		0.8041		80°	0.7058		0.6014	

Table 4.4 Flooding period for combinations of petals

Inwards Facing					Outward Facing				
	0%	25%	50%	100%		0	25%	50%	100%
40°	2.4800		3.6267		40°	2.8133		4.6367	
60°	2.4800	2.8467	2.9067	3.2133	60°	2.8133	3.6400	3.8400	4.0733
80°	2.4800		2.3400		80°	2.8133		3.0133	

Table 4.5 C_d values for combinations of petals

Inwards Facing					Outward Facing				
	0%	25%	50%	100%		0	25%	50%	100%

40°	0.6074		0.4356		40°	0.5821		0.3451	
60°	0.6074	0.5749	0.5434	0.5048	60°	0.5821	0.4552	0.4126	0.3935
80°	0.6074		0.6509		80°	0.5821		0.5501	

Table 5.1 provides a comparison between the coefficient of discharge values in different combination petals and the corresponding non-combinational petals. The corresponding non-combinational petals mean the two non-combinational petals which are used to generate the combinational petals. For example, for experimental set 6 the corresponding orifice plates are the 4 and 1 experimental sets (see Table 3.3).

4.3 Assessment of Data for Projected Area

From Table 4.3 and 4.5 it can be seen that a large variation in the value of the coefficient of discharge occurs dependent upon the petalling. This is due to the petals blocking the orifice entrance effectively changing the area. Therefore, calculations have been performed using a projected area, defined as the area left after the shape of the petals has been projected onto the plane of the orifice. This projected area reduces with reducing fold angle and increasing integrity. The calculation of the projected area allows a comparison with the coefficient of discharges calculated using the total area of the orifice, the area enclosed by the folded lines of the petals which is the same as the non-petalled state. Table 4.6 shows the coefficient of discharge for each set of data, calculated with the projected area, in comparison to the coefficient of discharge calculated with the total orifice size.

Table 4.6 Comparison of C_d between total and projected area

Set	Bending Angle (°)	Integrity (%)	Direction	Area	Projected Area C_d	Total Area C_d
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1	60	50	Uniform	3063	0.91	0.57
2	40	50	Uniform	2085	0.86	0.37
3	80	50	Uniform	4262	0.92	0.80
4	60	100	Uniform	2450	1.01	0.50
5	60	25	Uniform	3828	0.78	0.61
6	60	50	Combination	2756	0.97	0.54
7	40	50	Combination	2267	0.94	0.44
8	80	50	Combination	2756	1.16	0.65
9	60	25	Combination	3139	0.90	0.57
10	0	0	Combination	3675	0.81	0.61
11	60	50	Uniform	3063	0.69	0.43
12	40	50	Uniform	2085	0.71	0.30
13	80	50	Uniform	4262	0.69	0.60
14	60	100	Uniform	2450	0.79	0.39
15	60	25	Uniform	3828	0.62	0.48
16	60	50	Combination	2756	0.73	0.41
17	40	50	Combination	2267	0.75	0.35
18	80	50	Combination	2756	0.98	0.55
19	60	25	Combination	3139	0.71	0.46
20	0	0	Combination	3675	0.78	0.58

21	0	0	No Petals	4900	0.71	0.71
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4.4 General Observations

As an example the inward facing uniform petal experimental set 4 is used to describe the flooding period and the data processing. The internal water level time history for the flooding process is shown in Figure 4.3.

The start time for the flooding is taken to be when there is a change in the internal water height. Another key factor is how to choose the end time. Due to dynamic effects it is unreasonable to choose the end time as the time at which the internal water level first reaches the external free surface. Therefore a polynomial curve has been fitted to the data and when this reaches 0 this is the end point.

In this process, there are three typical periods which can be observed, different to those depicted in figure 1.1. The first period has a short time period from 0 to 0.1 s. During this period most of the floodwater gathers into a water jet at the centre of the cylinder and only a small part of the floodwater reaches the sidewall of the cylinder, making measurement difficult. As this period is short compared to the whole process, the start time is regarded as the time when water reaches the sidewall of the cylinder although it has started slightly before then. The second period is from 0.1 s to 1.2 s where the internal water level increases in an oscillatory manner as a result of the dynamic effects. The interaction between the water inside and the ingressing floodwater has an effect on the actual water level in the cylinder. The water jet can be observed as a bulge at the centre of the water surface during this period and the protruding height decreases with time. The third period is from approximately 1.2 s, in this example, to the end of the flooding. The increase of the water level becomes relative steady and the growth rate decreases as the water level increases. The effect of the water jet can now be ignored. Finally, after the water level reaches 0 a slight oscillation occurs.

There are some important differences in the behaviour between the outward pointing petals and the inwards pointing ones as illustrated by experimental set 14 shown in Figure 4.4. There are still three periods similar to the experimental set 4. In the first period, the initial time is shorter, i.e. 0.04 s, and it can only be seen from the data. This is because when the petals point inwards it not only makes the water flow towards the centre but also prevents the small quantity of water flowing towards the sidewall. However, when the petals point outwards, although there is still a water jet in the centre, water is no longer prevented from flooding to the sides and hence the wave probes can detect the water level changes much earlier than in the inward orifice plate cases. The second period seems less “violent” than the inward orifice plate, because the outward petals weaken and disturb the water jet resulting in a smaller dynamic effect. Unlike the outward petals, the inward petals sometimes can enhance the water jet by increasing the flow of the water which has a stronger vena contracta and larger velocity. The third period is similar to the experimental set 4 but is smoother. Moreover, the overall flooding time is longer than the inward orifice plate with the same petals.

Also included, in figure 4.5, for interest is the flooding process of the orifice plates, considered in previous research Wood (2010), with no petals.

It can be observed that the process is similar to the inward facing petals orifice plate. The dynamic effect is more violent than experimental set 4 and the flooding time is also shorter. Importantly, the proportions of both the first period and the second period are larger than the experimental set 4 orifice plates. In conclusion, the first period and the second period last longer with an increase in dynamic effects. When compared to the second period, the dynamic effects of the first period cannot be ignored and hence the both should be taken into the calculation for the coefficient of discharge value. Furthermore it can be seen that the outward facing petals created a coefficient of discharge lower than that of the inward facing plates. However, both the inward and outward facing plates were much lower, in terms of coefficient of discharge than the plates with no petals.

5. Discussion

It can be seen that a smaller coefficient of discharge means a smaller flow rate and therefore a longer flooding period; because of this correlation only the value of coefficient of discharge is considered in the discussion that follows.

5.1 The effect of petal bending angle

It is seen from the results in Tables 4.2 and 4.4 that in general most of the petals on the orifice will obstruct the flow and reduce the value of coefficient of discharge therefore when the bending angle increases the coefficient of discharge becomes larger and as the damage integrity ratio becomes larger the coefficient of discharge decreases. Importantly when the bending angle is 80° and the damage integrity ratio is 1, the most extreme scenario tested, the coefficient of discharge is larger than that of the orifice plate without petals. This result shows that the petals can enhance the flow rate and increase the coefficient of discharge. This phenomenon is due to the reduced effect of the sharp edge on the flow water; when the bending angle is near to 90° the petals make the orifice behave similarly to a pipe where the coefficient of discharge is 1. In this way the flooding water is funnelled by the petals. It was found, through interpolation, that when the bending angle is below 70° , the petals partly block the floodwater whereas when it is higher than 74° , the petals enhance the floodwater. Most petals created in ship damage incidents have a small average bending angle particularly in double hulls as shown by Wu et al. (2004). However in some cases large bending angle petals are created which can enhance the floodwater and this could be dangerous to stability and structural strength. It is therefore vital that work such as Ramajeyathilagam and Vendhan (2004), Ozguc et al. (2006), Webster (2007) and Niklas (2008) continues to model the manner in which damage occurs during different scenarios to give an effective estimation of the coefficient of discharge value and flow rate.

5.2 The effect of petal integrity

Similarly, the effect of petal integrity is also observed in Table 4.2 and 4.4 where it is found that an increase in petal integrity ratio can strengthen the corresponding effect of the bending angle. An increase in the integrity ratio can reduce the coefficient of discharge when the bending angle is low and increase it when the bending angle is high. From Tables 4.2 and 4.4, it can be seen that the coefficient of discharge has a large increase when the integrity ratio changes from 0 to 0.25 but follows a gentler slope from 0.25 to 1. It can therefore be seen that there is a difference between the coefficients of discharge for the orifice plate with and without petals and that the configuration of petalling is vital for the determination of accurate coefficient of discharge for damage scenarios.

5.3 The effect of petal combination

With regard to the effect of petals in combination, Table 5.1 summarises a comparison between the values of coefficient of discharge for different combinations of petals.

Table 5.1 Comparison of combinational and non-combinational petals

Experimental set	1 or 6	5 or 9	2 or 7	3 or 8	10 or 21
Experimental set 4	0.5048	0.5048	0.5048	0.5048	0.5048
Inwards combination of petals	0.5434	0.5749	0.4356	0.6509	0.6074
Inwards Uniform petal	0.5694	0.6105	0.3663	0.8041	0.7058

From Table 5.1, it is observed that the coefficient of discharge of the orifice plates with combinations of petals can be approximated from the corresponding uniform plates by their mean coefficient of discharge with an average error of less than 1% and a maximum error of 3%.

5.4 The effect of petal direction

From Tables 4.2 and 4.4, the coefficients of discharge for all of the orifice plates with outward facing petals are smaller than those for the corresponding inward facing petals. This is because the outward petals can obstruct or enhance the floodwater, like the inward petals, and they also block the flow along the lower surface of the bottom plate. The horizontal flow outside the orifice is affected by the outward petals and this is the main factor which leads to a reduction in the coefficient of discharge. However, at high bending angle, the outward facing petals also enhance the flow rate in a similar manner to those facing inwards. When the bending angle is 80° and the damage integrity ratio is 1, the observed coefficient of discharge is larger than that of the orifice plate without petals. This is because the petals create an incomplete pipe which enhances the flow rate and this has a stronger effect than the obstruction of the outward petals to the flow in the horizontal direction. The increase in integrity ratio has a complex effect on the values of coefficient of discharge, particularly at a bending angle of 80° degrees. However, if the effects of outward petals are divided into two independent parts, i.e. the enhancement of the vertical floodwater and the obstruction of the horizontal flow, the complex effects of the integrity can be explained. When the bending angle is at 80° the increase in integrity ratio has two effects: an increase in coefficient of discharge by enhancing the vertical floodwater and a decrease in coefficient of discharge by obstructing the horizontal flow. For the integrity ratio from 0 to 0.5, the horizontal flow effect is stronger and hence the coefficient of discharge reduces. For integrity ratios of 0.5 to 1, the vertical floodwater effect is stronger as a result of the incomplete pipe and hence the coefficient of discharge becomes larger. However, this assumption ignores the interaction between the two effects and therefore more research is required on outward facing petals and the manner in which the flow behaves in this scenario. Importantly, the flooding period of the outward facing petals orifice plates is longer than that of the corresponding inward facing petals. The flow is less violent than that in the inward petals which can be observed from

the flooding process curves. As the accuracy of the estimation is better in less violent flow cases, the coefficient of discharge of outward facing petals is more reliable and this relationship can be used as a reference for calculating the coefficient of discharge the inward facing petals.

5.5 Comparison of area calculation methods

From Table 4.6 the mean value of coefficient of discharge and the coefficient of variation can be determined for the orifices depending on the direction in which the petals are pointing and the method by which the coefficient of discharge was calculated. These values are shown in Table 5.2.

Table 5.2 Mean and variation in the coefficient of discharge

	Outward Projected	Outward Total	Inward Projected	Inward Total
Mean	0.75	0.46	0.93	0.57
Cov (%)	13	22	12	21

From the values in table 5.2 it can be seen that the value for the coefficient of discharge changes dependent upon the definition of the area used to calculate it. As expected, in the case of the mean value this is considerably higher for the projected area. This is because the projected area is lower than the previously used total area. This results in an increase of 0.36 for the inward and 0.29 for the outward facing petals over the total area calculation. In both projected area calculations these values are higher than the general approximation for coefficient of discharge of 0.6. For some instances of the inward facing petals the coefficient of discharge becomes larger than 1. This is due to the nature of these petals behaving like an inlet increasing the velocity due to the decrease in area. Furthermore, the variation in the coefficient of discharge is also decreased by about 10% allowing much of the variation in the flow to be taken account of during the calculation of the coefficient of discharge.

6. Conclusion

Damaged structures occur despite the best efforts to increase safety. In the event of damage it is vital that modelling tools are available to assess the damage in order to prevent loss of life, to minimise the impact on the environment and to reduce the cost of repair or recovery. One important factor in this modelling is the coefficient of discharge which is used in current software solutions to predict the flooding rate. A series of experiments have been conducted to investigate the effects of different petal properties on the coefficient of discharge on compartment flooding of marine structures. A number of factors to categorise the damage have been chosen, such as the bending angle, integrity ratio, petal direction, and combinations of different petals, based on literature of damaged marine structures. 21 groups of experiments with different petal properties were investigated. The experimental results have been validated against those of previous research and are found to be reliable compared with similar research. The results show that an increase in bending angle increases the coefficient of discharge and if this increase is large enough the flow rate can be increased to a point to endanger the safety of the structure. It is found that a damage integrity ratio is a better way to describe the petals over the area that an increase in this ratio enhances the effect of the bending angle. The coefficient of discharge for combinations of different petals can be estimated using the coefficient of discharge from the average value of the uniform petals that make up that combination. The value of coefficient of discharge of outward facing petals is always smaller than that of the corresponding inward petals. Furthermore, two different methods for calculating the coefficient of discharge have been investigated showing that the variation exhibited when calculating using the total area of the orifice can be removed by considering the projected area of the petals. The experiments conducted in the present research have found trends in the coefficient of discharge of the orifice based on the petalling of the damage and this allows a better estimation of the coefficient of discharge which can be used to improve emergency response and damage tolerant design.

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Figure 1.1 Main phases of the flooding process (Ruponen, 2007)

Figure 1.2 Damage to a ship side struck by a bulb in a collision

Figure 2.1 Flow through an orifice, from one tank to another

Figure 3.1 Final experimental set-up

Figure 3.2 Illustration of the holes created by a bulbous bow

Figure 3.3 Orifice plate with 100% integrity

Figure 3.4 Orifice plate with 50% integrity

Figure 3.5 Orifice plate with 25% integrity

Figure 4.3 Flooding process of experimental set 4

Figure 4.4 Flooding process of experimental set 14

Figure 4.5 Flooding process of the orifice plate without petals