Considerations on the Survivability Assessment of Damaged Ships

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ABSTRACT

Fundamental considerations on the assessment of survivability against flooding of damaged passenger ships are discussed in the context of a review and verification of the recently introduced SOLAS (2009) regulations. They regard the explicit introduction of the operational wave profile for the survivability assessment of individual ships, the analysis and formulation of ship's survivability with respect to sea state, and the treatment of uncertainty inherent to the survivability problem. The conducted analysis provided evidence for a systematic bias in the current regulations. The intrinsic randomness of critical waves results to *irreducible* uncertainty for the survivability estimations. In view of this, the diversity of the so far survivability estimations appears to be rather a confidence problem of individual assessments. The specialization to damage cases and the introduction of quality measures are suggested as a rational enhancement of the assessment methods and consequently for the identification of safe individual ships.

KEYWORDS

Survivability; flooding; damage stability; critical waves; uncertainty; collision; SOLAS

INTRODUCTION

International, harmonized damage stability regulations based on the probabilistic concept of survivability were recently established for passenger and dry cargo ships (*IMO*, *Res. MSC.216(82)*). A series of investigations and verification studies on the survivability assessment were simultaneously triggered. The so far findings regarding the performance of the adopted method were not conclusive.

In this respect, the fundamentals of the survivability assessment approach are revisited to emphasize the probabilistic nature of the problem, which may interpret the incidental behaviours recorded so far in relevant early investigations, and to point out some missing elements. The present considerations suggest a direct enhancement and improvement of the efficiency of the adopted approach

ON THE SEA STATE IN SURVIVABILITY

Sea state statistics

The behaviour, and eventually the survivability, of the damaged ship in presence of waves is a rather complicated phenomenon because of the induced dynamics and the ship motion, the flooding process and the dynamics of the flooding water.

The wave statistics in case of side collision damages Fig.1, as updated by the HARDER project (*Tagg and Tuzcu*, 2002) and which are in the background of the current SOLAS regulations, suggest that 70% of collisions occur in waves (and 30% in calm water). However, based on the same statistics, 40% of the total collisions occur in lower waves (of height less than 1.0 m) and just 10% in rough waves (height over 2.0 m).

These statistics also suggest that 50% of collision events occur practically in calm water (H_s<0.5 m), where the induced dynamics are limited or even negligible; and, that for 50% of the collision cases the dynamics of the wave conditions may determine the behaviour of the damaged ship.

The wave statistics of Fig 1 describe the wave conditions independently of the ship particulars, ship type or service routes. Thus, such information is directly useful for the survivability analysis of the global merchant fleet. But, for individual ships the *operational* wave *profile* should be additionally taken into account for the specialization of the waves in case of collisions. Nevertheless the distribution of Fig. 1 can be still used without any further elaboration if the operational wave profile is assumed to be of uniform probability. Such basic simplified approach is currently applied in the SOLAS'09 adopted method.

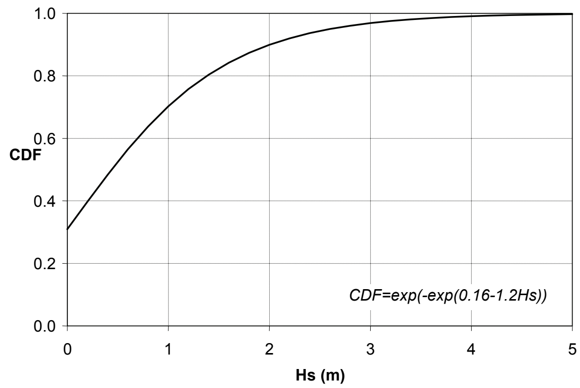

Fig. 1 Wave statistics in collision damages, independently of ship particulars (*HARDER*, 2002)

For more realistic wave environments, which may be encountered throughout the design life of a ship, the corresponding wave probability in collisions should be derived too. Fig. 2 presents two characteristic sample cases where operational wave profiles are assumed for Atlantic Ocean (*BMT*, 1986) and Mediterranean Sea (*Athanassoulis et al.*, 2006) conditions. Large differences of 20-30% between open and closed seas become evident. Characteristically, the probability of encountering waves lower than 2.0 m during a collision event equals 0.80 and 0.99 for Atlantic and Mediterranean respectively. This large difference has a direct impact on the survivability of ships and it may be also valid for the same ship, if assumed to serve in different environments.

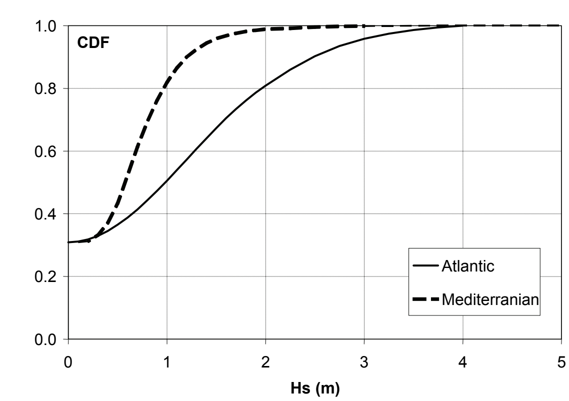

Fig. 2 Wave statistics in case of collisions at specific environment

Fig. 2 underlines that a damage event in the open ocean would be related to the presence of higher waves, whereas if the ship gets damaged in closed sea then lower waves should be expected. This is independent of the probability (frequency) of collisions, which might be considerably lower for ocean routes, while larger for limited water conditions.

The wave statistics is the prime constituent of ship's survivability in waves; and the expected waves in case of damage clearly dependent on the wave operational profile of individual ships. This fundamental property is not taken into account yet by the current survivability assessment approach (SOLAS'09), which is limited to the very basic information of Fig. 1

The conditional probability distributions p_{wcol} presented in Fig. 2 are derived by

$$p_{wcol} = p_{w|col} p_w \tag{1}$$

where $p_{w|col}$ the probability of waves is case of collisions and without consideration of ship's particulars (which can be directly derived from Fig. 1 for H_s>0) and p_w the assumed probability of waves corresponding to the ship's *wave operational profile*. The probability distribution is complemented with the calm water probability (here assumed equal to abt. 0.30, Fig. 1).

Sea state in survivability analysis

The above statistical facts are taken into account to analyze the survivability of ships with respect to sea state. Thereby the probability s for a ship to survive after a collision event can be written as the sum of the probabilities to survive in calm water and in waves.

$$s = p_c s_c + p_w s_w \tag{2}$$

where indices c and w denote calm water and wave conditions respectively, p is the partial probability and s the probability to survive.

To survive some damage case in waves, it should be necessary to assume that the ship may survive this damage in calm water condition as well. Then equation (2) is written as

$$s = s_c \left(p_c + p_w s_{w|c} \right) \tag{3}$$

where $s_{w|c}$ is the probability to survive in waves on the condition that the ship survives in calm water. Equation (3) analyzes the survivability with respect to sea state on the assumption that waves and induced dynamics comprise the determining factor for ship's loss mechanisms and therefore of survivability.

Now if the partial probabilities p_c and p_w would be evaluated from the wave statistics of Fig. 1, they would result to p_c=0.3 and p_w=0.7, in a strict formulation and without particular provisions for the *operational wave profile*. However, when taking into account the fact that in the presence of wavelets the dynamics are limited and the ship behavior should be converging to that of calm water, additionally assume a wave height of 0.5 m as a conventional height for this differentiation, and the wave statistics of Fig. 2, then the partial probabilities are modified to the values of p_c=0.4 and p_w=0.6.

Then, applying these probabilities in equation (3) the final expression for the probability to survive collision damages becomes

$$s = s_c\left(0.4 + 0.6 s_w\right) \tag{4}$$

where s_c the probability to survive in calm water including wavelets and s_w to survive in waves. It is noted that the partial probabilities should not be considered as constants but rather evaluated from appropriate wave statistics for individual ships.

Overestimation of Waves by SOLAS'09

Assuming a survivability analysis according to equation (3), then the survivability model adopted by SOLAS'09 can be reviewed in comparison and to figure out that wave conditions are overestimated in the current regulations, and in consequence some notable underestimation of survivability against flooding results.

The formulation applied in SOLAS'09, assumes the *flooding stage* as the differentiating factor for ship's loss mechanism due to flooding. Thereby two distinct flooding stages are recognized, the intermediate and the final, with corresponding survivability factors s_{inter} and s_{final}. The s_{inter} used to formulate the possible dynamics and deterioration of ship's stability, may lead to ship's loss during the flooding of below waterline damaged spaces until some final equilibrium is met; and s_{final} the probability to survive the final equilibrium against the waves and a possible extension of flooding due to waves' action. The total survivability is taken as the worst between them, i.e. s=min$\{s_{inter}, s_{final}\}$.

The two analyses of survivability, namely with respect to the sea state (equation 3) or to the flooding stage (SOLAS) are actually convergent with respect to the basic conditions, those of '*intermediate flooding in calm water*' and '*final flooding in waves*' as shown in Table; whereas they differ for the ship loss in '*intermediate flooding in waves*' where this is considered to be caused by waves and therefore incorporated into s_w for the present analysis; note that in SOLAS formulation this is due to partial intermediate flooding and is incorporated into s_{inter}. This particular condition could be however separately formulated by further analysis of s_w and s_{inter} but this is herein not an essential detail. The left bottom conditions of Table 1'*full flooding in calm water*' are the trivial survival conditions and herein of major interest.

Obviously, the estimated probability s to survive the damaged ship should be independent of the applied analysis method. However, following a detailed comparison between the two formulations a systematic difference could be figured out, with SOLAS underestimating s (by values 0.1÷0.2) and with the higher differences resulting in the range of higher s_{inter} and intermediate s_{final}.

Table 1 Domain of the different *s*-factors

	s_{calm}	s_{wave}
s_{inter}	*Intermediate flooding in calm water*	*Intermediate flooding in waves*
s_{final}	*(Final flooding in calm water)*	*Final flooding in waves*

This difference is independent of any possible accuracy of the component factors (s_{inter}, s_{final}, s_c, s_w). This is because of the sea state statistics that are not taken into account by SOLAS at this level of analysis, and in consequence the wave conditions result overrated. In particular, the trivial survival conditions '*final flooding in calm water*' of Table 5 appear disregarded (which becomes quite apparent at the limits s_{inter}=1 and s_{final}=0).

Besides above deviation, the SOLAS formula appears also inefficient indicator for survivability enhancement. Since s=min$\{s_{inter},s_{final}\}$ any survivability changes appear dependent solely on one component factor, and if further taking into account that $s_{final}<s_{inter}$, then any intended increase of total survivability s results to required increase for s_{final}. In other words, *the survivability in waves appears to be the driving factor for the optimization of the overall survivability of the damaged ships*. However, the survivability improvement is actually achieved by the simultaneous increase of the survivability in calm water as well, as expressed by equations (3), (4).

THE UNCERTAINTY OF SURVIVABILITY

The Critical Waves

So far it is rationally accepted that a damaged ship with non-zero stability may withstand waves up to some finite wave height, the *critical waves*. Above this limit the ship may capsize under the action of higher waves. The critical waves depend on the damage case and the particulars of the potentially flooded spaces. Critical wave heights were considered as a transition band between survive and non-survive boundary conditions (Vassalos et al. 1996). Later it was clarified that the critical wave height of a damage case is a discrete height, whereas the transition band is the effect of considering the survivability in finite times (Spanos & Papanikolaou, 2007). Therefore all wave heights larger than the critical wave height are eventually non-survive wave conditions, and the damaged ship survives (for infinite time) all waves heights lower than the critical one.

Therefore, to survive some collision damage in waves (unconditionally to time) is equivalent to encounter waves lower than the corresponding critical waves. And then the probability to survive in waves is written as

$$s_w = P\left(H_s < H_{s,cr}\right) \tag{5}$$

Equation (5) is the basic assumption for the survivability in waves; and given the information for waves like that of Fig. 1 and Fig. 2 then the main interest is concentrated on the estimation of the critical waves $H_{s,cr}$.

Intrinsic Randomness of Critical Waves

For a specific ship and damage case the critical wave height $H_{s,cr}$ depends on parameters characterized by low or high uncertainty, as well as on direct random variables. Random variables are

- the damage opening, in terms of location, size and shape
- the wave properties other than wave height, like wave periods and directional dispersion
- the wind, and even the currents which may affect the lateral orientation of the ship
- the loading and the content (permeability) of the potentially flooded spaces

Parameters suffering by minor uncertainty are

- the ship loading condition, in terms of weight distribution at the time of accident
- the status of internal openings that connect ship's compartments

Thereby, if we would be looking for the unconditional critical wave height this would be the expected value over all probable conditions, namely the integral of critical waves corresponds to the long range of conditions as determined by all above random and uncertain parameters. An attempt to estimate this value for one specific damage case (and with the present computational means) is quite laborious. While considering the large number of possible damage cases that need to be taken into account in survivability assessment, it proves impractical as well.

The critical wave height $H_{s,cr}$ would rather be regarded as a *random variable* of some distribution $f(H_{s,cr})$ for given stability parameters. Such distribution is yet unknown. However, the main properties can be statistically estimated, and subsequently provide the means for a first estimation of the damage survivability. The integral over $f(H_{s,cr})$ distribution, weighted with the waves distribution $f'(H_s)$ like Fig. 3, Fig. 2, provides the expected survivability s_w of the damage case.

$$s_{wave} = \iint_{H_s<H_{s,cr}} f'\left(H_s\right) f\left(H_{s,cr}\right) dH_{s,cr} dH_s \tag{6}$$

A first approximation of $f(H_{s,cr})$ can be obtained with a regression analysis of critical waves over the statistical data and for the damage stability parameters of GZ_{max} and *Range* of residual stability similar to SOLAS'09 approach (*Tagg* *and Tuzcu*, 2002). This approximation might be further refined by considering more detailed distributions for $f(H_{s,cr})$. However even if a perfect description would be determined, such improvements would have impact on the general average survivability only, whereas the essential problem of survivability of individual damaged ship would be not improved as discussed below.

Critical Waves for Damaged ROPAX Ships

Beyond the inherent randomness of the critical wave it strongly depends on particulars of damage cases, namely the arrangement of the damaged compartments that are flooded or can be flooded by the waves or even progressive flooding; this makes the critical waves even more complicated with wide probabilistic spread.

For damage cases of ROPAX ships, which are characterized by the presence of large open spaces closely and above the waterline, like that of car deck, and which are vulnerable in flooding due to waves, the critical waves may systematically differ from other damage cases (Vassalos & Jasionowski*,* 2007), and it makes sense to deal separately with these ships.

Next figure presents a sample of critical wave heights for ROPAX ships in different damage cases in relation to the maximum righting level GZ_{max}. These data were generated within a variety of European research projects over the last decade. The survivability formulation in SOLAS'09 is founded on similar information.

The critical wave heights in Fig. 3 appear well gathered. Outside the (shaded) region, there are no data encountered, either because the residual stability (GZ_{max}) is not sufficient (for the region above the upper outline), or opposite, the stability is over sufficient (for the region below the lower outline).

This diagram simultaneously demonstrates the remarkable dispersion of critical waves. Characteristically for GZ_{max}=0.2 m the critical height may differ by at least 4.0 m; while, since the dispersion is sample dependent, for a larger dataset the range would be slightly wider. The dispersion is due to two reasons, the different damage cases and the intrinsic randomness of critical wave, as discussed above.

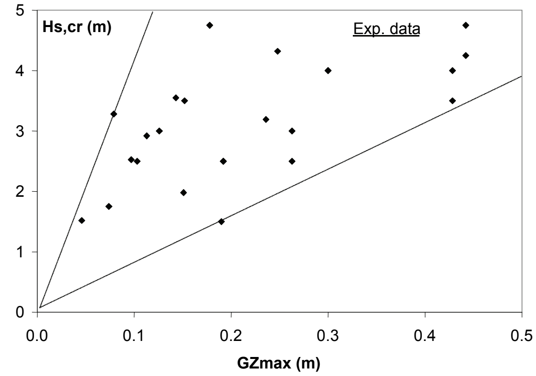

Fig. 3 Critical wave heights for ROPAX ships

For survivability assessment models, the prime objective is to reproduce the trend observed in the data of Fig. , namely the increase of critical waves with an increase of damage stability. Concurrently, to pursuit the best reproduction of dispersion as much as possible by trying to set up a wide and unbiased data set. Although a large sample would be required to definitely conclude on the achievement of these objectives (particularly when taking into account any ship type and damage case in aggregate) a rather good approximation is already encountered with the present dataset, which permits to recognize some distribution range and even to assume some first distribution function over that range.

Uncertainty of Survivability Estimations

The full uncertainty for the critical waves, as analyzed above, is eventually incorporated into the estimations for survivability of the damaged ship. Uncertainty is not somehow cancelled or reduced, but it is transformed to the level of confidence for individual assessments.

In the following, the uncertainty of the survivability in waves is estimated for ROPAX ships. This is attempted by comparison of the survivability according to SOLAS'09 together with the more accurate estimations by exploiting the critical waves as they are indicated by the model tests of Fig. 3. Thereby in Fig. 4 the absolute differences are plotted versus the probability to survive *s* based on experimental data (diamond symbols). There, the differences appear scattered and larger the lower the *s*-factor is, whereas both approaches appear convergent when *s* tends to value one.

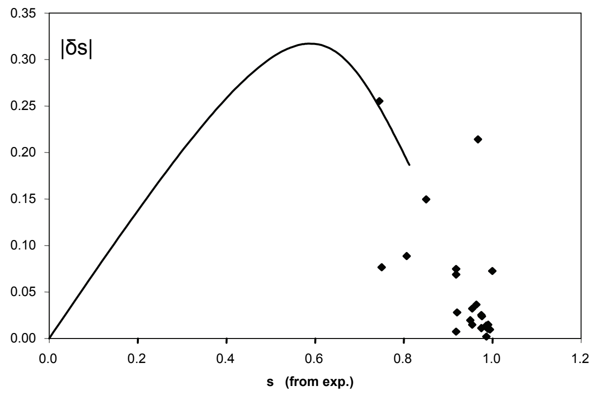

Fig. 4 Intrinsic uncertainty for survivability in waves

In order to extent the picture of differences at the range of lower *s* values, the outlines of Fig. 3 are employed to produce the dashed line of Fig. 4. This diagram presents the expected maximum uncertainty of s-factor, and since it depends on the sample outlines, it is actually a conservative estimation, though still representative.

Differences $|\delta s|$ represent the incorporated uncertainty, which may result to maximum values up to $|\delta s|$=0.30 for the intermediate values of *s*-factor, whereas at both ends uncertainty is reduced. Such levels of uncertainty are remarkably large. Characteristically, for *s*=0.70 then SOLAS *s*-factor may range between *s*=[0.45, 0.95] since $|\delta s|$=0.25!

Fig. 4 shows that the confidence level for intermediate survivability values is rather low and more reliable estimations may be expected at the range of extreme values, approaching one or zero. This situation is a direct consequence of the uncertainty on critical waves, combined with the wave statistics of Fig. 1. If the damage stability is sufficiently large to enable the ship to survive in higher waves (e.g. above 3.0 m) then survivability tends to *s*=1.0 regardless of particular assessment approach, by model tests or SOLAS. Similarly, if there is no sufficient stability to survive any waves then both approaches converge to *s*=0.0.

In other words, the higher waves a damaged ship may survive the higher the confidence is, simply because probability to get damaged at higher waves gets gradually lower; and if stability is much lower and negligible then the ship does not survive any damage case with confidence again. These two extreme situations are reproduced in Fig. 4, while all intermediate conditions suffer necessarily by irreducible uncertainty.

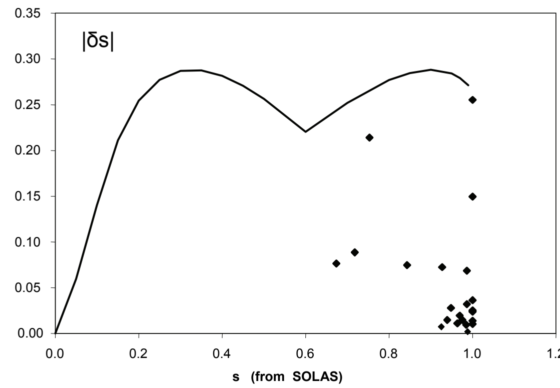

Fig. 5 Uncertainty for survivability in waves of SOLAS'09

The uncertainty of Fig. 4 is transformed to that of Fig. 5 versus the s-factor according to SOLAS'09. This is of practical value as it indicates the uncertainty level of the survivability estimations currently in force. Uncertainty appears around $|\delta s|$=0.25 along the major range. Noting that even for *s*=1.0 uncertainty is still of such high level. This limit is significant because the larger percentage of damage cases considered in survivability assessment result to *s*=1.0 and, additionally the related uncertainty is here of *negative* sign, which means overestimated *s*.

Improving Confidence in Survivability Assessment

In the previous sections it was illustrated that due to the intrinsic uncertainty for critical waves irreducible uncertainty in the estimations for survivability is inevitable. Thus in order to improve confidence there are two reasonable approaches

- either try to reduce uncertainty, by pursuing refined estimations for the critical waves, by use of tank model tests or even consider specific classes of damage cases
- or/and to avoid the uncertain conditions, by establishing damage cases away from the wave range that collision events occur

It is thus underlined that the problem in the survivability assessment of damaged ships is that of the confidence in individual assessments and not in the general level of survivability of ships. Therefore aiming to improve confidence *it is rational* to *raise the related confidence level for* *those individual cases that apparently suffer by uncertainty, instead of raising the general level of survivability as a countermeasure to the so far encountered diversity.*

Fig. 6 presents the uncertainty for the survivability in waves of ROPAX ships as a function of GZ_{max}, one of the two parameters currently in use in damage survivability regulations. This diagram derives directly from the outlines of critical waves of Fig. 3 and wave heights of Fig. 1. Here, uncertainty is apparently reduced for the larger GZ_{max}. However according to current regulations, damage cases with GZ_{max}>0.12 m are not distinguished.

Therefore, if we would account for the associated uncertainty of the different damage cases (considered in survivability) it would be also possible to evaluate the general level of uncertainty (implicitly confidence) and then judge whether the balance between cases of higher uncertainty and those of lower could be assumed tolerable. Two vessels of equal survivability, as expressed through the attained index-A of regulations, which would differ with respect to the confidence, should be treated differently, namely the one with the lower confidence would obviously require enhanced measures.

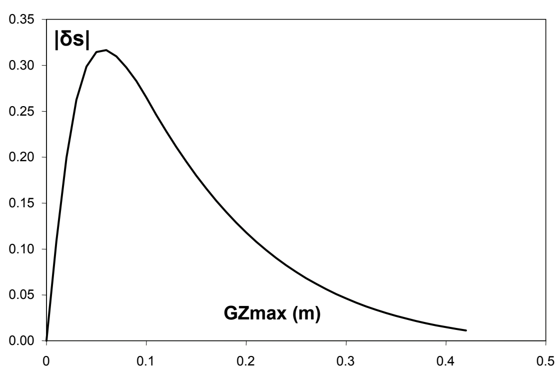

Fig. 6 Uncertainty for survivability estimations

To this purpose equation (6) readily provides an estimation of the associated uncertainty of the attained index A

$$|\delta A| = \sum_i p_i |\delta s_i| \qquad (6)$$

where *i* index accounts for the different damage cases, *p* is the probability of *i*-th damage case and |δs| is evaluated from Fig. 6

Thus by supplementing the survivability assessment methods with appropriate quality measure (eq. 6) a more rational interpretation of the obtained estimations can be achieved as well as an improved guidance for ship designers to control and optimize ship safety.

CONCLUSIONS

The significance of sea state in ship's survivability assessment was discussed as a fundamental determinant for the behaviour of the damaged ship, which may directly improve the account and control of problem's complexity.

For the survivability assessment method adopted by the current SOLAS'09 regulations, a systematic underestimation was identified, which is attributed to a non-satisfactory consideration of the calm water flooding conditions. Additionally, ship's individual *operational wave profile* is underlined as a basic missing element of the present survivability assessment approach. Beyond the refinements, the current approach (and relevant revisions) can be still considered as well founded.

It is also pointed out that the related confidence of estimations is low, as a consequence of the *intrinsic* and *irreducible* uncertainty related to the determination of the critical wave heights and the statistical foundations of the approach.

Therefore the necessity for a supplementary *quality assessment index* is suggested as a measure towards more rational assessments and improved interpretation of the survivability estimations.

ACKNOWLEDGEMENTS

The herein expressed views were elaborated within the European Commission research project GOALDS (Goal Based Damage Stability, FP7-SST-2008-RTD-1-233876, www.goalds.org,). It is not implied that views are necessarily shared by other members of the consortium. The European Commission and the authors shall not in any way be liable or responsible for the use of any knowledge, information or data presented, or of the consequences thereof.

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