# Investigation of the Applicability of the IMO Second Generation Intact Stability Criteria to Fishing Vessels

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**ABSTRACT**

In this work, the vulnerability of seven fishing vessels of mid and small size, representative of the Spanish fleet, to some of the failure modes covered by the IMO Second Generation Intact Stability Criteria, has been studied. The latest draft proposals for Level 1 and 2 checks for parametric roll, pure loss of stability and dead-ship condition, as presented in the IMO SDC 1 (2013), have been applied to the aforementioned sample vessels. The results are commented, and some notes regarding the applicability of this criteria a as a design tool are also included.

**Keywords:** *Second generation intact stability criteria, parametric roll, pure loss of stability, dead ship condition, fishing vessels stability*

## 1. INTRODUCTION

The Second Generation Intact Stability Criteria have been under development by the IMO SLF Sub-Committee for the last ten years, beginning in the 48th session of the SLF (Peters *et al.*, 2011). The main aim of these criteria is to increase the ship safety by quantifying its tendency to experiencing one of the so called failure modes. These are basically dynamic instabilities derived from the interaction while sailing between the ship and the waves and wind, and which are not covered by the traditional intact stability requirements. These failure modes include five phenomena: parametric roll resonance, loss of stability in stern waves, broaching, dead-ship condition and excessive accelerations.

The structure of the criteria is the same for all the aforementioned failure modes. They follow a three level arrangement: the Level 1 represents the easiest method of evaluation, and also the most conservative one. If the vessel fails to comply with Level 1, a Level 2 check has to be carried out, where a more detailed evaluation, also more complicated, is proposed. Finally, if the vessel is also find to be vulnerable under Level 2 criteria, a direct assessment has to be done, where stability operational guidelines have to be developed from the detailed analysis of more realistic sailing situations.

Regarding the development of the criteria, their current status can be found in the report of the Correspondence Group on Intact Stability to the SDC 1. Parametric roll and loss of stability draft criteria have been already agreed and draft explanatory notes developed, broaching and dead-ship condition draft criteria and explanatory notes are also available and excessive acceleration criteria are still under discussion (IMO SDC 1/5/3, 2013).

Second generation intact stability criteria are mainly focused on cargo and passenger ships; although some fishing vessels have been considered in the different applicability analysis of the criteria (three vessels in IMO SLF55/Inf.15 (2012a) and IMO SDC 1/Inf.8 (2013) and two in IMO SLF55/Inf.15 (2012b)), they´re very few compared to the rest of the typologies.

The fleet of fishing vessels is the largest worldwide. Moreover, the fishing activity is known for being one of the most dangerous industrial activities in many countries, such as Spain (MIT, 2014), U.K. (Roberts, 2010) or the U.S. (BLS, 2013).

Most of the effort spent on increasing the safety of fishing vessels has been directed at improving the crew training in the fields of static stability (cargo stowage, post-construction modifications, overloading and reduction in freeboard) and ship operation (flooding prevention) (Míguez-González *et al.*, 2012a). In fact, fishing vessel stability criteria, with the exception of the IMO Weather Criterion (which is not mandatory for all of them), are based on static stability principles. However, dynamical instabilities (parametric roll, loss of stability, broaching, dead ship condition) are also known to affect fishing vessels and to be the possible cause of many accidents (Mata-Alvarez-Santullano & Souto-Iglesias, 2014). And neither of them are analysed during the vessel design process or included within crew training programs.

Related to this fact, and in addition to their possible implementation as mandatory requirements, the application of second generation intact stability criteria as complementary design tools, could lead to very important increases in the safety of this type of vessels. So, the main objective of this work is to evaluate the suitability of the proposed second generation intact stability criteria to fishing vessels, and their application as a design tool to improve their safety levels from the dynamic stability point of view.

In order to do this, the draft second generation intact stability criteria proposed in IMO SDC 1/Inf.8 (2013), including parametric roll, pure loss of stability and dead-ship condition failure modes, have been applied to a sample of seven fishing vessels. These are representative of the different typologies present on the Spanish fleet of mid-sized fishing vessels, including trawlers, longliners and purse seiners, with lengths ranging from 20 to 70 meters. From the obtained results, the vulnerability of the different vessels to the aforementioned failure modes and the suitability of these draft criteria as a first stage design tool have been analysed.

## 2. TEST VESSELS

One of the main characteristics of the fishing vessel fleet is its vast heterogeneity; the arrangement of the different ships depends on the used fishing gear, on tradition and regional factors or on regulatory issues. This fact makes it very difficult to analyse fishing vessels as a whole. In our case, the mid-sized Spanish fishing fleet, which is the largest in Europe in terms of tonnage, has been selected (EU Commission, 2014). From this, we focused on the vessels of more than 20 m long (usually operating in open seas), which in the Spanish case, are more than 1400 units (MAGRAMA, 2013).

The selected ships try to cover all the main typologies present on the aforementioned fleet, and two medium sized stern trawlers (named Trawler 1 and 2), one large stern trawler (Large Trawler), one longliner (Longliner), one medium size purse seiner (Purse Seiner) and one large tuna purse seiner (Tuna Purse Seiner), were chosen. Experimental head sea data of the Trawler 2, is available in Míguez-González *et al.* (2012b).

Table 1: Vessel characteristics (1).

| Vessel | $L_{Pp}$ (m) | B (m) | d (m) |
|---|---|---|---|
| Trawler 1 | 25.70 | 8.50 | 3.25 |
| Trawler 2 | 29.00 | 8.00 | 3.30 |
| Large Trawler | 60.60 | 12.50 | 4.60 |
| Longliner | 24.00 | 8.20 | 3.20 |
| Purse Seiner | 21.00 | 7.00 | 2.70 |
| Tuna Purse Seiner | 67.60 | 14.00 | 4.80 |
| TS Trawler ($d_1$) | 22.00 | 6.90 | 2.30 |
| TS Trawler ($d_2$) | 22.00 | 6.90 | 2.46 |

Table 2: Vessel characteristics (2).

| Vessel | $L_{Pp}/B$ | B/D | D/d | $C_b$ | $C_m$ |
|---|---|---|---|---|---|
| Trawler 1 | 3.02 | 1.51 | 1.73 | 0.56 | 0.85 |
| Trawler 2 | 3.63 | 1.38 | 1.76 | 0.57 | 0.86 |
| Large Trawler | 4.85 | 1.63 | 1.66 | 0.54 | 0.88 |
| Longliner | 2.93 | 1.41 | 1.81 | 0.68 | 0.90 |
| Purse Seiner | 3.00 | 2.19 | 1.19 | 0.67 | 0.89 |
| Tuna Purse Seiner | 4.83 | 1.54 | 1.90 | 0.53 | 0.93 |
| TS Trawler ($d_1$) | 3.19 | 2.06 | 1.46 | 0.47 | 0.74 |
| TS Trawler ($d_2$) | 3.19 | 2.06 | 1.36 | 0.48 | 0.75 |

Table 3: Vessel characteristics (3).

| Vessel | $A_L$ ($m^2$) | Z (m) | $\phi_{fl}$ (deg) |
|---|---|---|---|
| Trawler 1 | 145 | 4.47 | 64.3 |
| Trawler 2 | 162 | 4.38 | 65.4 |
| Large Trawler | 415 | 5.57 | 53.6 |
| Longliner | 120 | 4.09 | 68.6 |
| Purse Seiner | 83 | 3.50 | 54.3 |
| Tuna Purse Seiner | 361 | 7.60 | 69.1 |
| TS Trawler ($d_1$) | 95 | 3.37 | 57.2 |
| TS Trawler ($d_2$) | 91 | 3.37 | 57.2 |

Moreover, and for comparison purposes, a typical U.K. beam trawler (named TS Trawler), which has been broadly studied (Neves & Rodríguez, 2006), has also been selected.

The main characteristics of the analysed vessels are included in Tables 1 and 2. In Table 3, some of the parameters needed for the evaluation of the IMO Weather Criterion are presented, where $A_L$ is the projected lateral area over the waterline, Z is the distance from the centre of $A_L$ to the half of the mean draft and $\phi_{fl}$ is the first downflooding angle.

Table 4: Tested Conditions.

| Vessel | Fn | d (m) | $GM_T$ (m) | $\omega_0$ (rad/s) |
|---|---|---|---|---|
| Trawler 1 LC1 | 0.32 | 3.25 | 0.653 | 0.692 |
| Trawler 1 LC2 | 0.32 | 3.25 | 0.350 | 0.507 |
| Trawler 2 | 0.31 | 3.30 | 0.350 | 0.539 |
| Large Trawler | 0.31 | 4.60 | 0.350 | 0.345 |
| Longliner LC1 | 0.34 | 3.20 | 0.495 | 0.625 |
| Longliner LC2 | 0.34 | 3.20 | 0.350 | 0.526 |
| Purse Seiner | 0.36 | 2.70 | 0.350 | 0.616 |
| Tuna Purse Seiner LC1 | 0.34 | 4.80 | 0.916 | 0.498 |
| Tuna Purse Seiner LC2 | 0.34 | 4.80 | 0.350 | 0.308 |
| TS Trawler LC1 | 0.32 | 2.30 | 0.730 | 0.902 |
| TS Trawler LC2 | 0.32 | 2.46 | 0.436 | 0.697 |

Regarding the tested loading conditions, in all cases the design draft has been selected; in the case of the TS Trawler, two different drafts, for which experimental data are available (Paffet, 1976), have been chosen. When the real GM was available for the selected draft, that was the applied value; in addition, another condition with the minimum GM according to the Torremolinos Protocol (350 mm), was also defined for these cases. When no data was available, the minimum GM of 350 mm was selected.

The natural roll frequency for all cases was computed by using a roll radius of gyration (including added inertia) of $0.43 \cdot B$, estimated from the experimental data in Míguez-González *et al.* (2012b). In all cases, no bilge keels were considered ($A_{BK} = 0$), and the design speed was chosen to compute the reference ship speed ($V_{PR}$).

## 3. CRITERIA DESCRIPTION

In this work, the vulnerability of the selected vessels to parametric roll, pure loss of stability and dead-ship condition failure modes have been analysed by applying the proposals contained in the different annexes of IMO SDC 1/Inf.8 (2013). Parametric roll criteria and their explanatory notes are contained in Annexes 1 and 3; pure loss of stability criteria and their explanatory notes in Annexes 2 and 4; and dead-ship condition criteria in Annex 16. The draft explanatory notes of dead-ship condition are included in IMO SDC 1/Inf.6 (2013).

### 3.1 Parametric roll

The phenomenon of parametric roll is generated by the variation of the roll restoring term due to the wave passing along the hull. Its effects are more intense in longitudinal waves, when the wave encounter frequency approximates the double of the ship roll natural frequency. Under these conditions, roll motion can reach very large amplitudes.

The parametric roll vulnerability criteria are divided into two levels, both based on the analysis of the *GM* variation in longitudinal waves. In the Level 1, the *GM* in calm water is compared to the amplitude of *GM* variation ($\Delta GM$) in a longitudinal wave of wavelength equal to ship length and a constant steepness of $S_W = 0.0167$. The ship is considered vulnerable if:

$$\frac{\Delta GM}{GM} > R_{PR} \tag{1}$$

Where $R_{PR}$ represents roll linear damping, that may be taken as 0.5 or a value dependant on bilge keel area and midship coefficient.

The Level 2 presents two checks. The first one is similar to that of Level 1, but computations have to be made for a set of 16 waves, with different lengths and steepness's, and the results of each wave case have to be weighted and summed up. Moreover, an additional requirement that takes into account the vessel forward speed has to be also considered. According to this first check, the ship will be considered vulnerable if:

$$C1 = \sum_{i=1}^{N} W_i C_i > R_{PR0} \tag{2}$$

Where $R_{PR0}$ is 0.06 or 0.1, $W_i$ is the wave case weight and $C_i$ is a coefficient equal to 1 if the ship is vulnerable under *GM* and speed checks, and 0 if not. *GM* vulnerability checks are the same as those of the first level criterion, but computed for each of the wave parameters. The ship is considered as vulnerable if:

$$GM(H_i, \lambda_i) < 0 \tag{3}$$

$$\frac{\Delta GM(H_i, \lambda_i)}{GM(H_i, \lambda_i)} > R_{PR} \tag{4}$$

The speed requirement consists on comparing the design speed of the ship ($V_D$) and a reference speed for parametric roll appearance ($V_{PRi}$), which depends on the metacentric height on waves and calm water, on wave conditions and on natural roll period. Although not specified in the rules, for a ship with two very different sailing conditions (such as trawlers), it could be important, in order to accurately evaluate this requirement, to take into account the two possible sailing speeds. In any case, the ship is considered vulnerable if:

$$V_{PRi} < V_D \tag{5}$$

If the ship is found to be vulnerable under the first check, a second check has to be done. This has a similar structure to the previous one; the ship will be considered vulnerable if:

$$C2 = \sum_{i=1}^{N} W_i C_i > R_{PR1} \tag{6}$$

In this case, $Wi$ is again the wave case weight (which are obtained from a wave scatter diagram with 306 wave cases) and $Ci$ is a coefficient equal to 1 if the roll motion of the ship, computed by using an uncoupled equation of roll motion, is over 25 degrees, and 0 if it is not.

## 3.2 Pure loss of stability

The reduction of the transverse stability of the ship, when it sails in stern seas and wave crest persists for a long time near amidships, is the cause of this failure mode. In waves of wavelength similar to ship length, and in low stability conditions, it could lead to large roll and even capsizing.

Pure loss of stability criteria are only of application to ships of length of more than 24 m and speeds of Froude over 0.2, 0.26 or 0.31 (to be decided), and are also divided into two levels. Level 1 is similar to that of the parametric roll failure mode, and consists on evaluating the minimum $GM$ ($GM_{min}$) when a wave of wavelength equal to ship length and a constant steepness of $S_W$ = 0.0334 passes the ship. The vessel would be considered as vulnerable if:

$$GM_{\min} < R_{PLA} \tag{7}$$

where $R_{PLA}$ is the minimum value between 0.05 m and a speed and draft dependant factor.

The second level check consists of three criteria ($CR_j$), computed for two possible set of waves (16 or 306 cases).

$$CR_{j=1:3} = \sum_{i=1}^{N} W_i Cj_i \tag{8}$$

Each $CR_j$ is obtained by weighting the coefficients $Cj_i$, which are evaluated for each wave condition; $C1_i$ is equal to 1 if the angle of vanishing stability ($\varphi_v$) is over 30 degrees or the angle of steady heel in waves ($\varphi_s$) is over 15 or 20 degrees; $C2_i$ is equal to 1 if the maximum loll angle ($\phi_{loll}$) is over 25 degrees; and $C3_i$ is equal to 1 if the maximum GZ value is under $8 \cdot (H/\lambda) \cdot d \cdot Fn^2$ .

So, the ship is considered vulnerable if:

$$\max(CR_1, CR_2, CR_3) > R_{PL0} \tag{9}$$

Where $R_{PL0}$ is 0.06 for the first set of waves and 0.15 if the second option is adopted.

## 3.3 Dead-ship condition

The dead ship condition of a ship takes place when all of its machinery becomes out of operation, disabling its propulsive and manoeuvring capabilities. Under these conditions, the vessel may be affected by severe beam wind and waves, not being able to escape this dangerous situation. The objective of the dead ship stability criteria, is to ensure that the ship is able to withstand the effect of the aforementioned beam excitations for a given amount of time.

As in the case of the previous two failure modes, they are divided into two levels. The Level 1 check corresponds to the well-known IMO Weather Criterion (Severe Wind and Rolling Criterion), included in the IMO 2008 Intact Stability Code, but with a modification on the wave steepness's for large draft vessels.

The Level 2 assessment proposes a probabilistic approach for evaluating the vessel vulnerability to the analysed failure mode. The procedure consists on determining the long term vulnerability of the ship by computing the coefficient $C$; if it is under the reference value of $10^{-3}$, the ship is considered as non-vulnerable.

To obtain this long term coefficient, a short term vulnerability index $C_S$ is computed for different wave and wind conditions, characterized by the significant wave height ($H_S$), the zero crossing period ($T_Z$) and the wind speed ($U_W$). Once computed, the $C$ index is obtained as a weighted average of the $C_S$ values:

$$C = \sum_{H_S}\sum_{T_Z}(W(H_S,T_Z)\cdot C_S(H_S,T_Z,U_W)) \qquad (10)$$

The short term environmental conditions, together with the probability weighting factors ($W$ ($H_S$, $T_Z$)), are obtained by applying the North Atlantic scatter diagram (IACS Recommendation 34), although other wave cases may be accepted.

The short term vulnerability index is obtained by considering the ship as a 1 d.o.f. linear system which rolls under the action of beam irregular waves and gusty winds, which spectra are obtained from the corresponding short term wave characteristics ($H_S$, $T_Z$). After obtaining some parameters from the residual righting lever curve under the effect of steady wind moment, the roll standard deviation and zero crossing frequency corresponding to the wave and wind moment spectra are obtained by solving the roll equation in frequency domain.

The short term vulnerability index represents the probability of capsizing in the analysed conditions in a given exposure time (3600 s in this case), and is computed from the vessel roll characteristics defined above and two virtual capsizing angles, obtained by equalling the area under the residual righting lever curves and a linearized (in the equilibrium heel angle due to steady wind), residual righting lever curve.

In the method draft explanatory notes (IMO SDC 1/Inf.6, 2013), in addition to the description of the applied methodology, a procedure for computing the effective wave slope coefficient and an alternative methodology for computing the $C_S$ index are also included. Moreover, a method for estimating the necessary roll damping coefficients is presented, based on the least squares fitting of the equivalent linear roll damping coefficient obtained by the Ikeda method for different roll amplitudes.

## 4. RESULTS AND DISCUSSION

In this section, the results obtained from the application of parametric roll, pure loss of stability and dead-ship condition criteria are presented and commented. The ones corresponding to the first two failure modes, have been already presented in Míguez-González et *al.* (2014), where draft requirements described in IMO SLF 55/WP.3 (2013) for parametric roll, loss of stability and broaching, were applied to the same sample vessels.

### 4.1 Parametric roll

In this case, Level 1 and Level 2 first check have been carried out. The Level 1 results are shown in Table 5, where $\Delta GM$ is the $GM$ variation on the specified waves and $\Delta GM_{alt}$ is the alternative $GM$ variation in waves computed considering the waterplane inertias at drafts $d_h$ and $d_l$. The Level 2 first check results are shown in Table 6. There, $\Delta GM_{max}$ is the maximum $GM$ variation for all the 16 wave cases, $GM_{avg}$ is the corresponding average $GM$ for that wave case and $V_{PR}$ is the reference ship speed for resonance in that conditions.

According to the results, all ships, excepting the Large Trawler and the Tuna Purse Seiner in the low $GM$ condition, pass Level 1 check.

Table 5: Parametric roll. Level 1 results.

| Vessel | *ΔGM* *(m)* | $\Delta GM_{alt}$ *(m)* | *ΔGM/GM* | Level 1 |
|---|---|---|---|---|
| Trawler 1 LC1 | 0.090 | 0.164 | 0.251 | Pass |
| Trawler 1 LC2 | 0.090 | 0.164 | 0.468 | Pass |
| Trawler 2 | 0.102 | 0.133 | 0.379 | Pass |
| Large Trawler | 0.109 | 0.251 | 0.718 | Fail |
| Longliner LC1 | 0.051 | 0.062 | 0.126 | Pass |
| Longliner LC2 | 0.051 | 0.062 | 0.178 | Pass |
| Purse Seiner | 0.035 | 0.046 | 0.130 | Pass |
| Tuna Purse Seiner LC1 | 0.154 | 0.295 | 0.322 | Pass |
| Tuna Purse Seiner LC2 | 0.153 | 0.295 | 0.843 | Fail |
| TS Trawler LC1 | 0.095 | 0.205 | 0.281 | Pass |
| TS Trawler LC2 | 0.107 | 0.181 | 0.414 | Pass |

Table 6: Parametric roll. Level 2 results. 1st check.

| Vessel | $\Delta GM_{max}$ *(m)* | $GM_{avg}$ *(m)* | $\Delta GM_{max}/GM_{avg}$ | $V_{PR}$ *(m/s)* | Level 2 |
|---|---|---|---|---|---|
| Trawler 1 LC1 | 0.075 | 0.650 | 0.115 | 1.186 | Pass |
| Trawler 1 LC2 | 0073 | 0.347 | 0.211 | 2.040 | Pass |
| Trawler 2 | 0.085 | 0.353 | 0.241 | 0.728 | Pass |
| Large Trawler | 0.104 | 0.360 | 0.287 | 1.707 | Pass |
| Longliner LC1 | 0.044 | 0.495 | 0.089 | 1.110 | Pass |
| Longliner LC2 | 0.045 | 0.349 | 0.128 | 0.935 | Pass |
| Purse Seiner | 0.034 | 0.352 | 0.097 | 1.171 | Pass |
| Tuna Purse Seiner LC1 | 0.152 | 0.895 | 0.169 | 2.090 | Pass |
| Tuna Purse Seiner LC2 | 0.152 | 0.330 | 0.460 | 3.069 | Pass |
| TS Trawler LC1 | 0.090 | 0.719 | 0.125 | 1.019 | Pass |
| TS Trawler LC2 | 0.100 | 0.444 | 0.225 | 0.473 | Pass |

Regarding Level 2 check, all ships pass the criteria for all wave cases ($C1$ = 0). The criteria, for these vessels, are consistent, as no vessel is found to be non-vulnerable under Level 1 and vulnerable under Level 2.

In Míguez-González et *al.* (2014) and references therein, these results were analysed and compared to experimental data present in the literature, in order to analyse the suitability of the criteria to these small vessels. In the cases of the Trawler 2 and the TS Trawler, small variation of *GM* in waves has been obtained. So, both of them have been considered as non-vulnerable, while experimental data have shown their large tendency to developing parametric roll. However, the small wave heights and probabilities (weighting factors, which represent a small probability for the ship facing them in real sailing), associated with the waves of small wavelength that correspond to these ships length, is the cause of this consideration. Moreover, the results obtained for the Tuna Purse Seiner were also compared to experimental data available, showing a good consistency.

From the different typologies of vessels studied, it can be seen that those ships with larger bow flares and hanging sterns, such us trawlers and the tuna purse seiner, are the most vulnerable to this failure modes, presenting the largest *GM* variations from all the sample.

## 4.2 Pure loss of stability

Pure loss of stability criteria are of application to all the sample ships, as their speeds are, in all cases, equal or over $Fn$ = 0.31. Level 1 and Level 2 (Option A, 16 reference wave cases) checks have been carried out. The results of the Level 1 check are presented in Table 7, where $GM_{min}$ is the minimum *GM* as the specified wave passes the ship, and $GM_{min\_alt}$ is the alternative minimum *GM* computed considering the waterplane inertia at draft $d_L$. The Level 2 results are presented in Table 8, where $GZ_{max}$ is the minimum smallest *GZ* curve maximum for all the 16 wave cases, $\varphi_v$ , $\varphi_s$ and $\phi_{loll}$ are respectively the vanishing stability, the steady heel and the loll angles for that condition and $R_{PL3}$ is the vulnerability limit for the presented $GZ_{max}$.

As can be seen, the largest vessels (Large Trawler and Tuna Purse Seiner in the two loading conditions), together with the TS Trawler in the low GM condition, are found to be vulnerable under Level 1 check.

Table 7: Pure loss of stability. Level 1 results.

| Vessel | $GM_{min}$ (m) | $GM_{min\_alt}$ (m) | Level 1 |
|---|---|---|---|
| Trawler 1 LC1 | 0.452 | 0.488 | Pass |
| Trawler 1 LC2 | 0.148 | 0.184 | Pass |
| Trawler 2 | 0.172 | 0.075 | Pass |
| Large Trawler | 0.193 | -0.147 | Fail |
| Longliner LC1 | 0.391 | 0.342 | Pass |
| Longliner LC2 | 0.246 | 0.197 | Pass |
| Purse Seiner | 0.276 | 0.231 | Pass |
| Tuna Purse Seiner LC1 | 0.626 | 0.028 | Fail |
| Tuna Purse Seiner LC2 | 0.060 | -0.540 | Fail |
| TS Trawler LC1 | 0.520 | 0.105 | Pass |
| TS Trawler LC2 | 0.271 | -0.113 | Fail |

Table 8: Pure loss of stability. Level 2 results. Option A.

| Vessel | $GZ_{max}$ (m) | $\varphi_v$ (deg) | $\phi_s$ (deg) | $\phi_{loll}$ (deg) | $R_{PL3}$ | Level 2 |
|---|---|---|---|---|---|---|
| Trawler 1 LC1 | 0.422 | 90 | 0 | 0 | 0.084 | Pass |
| Trawler 1 LC2 | 0.199 | 70 | 0 | 0 | 0.085 | Pass |
| Trawler 2 | 0.746 | 125 | 0 | 0 | 0.075 | Pass |
| Large Trawler | 0.187 | 51 | 0 | 0 | 0.115 | Pass |
| Longliner LC1 | 0.392 | 82 | 0 | 0 | 0.088 | Pass |
| Longliner LC2 | 0.293 | 73 | 0 | 0 | 0.089 | Pass |
| Purse Seiner | 0.269 | 78 | 0 | 0 | 0.086 | Pass |
| Tuna Purse Seiner LC1 | 0.995 | 111 | 0 | 0 | 0.148 | Pass |
| Tuna Purse Seiner LC2 | 0.451 | 95 | 0 | 0 | 0.136 | Pass |
| TS Trawler LC1 | 0.254 | 70 | 0 | 0 | 0.056 | Pass |
| TS Trawler LC2 | 0.144 | 58 | 0 | 0 | 0.060 | Pass |

Regarding Level 2 check, all vessels were found to be non-vulnerable (all criteria were fulfilled in all wave cases), and criteria are consistent for this set of vessels.

Like in the case of parametric roll failure mode, in Míguez-González et *al.* (2014) and references therein, the obtained results were compared with available experimental data. Regarding both the TS Trawler and the Tuna Purse Seiner, a large tendency to capsizing in stern seas has been described, showing a good agreement between the vulnerability analysis and the towing tank test data. In the case of the Trawler 2, and although some reduction of stability in stern seas has been shown in the literature, no capsizing occurred in any of the tested conditions. So, results seem to be consistent also for this vessel. Again, the vessels with larger bow flares and hanging sterns (trawlers and tuna purse seiner), are shown to be more vulnerable than the others.

### 4.3 Dead-ship condition

As have been already mentioned, the Level 1 and Level 2 dead-ship condition checks have been carried out. In Table 9, the intact stability characteristics of the different vessels are shown (all *GM* values are over the minimum, as shown in Table 4). As it can be seen, there are two vessels, the Trawler 1 and the TS Trawler in the low *GM* conditions, which do not fulfil the minimum requirements stated by the Torremolinos Protocol.

Regarding the Level 1 check, in Table 10 the obtained results are presented. There, $\phi_0$ is the angle of equilibrium under the steady wind heel lever, $\phi_1$ is the windward roll angle and $\phi_2$ is the minimum between the downflooding angle and 50 degrees. *a* and *b* are the areas under the *GZ* and wind heeling lever curves stated in the IMO Weather Criterion. It can be appreciated that all ships, with the exception of the TS Trawler, but including the Trawler 1 in the low GM condition (LC2), pass the Level 1 check.

In Table 11, the results of the Level 2 check are presented. In there, $\phi_{Smax}$ is the maximum steady heel angle for all the wave conditions tested, $\sigma_{\phi Smax}$ is the maximum roll standard deviation, $T_{Z\phi max}$ is the maximum roll zero crossing period and *C*, is the long term probability failure index.

Table 9: Intact stability results.

| Vessel | *Area 0 – 30 (m.rad)* | *Area 0-40 (m.rad)* | *Area 30 -40 (m.rad)* | *Max. GZ (m)* | *Max. GZ Angle (deg)* |
|---|---|---|---|---|---|
| Trawler 1 LC1 | 0.0833 | 0.1506 | 0.0673 | 0.489 | 47.3 |
| Trawler 1 LC2 | 0.0426 | 0.0795 | 0.0369 | 0.271 | 44.5 |
| Trawler 2 | 0.0560 | 0.1093 | 0.0532 | 0.863 | 75.5 |
| Large Trawler | 0.0642 | 0.1189 | 0.0547 | 0.321 | 35.5 |
| Longliner LC1 | 0.0759 | 0.1434 | 0.0675 | 0.461 | 45.0 |
| Longliner LC2 | 0.0565 | 0.1095 | 0.0530 | 0.360 | 43.6 |
| Purse Seiner | 0.0550 | 0.0960 | 0.0435 | 0.301 | 45.8 |
| Tuna Purse Seiner LC1 | 0.1282 | 0.2366 | 0.1084 | 1.079 | 64.5 |
| Tuna Purse Seiner LC2 | 0.0550 | 0.1036 | 0.0515 | 0.575 | 60.0 |
| TS Trawler LC1 | 0.078 | 0.1277 | 0.0497 | 0.304 | 41.4 |
| TS Trawler LC2 | 0.0507 | 0.0850 | 0.0341 | 0.203 | 37.7 |

Table 10: Dead ship condition. Level 1 results.

| Vessel | $\phi_0$ (deg) | $\phi_1$ (deg) | $\phi_2$ (deg) | *b* (m.rad) | *a* (m.rad) | Level 1 |
|---|---|---|---|---|---|---|
| Trawler 1 LC1 | 7.4 | 24.2 | 50 | 0.1396 | 0.0743 | Pass |
| Trawler 1 LC2 | 15.3 | 21.5 | 50 | 0.0432 | 0.0392 | Pass |
| Trawler 2 | 12.6 | 22.8 | 50 | 0.1029 | 0.0474 | Pass |
| Large Trawler | 9.4 | 12.4 | 50 | 0.0919 | 0.0166 | Pass |
| Longliner LC1 | 6.6 | 25.7 | 50 | 0.1549 | 0.0651 | Pass |
| Longliner LC2 | 9.2 | 23.9 | 50 | 0.1059 | 0.0447 | Pass |
| Purse Seiner | 8.8 | 25.5 | 50 | 0.0855 | 0.0489 | Pass |
| Tuna Purse Seiner LC1 | 3.6 | 17.3 | 50 | 0.3114 | 0.0505 | Pass |
| Tuna Purse Seiner LC2 | 9.5 | 13.4 | 50 | 0.1148 | 0.0172 | Pass |
| TS Trawler LC1 | 8.3 | 23.4 | 50 | 0.0672 | 0.0777 | Fail |
| TS Trawler LC2 | 12.2 | 22.6 | 50 | 0.025 | 0.0507 | Fail |

The roll damping coefficients of the different vessels, were obtained from the experimental data of a stern trawler with no bilge keels (Trawler 2), described in Míguez-González *et al.* (2013).

It can be seen that all the small vessels (with the exception of the Trawler 2), fail the Level 2 criteria.

Table 11: Dead ship condition. Level 2 results. No Bilge Keels.

| Vessel | $\phi_{Smax}$ (deg) | $\sigma_{\phi max}$ (deg) | $Tz_{\phi max}$ (s) | *C* | Level 2 |
|---|---|---|---|---|---|
| Trawler 1 LC1 | 18.0 | 10.1 | 10.7 | 2.38E-03 | Fail |
| Trawler 1 LC2 | 32.0 | 12.4 | 11.8 | 2.97E-03 | Fail |
| Trawler 2 | 25.0 | 11.7 | 9.4 | 4.60E-04 | Pass |
| Large Trawler | 18.0 | 11.3 | 14.0 | 1.46E-05 | Pass |
| Longliner LC1 | 14.0 | 12.5 | 9.8 | 1.28E-02 | Fail |
| Longliner LC2 | 19.0 | 14.6 | 10.2 | 9.24E-03 | Fail |
| Purse Seiner | 19.0 | 13.5 | 9.4 | 2.02E-02 | Fail |
| Tuna Purse Seiner LC1 | 8.0 | 9.0 | 13.5 | 5.53E-05 | Pass |
| Tuna Purse Seiner LC2 | 20.0 | 11.1 | 18.2 | 3.02E-07 | Pass |
| TS Trawler LC1 | 24.0 | 12.1 | 12.5 | 1.11E-02 | Fail |
| TS Trawler LC2 | 34.0 | 20.1 | 16.6 | 1.60E-02 | Fail |

Table 12: Dead ship condition. Level 2 results. Bilge keel effect included.

| Vessel | $\phi_{Smax}$ (deg) | $\sigma_{\phi max}$ (deg) | $Tz_{\phi max}$ (s) | *C* | Level 2 |
|---|---|---|---|---|---|
| Trawler 1 LC1 | 18.0 | 8.9 | 11.0 | 4.37E-04 | Pass |
| Trawler 1 LC2 | 32.0 | 11.1 | 12.0 | 9.91E-04 | Pass |
| Trawler 2 | 25.0 | 10.5 | 9.5 | 8.61E-05 | Pass |
| Large Trawler | 18.0 | 10.1 | 14.1 | 1.58E-06 | Pass |
| Longliner LC1 | 14.0 | 10.9 | 9.9 | 3.20E-03 | Fail |
| Longliner LC2 | 19.0 | 12.9 | 10.3 | 2.43E-03 | Fail |
| Purse Seiner | 19.0 | 11.9 | 9.5 | 5.94E-03 | Fail |
| Tuna Purse Seiner LC1 | 8.0 | 7.9 | 13.6 | 3.84E-06 | Pass |
| Tuna Purse Seiner LC2 | 20.0 | 9.9 | 18.3 | 1.59E-08 | Pass |
| TS Trawler LC1 | 24.0 | 10.7 | 13.1 | 3.12E-03 | Fail |
| TS Trawler LC2 | 34.0 | 17.9 | 17.2 | 5.44E-03 | Fail |

In order to investigate the influence of the damping coefficients on the obtained results, a new computation including a 40 % increase in damping was carried out. This increase could reflect the effect of bilge keels (Chun *et al.*, 2001), which are installed in all of these vessels in the reality.

In this new case (Table 12), the Trawler 1 is found to be non-vulnerable in all conditions, while the small vessels are again found vulnerable. However, a very significant decrease of the probability index (*C*) is shown.

In all cases, a very high tendency to capsizing could be seen in the small vessels, while larger vessels seem to be safer from the dead-ship condition point of view. Regarding the consistency of the criteria, and considering the large effect of roll damping, the only relevant ship for analysis is that of Trawler 2, as experimental data of roll damping were available. According to it, criteria seem to be consistent. However, further analysis is necessary applying realistic values of damping coefficients.

## 5. CONCLUSIONS

In this work, the application of the draft second generation intact stability criteria for parametric roll, pure loss of stability and dead-ship condition, as presented in IMO SDC 1/5/3 to a sample of seven vessels representative of the Spanish fishing fleet, has been done. The objective of this study was to analyse their applicability to this fleet, in order to use them as a design tool to reduce the high number of accidents due to dynamic stability issues which usually affect this type of ships.

In order to do this, Level 1 and Level 2 checks were carried out for the three failure modes mentioned above, checking the consistency of the criteria and analysing the results to determine their suitability to a fleet to which, in principle, they were not focused to.

Regarding the pure loss of stability failure, a very good agreement between the results and available experimental data has been found, showing a very good consistence of the criteria.

In the case of parametric roll resonance, some discrepancies, mainly due to the environmental conditions under consideration in the criteria, have been found, especially for the small ships.

Finally, from the analysis of the dead–ship failure mode, it has been observed that small ships fail Level 2 criteria after passing Level 1, which shows some inconsistency of the criteria; however, and considering the observed large sensibility of the Level 2 check to the roll damping, a more precise estimation of the damping coefficients is needed to make a conclusion on this matter.

In any case, the proposed methodology look like a set of simple and easy to use set of tools that could be straightforwardly applied during the design stage, to analyse the vulnerability of the studied vessels to those failure modes.

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