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OVERVIEW OF THE RESULTS OF THE PROJECT ‘LOADS ON STRUCTURE AND WAVES IN ICE’ (LS-WICE)

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As an attempt to investigate several major research questions related to ocean wave-ice interaction, the HYDRALAB+ Transnational Access project ‘*Loads on Structure and Waves in Ice*’ (LS-WICE) was conducted in the Large Ice Model Basin (LIMB) at the Hamburg Ship Model Basin (HSVA) from 24 October to 11 November 2016. The experimental data from this extensive project have been analysed in several research studies reported in other scientific papers. Here, an overall review of the obtained results is presented, and some recommendations for further work are given based on the collected experience.

1. INTRODUCTION

As a result of climate change, Arctic sea-ice volume decreases opening northern waters for shipping and offshore engineering developments, which creates great future potentials. However, larger open-water areas in the Arctic are also associated with a less predictable environment, where storms and sparse ice features driven by large waves may create significant challenges for the safe navigation and sustainable developments. The reliable prediction of the new Arctic marine conditions requires wave models that can take into account the interaction between the dynamically changing ice cover and ocean waves, which is still an on-going research area. Understanding the ice-wave interaction mechanisms is also important for avoiding structural damage due to ice impacts on ships and structures operating in the marginal ice zone (Su et al., 2017). As an attempt to contribute to the research on several major topics related to wave-ice interaction, the LS-WICE project (Tsarau, 2017) was conducted in the Large Ice Model Basin (LIMB) at the Hamburg Ship Model Basin (HSVA) from 24 October to 11 November 2016 under the HYDRALAB+ program.

The main objective of the LS-WICE project was to collect unique experimental data which would be used for developing numerical models, validation analyses and further studies. Several series of experiments were performed to investigate linear monochromatic wave propagation under saline ice floes, including a test series in open water (series OW) to establish the baseline, Series 1000 for wave-induced ice fracture (Herman et al., 2017 and Herman et al., 2018), Series 2000 and 3000 for the wave dispersion and attenuation (Cheng et al., 2017, 2019) and for floe dynamics (Li & Lubbad, 2018), and Series 4000 and 5000 for ice-wave-structure interactions (Tsarau et al., 2017). This paper gives a brief overview of the results from the analyses of the LS-WICE experiments.

2. INSTRUMENTATION AND EXPERIMENTAL SETUP

Fig. 1 shows the principal setup of the experiments in the LS-WICE project. At the left end of the basin, a wave maker consisting of four flap-type wave generators spans the width of the basin. The right end is a parabolic-shaped beach to reduce wave reflection. The wave basin is 72 m long and 10 m wide; the depth is 2.5 m in the first 61 m from the wave maker and increases to 5 m in the last 11 m near the beach.

For experiments with ice, first a continuous ice sheet was created overnight; then the prepared ice sheet was freed from the tank sidewalls and afterwards cut into uniform-size rectangular floes by using electrical saws. Different floe sizes were used in different test series, and an intact ice sheet was used in Series 1000.

In total, 12 pressure sensors were installed to study wave attenuation, wave dispersion relations and wave reflection. Two ultrasound sensors were deployed in the area free of ice to quantify waves reflected from the ice edge. The sampling rate of these sensors was 50 Hz. Two Inertial Measurement Units (IMUs) were installed to measure the three orthogonal translational accelerations of two ice floes in Series 3000, and one IMU was used in Series 4000 to measure the floe accelerations during its impacts on the structure. A set of load cells were installed inside the structure and fixed to a rigid carriage. Additionally, a non-contact motion tracking system, Qualisys, measured three-dimensional spatial positions of 12 reflectors (light weight balls painted with reflecting materials) at a fixed frame rate of 100 Hz. These reflectors were positioned longitudinally on upper surface of ice floes, aligning with incident wave propagation direction, with 50 cm in between.

All experiments were documented with several video cameras installed on the tank ceiling, sidewalls and the carriage.

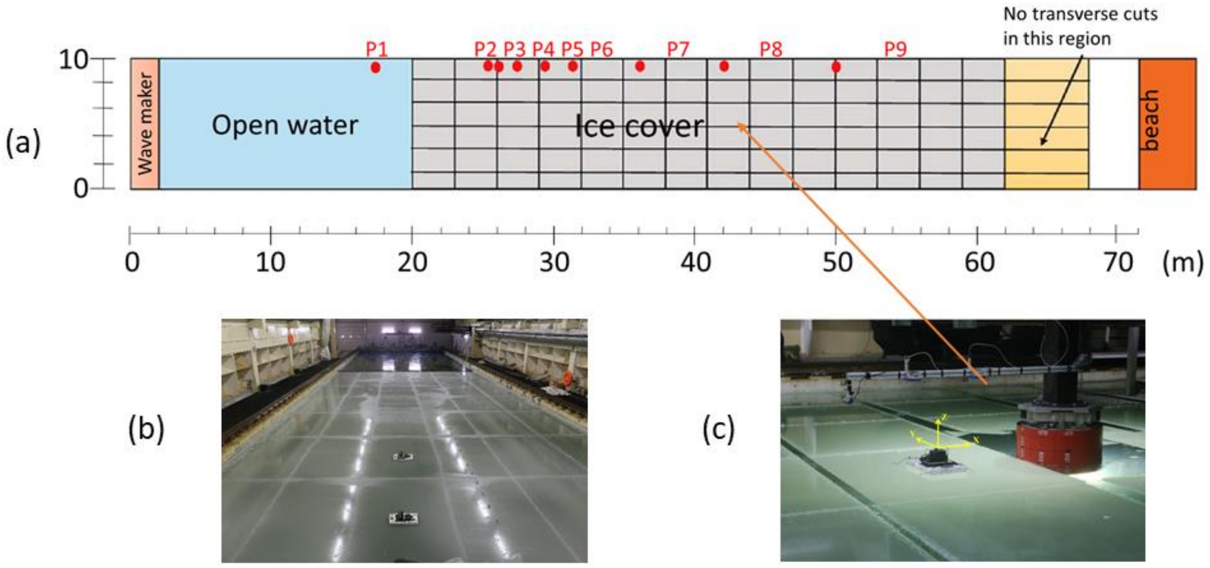

Figure 1. (a) Schematic of the experimental setup with broken ice shown as grey grids. Pressure sensors are numbered as P1 to P9. (b) Locations of the IMUs and the Qualisys reflectors. (c) Structure and its position in Series 4000.

3. WAVE-INDUCED ICE FRACTURE

Wave-induced ice fracture was analysed by Herman et al. (2018) based on the measurements and observations from Series 1000. They used digital images to obtain the floes' characteristics: surface area, minor and major axis and orientation of equivalent ellipse. This analysis shows that although the floe sizes cover a wide range of values (up to 5 orders of magnitude in the case of floe surface area), their probability density functions (PDFs) do not have heavy tails, but exhibit a clear cut-off at large floe sizes. Moreover, the PDFs have a maximum that can be attributed to wave-induced flexural strain, producing preferred floe sizes. It is also demonstrated that the observed floe size distribution (FSD) can be described by theoretical PDFs expressed as a weighted sum of two components, a tapered power law and a Gaussian, reflecting multiple fracture mechanisms contributing to the FSD as it evolves in time.

An example of a final result of the image analysis is shown in Fig. 2. As can be seen, the floe shapes are far from regular; most of floes are polygonal and elongated, and they tend to be longer in the across-tank direction than in the along-tank direction. Several processes were found to contribute to breaking and overall wear out of the ice: wave-induced flexural stress, overwash of the upper ice surface, floe-floe collisions and grinding of small ice fragments between larger ice floes. These processes might not be modelled the same as they are in the real world. Moreover, laboratory-grown ice is typically softer, weaker, and thinner than real-world sea ice. Thus, it was not surprizing that no regular breaking patterns similar to those repeatedly reported from the field were observed in this experiment. Nevertheless, the obtained laboratory data gave good insight into the processes governing ice fracturing by waves and can be used further to test alternative floe-size distribution models.

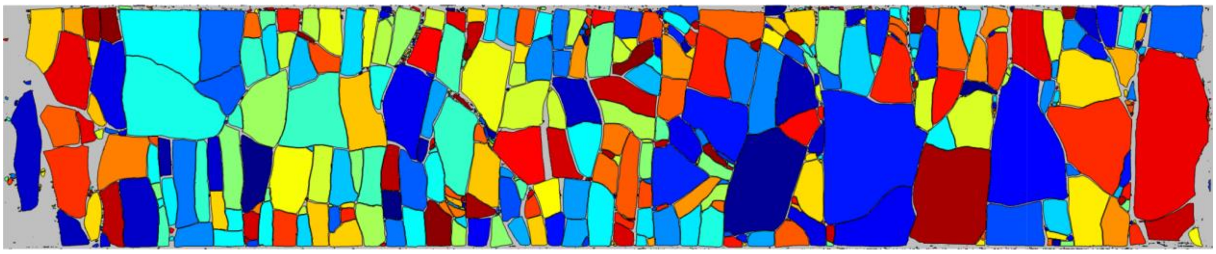

Figure 2. Results of the image analysis, where the identified ice floes are marked by black contours and randomly selected colours, and the open water is grey. The wave maker is to the left, and the beach to the right. The height of the image corresponds to the distance of 10 m (tank width).

4. WAVE DISPERSION AND ATTENUATION

Cheng et al. (2019) studied the effect of floe size on the wave dispersion and attenuation in Series 2000 and 3000. The wave number and amplitude for each run were calculated based on the pressure signals, which were first converted to meters of water using a calibrated pressure-depth relation. Fig. 3 shows the wave numbers obtained from the experimental data (in red) and also numerical results for floes with different sizes calculated based on the theory used by Cheng et al. (2019). Despite the scatter in the laboratory tests, both the experimental and theoretical results show that the wave number decreases when the floe size reduces.

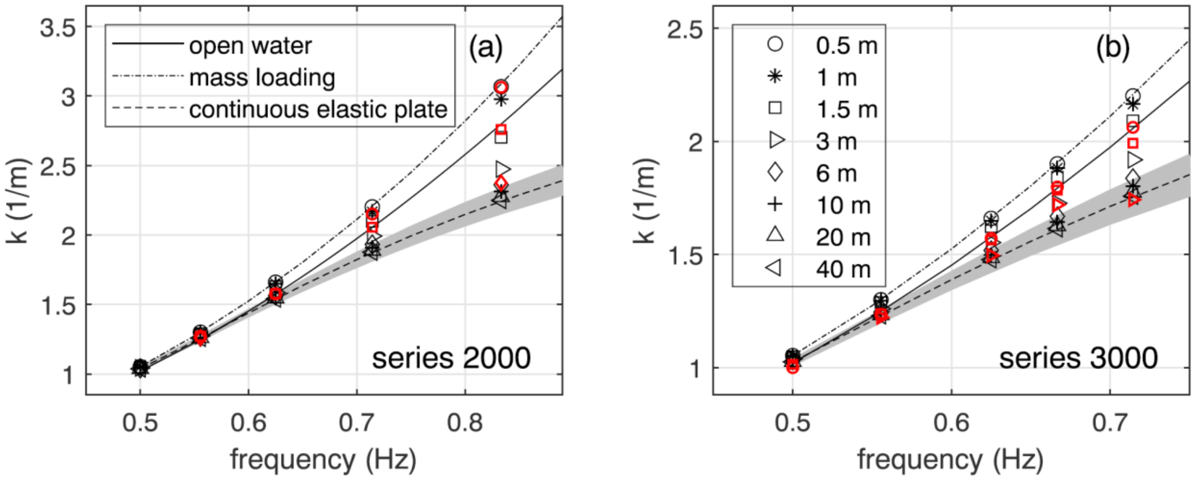

Figure 3. Wave number against frequency for Series 2000 (a) and 3000 (b): experiment (red) and theoretical results (black) for different floe sizes.

In the same study, the wave attenuation coefficient was identified by fitting the surface elevation with an exponential curve, that is, the snapshot method. The multiple modes that coexist due to the discontinuities in an ice cover create an undulating wave envelope, superimposed with an overall attenuating surface elevation. The result is an irregular amplitude variation, and therefore, the overall attenuation can be confidently measured only over a long distance. For each frequency and floe length, the measured attenuation coefficients are presented in Fig. 4.

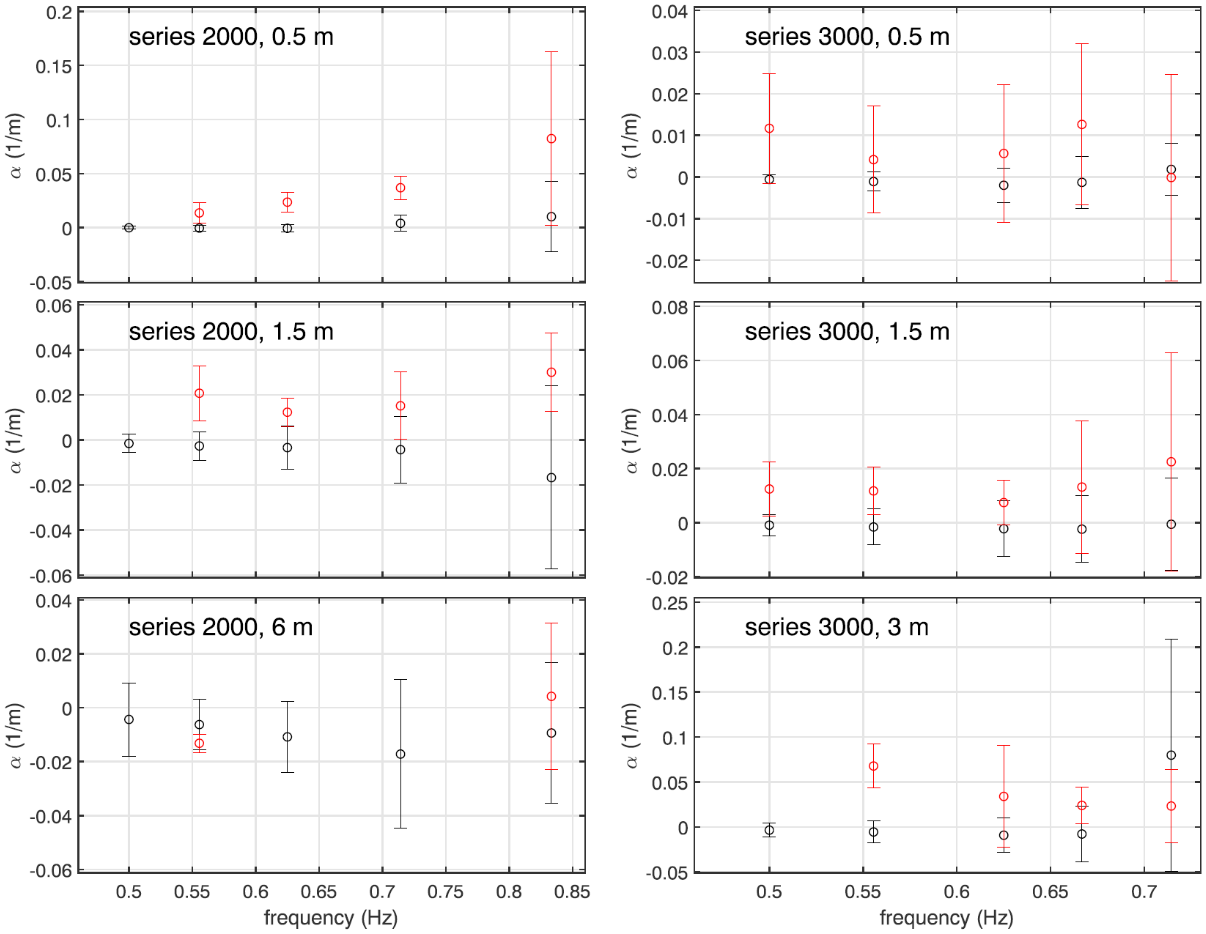

Figure 4. Attenuation coefficient *α*: experiment (red) and theoretical results (black) obtained by Cheng et al. (2019).

Fig. 4 shows both the large fluctuations and the discrepancy of the level of attenuation coefficients between the laboratory and theoretical results. These may indicate the presence of other damping mechanisms that were not revealed by this study, e.g., overwash, boundary layer effect under floes, floe-floe interactions and vortex shedding. An attempt to quantify the effect of floe-floe interactions on the overall damping was made in another study presented in the next section.

5. FLOE DYNAMICS

One experimental data set in the extensive LS-WISE project was analysed for investigating collisions between floes forced by regular incident waves and their effect on wave attenuation (Li and Lubbad, 2018). As the inelastic collisions between neighbouring floes dissipate wave energy, they contribute to the overall wave attenuation, which was discussed in the previous section. This contribution was quantified and the results are presented below.

Collisions between four neighbouring ice floes, instrumented with Qualisys reflectors and two IMUs while having pressure sensors deployed nearby, were examined by using both the positional and acceleration measurements (Fig. 5). The loss of wave energy due to a collision event was calculated as the difference between kinematic energy of floes before and after the collision, for which the pre- and post- collision velocities were identified first. Collision frequency, defined here as the number of collisions taking place on the same side of one ice floe in one second, was also estimated based on so-called collision signatures in the measured signals (e.g. peaks in the acceleration data). It was found that the collision frequency matched well the wave forcing frequency (1 / T = 0.5 Hz in the studied case). Finally, the energy loss because of collisions in this study was quantified to be approximately -0.025 J/m^2, which was approximately 3% of the incident wave energy in open water and 10% of the total wave energy loss in the regions covered by the four neighbouring ice floes. Thus, this study implies that the wave energy dissipated by collisions were significant in the conducted experiment.

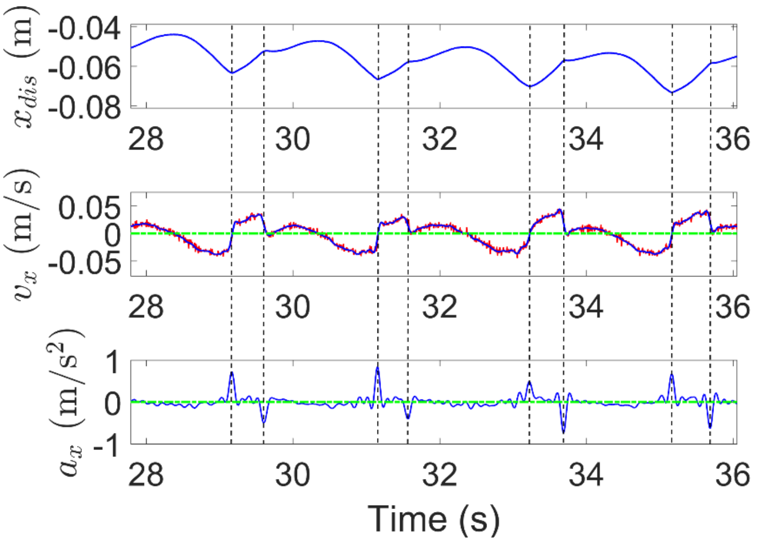

Figure 5. Displacement, velocity and acceleration of an ice floe in Series 3000 (Li and Lubbad, 2018).

6. FLOE IMPACTS ON THE STRUCTURE

In Series 4000 combined wave and ice actions on a fixed structure represented by a cylinder with a diameter of 0.69 m (in the model scale) were measured. Tsarau et al. (2017) presented an analysis of this experiment focusing on floe accelerations and forces during collision events. Some of the results from this study are highlighted here.

The cylindrical structure was located approximately in the middle of the ice tank at 43.7 m from the wave maker as shown in Figs. 1 (a) and (c). It was exposed to impacts from an adjacent ice floe, on top of which an IMU was installed to record accelerations (Fig. 1 c). Only accelerations along the surge direction (i.e., the direction of wave propagation) were studied, and the impact force was approximately estimated as $-m*a_{\mathrm{peak}}$, where m is the mass of the ice floe (including the mass of the IMU, which is negligible) and a_{peak} is the peak acceleration. Although a set of force transducers was installed between the structure and the rigid carriage, a direct measurement of the impact forces was not possible due to the structural response. However, the forces obtained from these transducers were clearly showing the amplitudes of the wave loads and, together with the IMU measurements, helped identify the collision occurrence and impact loads. Fig. 6 shows an example of this identification for Series 4120. The impact forces due to ice-structure collisions appear as long vertical spikes with positive peaks; spikes with negative peaks mainly appear on the black curves and are attributed to floe-floe collisions. The initial sinusoidal signal shows the load due to only waves, as it took some time before the ice floe started to collide with the structure.

Fig. 6 demonstrates that the impact force on the structure was 2-5 times higher than the maximum wave load. However, as also found from this analysis, the impact occurrence in the experiments was not regular: in some tests impacts occurred almost at every wave cycle, in others impacts were rare, and in some tests no impacts were detected at all. There were several parameters influencing the impact force and its occurrence: wave height and period, ice-floe kinematics in waves, including momentum exchange due to floe-floe interaction, and the interaction area between the structure and the ice floe. The latter was found to increase after several wave cycles, which eventually led to the breaking of the ice floe. As discussed in the previous sections, wave heights and floe dynamics are interconnected and depend on the overall attenuation rate. Thus, the results from this analysis should be considered together with the results from Sections 4 and 5.

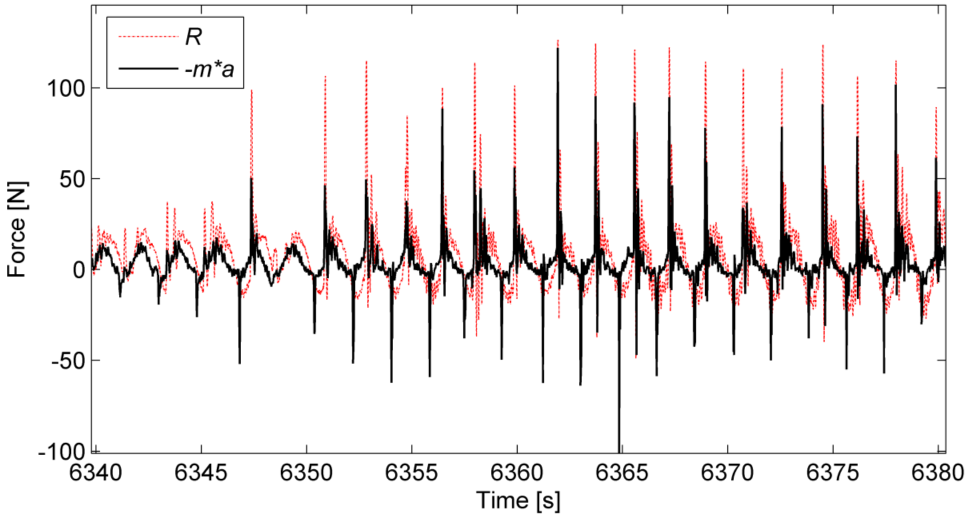

Figure 6. Time series of the impact force (black) on the structural response (red) during collision events in Series 4120.

7. SUMMARY AND RECOMMENDATIONS

The experimental data from the extensive LS-WISE project have been analysed in several research studies reported in other scientific papers (see the reference list below). In this paper, we attempted to give an overall summary of the work related to this project, its main results and their relations to each other. Further, various recommendations to improve the experimental setup and analysis techniques for studying wave-ice-structure interactions are given based on the experience from the presented investigations.

The floe-size distribution from the LS-WICE experiments on wave-induced fracture of ice can be described by theoretical PDFs. However, these results may not be directly interpreted as the floe-size distribution in the marginal ice zone because of the difficulty to scale all the underlying processes that were identified in this laboratory study. For further work, it is recommended to try to re-examine the published floe-size data without commonly made a priori assumptions regarding the form of the PDFs and to test alternative floe-size distribution models.

The tests on wave propagation through broken-ice covers showed that the wave number decreases when the floe size reduces. The obtained attenuation rates indicate uncaptured damping mechanisms such as overwash, boundary layer effects under floes, vortex shedding and floe-floe interactions. Only the effect of the latter was estimated to be approximately 10 % of the overall damping, and the other mechanisms should be studied further.

The experiment with the structure in the LS-WICE is one of the very few laboratory studies on wave-ice-structure interaction described in the literature, and thus, the experience from this experiment may provide a useful guideline for further investigations. Both the IMUs and the optical system showed to be effective to capture floe dynamics, which was important for estimating floe-impact forces on the structure. As these loads are highly dynamic, to measure them with load cells installed on the structure, one may need to apply a load-identification model, which must be calibrated for structural response prior to tests with ice. This was not done in the LS-WICE, but instead the forces were identified based on the floe accelerations, which showed to be also a reasonable approach.

Finally, the LS-WICE project has already provided the basis for several high-level research papers, as the ones discussed here, and hopefully, there are more to come soon.

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