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Simulation of Load Distribution along a Quay during Unparallel Berthing Manoeuvres

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ABSTRACT: The marine berths are normally secured for safety reasons with a system of fenders. Their role is to absorb and dissipate the kinetic energy of a ship coming into a contact with a berth, so the structural integrity of both the berth and ship's hull is preserved. Normally the combination of a number and the single fender strength indicate the ship's maximum allowable lateral speed in parallel berthing conditions (of course, with a safety margin frequently taken into account). More or less directly and/or approximately, this is also a general selection method for fender systems. The main objective of this conference contribution, as inspired by some suggestions and needs within a domestic marine society since the author's developed and successfully implemented fender effect in ship manoeuvring simulation, is to analyse the local loads in a particular fender around the region of contact during an oblique berthing. Various conditions of ship's lateral and angular velocities are tested. The results are compared with some practical shiphandling tips, as to be found in the literature, leading to a necessity of revision of the existing practice. The presented investigations are believed to be very helpful also for fender system designers.

1 INTRODUCTION AND OBJECTIVES

Deck officers simplify the problem of ship berthing, whether made on her own or with tugs assistance, to maintain proper local lateral velocities fore (at the bow) and aft (at the stern). Both movements are able to be measured by an onboard doppler log (with sensors in the mentioned locations), an onboard docking system (as the satellite-based one with two antennas, or where the linear velocity vector, e.g. from a satellite system, is integrated with the rate of turn from a gyroscopic sensor, or in which inertial sensors are finally applied), or a docking system ashore, if applicable. Some terminals report a maximum allowable lateral approach speed for various weather conditions and ship sizes. By default, the essentially parallel approach is therein assumed.

Of course, this practice really works when an attempt is made to restrict these velocities as close as possible to zero. However, some major or minor problems can happen if the bow and stern velocities are significantly non-zero, different from each other, or occurring at the ship's non-zero direction angle to a berth (thus making a 'single point' contact).

In the following a closer look into the ship-berth (or ship-fender) interaction phenomenon is intended, because the situation is more complex, as usual, in the real-world. The local loads in fenders and absorbed energies will be studied in detail. The problem is tackled by the comprehensive ship manoeuvring simulation with a full control over the fender effects. According to the author's opinion the existing full-mission ship-handling bridge simulators do not allow any analysis of loads in fenders, except for sending a 'broken fender' alert. Moreover, the implemented fender dynamic effect on ship manoeuvring motions is often not well modelled

2 SIMULATION EXPERIMENTS

The designed simulation experiment consists of a manoeuvring mathematical model of small chemical tanker 6000 DWT. The ship data as of direct interest in berthing problems are briefed in Table 1. Other hydrodynamic features of the model can be found e.g. in (Artyszuk, 2005). The model runs within the fast- and real-time interactive ship manoeuvring simulation software SMART (all the mechanical effects included) as developed by the Author. As to properly evaluate the fender forces the integration and recording time step 0.05s is adopted on the basis of some preliminary convergence simulation trials with the berthing manoeuvres in concern.

For reference purposes the deep water conditions near the berth are selected, since there is a significant scatter in the literature concerning the shallow water correction factors for added masses and hull hydrodynamic forces. The patterns of local loads in the fendering system in such circumstances are however believed to be very similar to those of deep water case, of course except for absolute values. Because the fender reaction forces really dominate when a contact with fenders is already established (even before or after that moment the hydrodynamic damping forces are too small to change the ship very slow motions in a rather short time period) the most important for the shallow water berthing simulation is the augmentation of added masses. Nevertheless, some characteristic shallow water aspects will be later raised in the study.

Table 1. The ship basic data.

Symbol	Value	Name
m[t]	8948	displacement (mass)
L[m]	97.4	length between perpendiculars
B[m]	16.6	breadth
T[m]	7.1	draught
k11[-]	0.056	surge added mass coeff.
k22[-]	1.004	sway added mass coeff.
k66[-]	0.83	yaw added inertia coeff.
rz[-]	0.2465	ship's gyration radius (length units)

Furthermore, the model of discretely spaced linear fenders, as described in (Artyszuk, 2003), is used in the research - the fender reaction increases proportionally to its compression while for decompression it practically disappears. Though the SMART environment is capable of implementing any nonlinear load-deflection chart of the fender (including the so-called hysteresis), the adopted linear characteristics enables a direct comparison of simulation results with those obtained by the analytical dynamic method for a single fender. The latter analytical approach, based on a set of linear ODEs, was introduced in (Artyszuk, 2003). In view of the current concern more results of this analytical method are contained in Table 4. The analytical method is universal in such a way that after some minor extensions it gives ship movements after the impact for any initial condition in terms of the direction angle, linear and angular velocities. This certainly could help to solve a dispute in the domestic literature (Magda, 2006) with regard to the Vasco Costa formula (Vasco Costa, 1964) for the berthing energy absorption, as based on the angular momentum conservation theory for non-elastic collisions.

A berth secured with 20 fenders (each of the maximum force 100t at the deflection 20cm that contributes to the energy absorption E_F=98.1kJ per single fender) is set up from the practical viewpoint. As opposed to (Artyszuk, 2003, 2005), in the present research the linear reaction of a fender during the decompression phase is additionally assumed, though set only at the level of 1% of the compression-related reaction at the same deflection. These fenders are spaced every 5m that corresponds to 1/20 of the ship's length, since trials with 10 fenders, arranged every $0.1L$, have failed in this sense that safe berthing speed under such circumstances is relatively low (even in deep water constituting the most favorable berthing conditions). It shall be here namely emphasized that the usual curvature of the ship's waterline contour (specifically the length of ship's parallel body), see Figure 1, leads in our case to the compression of just 11 to 13 fenders (of the total number 20) depending on the lateral speed. These are 6(7) aft, 1 center, and 4(5) forward fenders for the speed 0.3(0.6)kt.

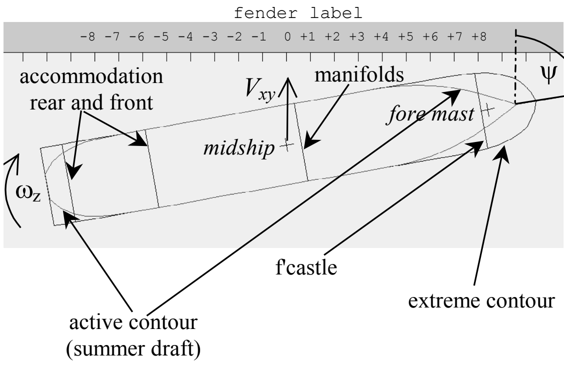

Figure 1. Situational sketch of portside berthing manoeuvre.

All the fenders are labeled according to their relative location against the ship's midship section (Fig. 1). There are 15 runs considered in the experiment, in which the ship after an initial excitation moves by inertia towards the berth - see Table 2.

Table 2. Summary of simulation runs.

Symbol	Heading	Mode of Motion v_y (sway)	/	ω_z(yaw)
R0.	090°	neg.	/	-
R1.	090°	neg.	/	-
A0.	088°	neg.	/	-
B0.	085°	neg.	/	-
C0.	080°	neg.	/	-
D0.	075°	neg.	/	-
E0.	070°	neg.	/	-
F0.	060°	neg.	/	-
B1.	085°	-	/	neg.
B2.	085°	pos.	/	neg.
B3.	085°	neg.	/	pos.
G0.	095°	neg.	/	-
G1.	095°	-	/	pos.
G2.	095°	pos.	/	pos.
G3.	095°	neg.	/	neg.

The first two runs (R0, R1) deal with a parallel approach at different lateral velocity (0.3m/s and 0.15m/s correspondingly). The other six in order (A0÷E0) constitute an oblique, constant heading bow-in (bow-first) berthing at a different ship-to-berth direction (starting from 2° up to 30°), in which the linear velocity v_{xy}=0.15m/s (0.3kt) is kept normal to the berth. Such a condition means the varying forward and lateral (negative to portside) velocities, v_x and v_y, according to the projections of total velocity vector in ship's body axes - see the first row of Table 4a. The consecutive three runs (B1÷B3) take a focus on a possible different combination of the linear and angular (positive to starboard) velocity as to arrive at the same local lateral velocity (equal to 0.15m/s) for the ship's hull point of the first contact. In the bow-in berthing the latter lies approximately at the one quarter of the ship's length (~25m) from the amidships position. The last four manoeuvres (G0÷G3) comprise some cases of the stern-in berthing at 5° to the berth. The varying combination of lateral and yaw velocities also contributes to the local contact velocity of order 0.15m/s, which is however now connected with the hull point placed 40m astern from the ship's midship.

3 ANALYSIS OF RESULTS

As aforementioned, of a great assistance in physical explaining and/or verifying the simulation results appears an application of the analytical method - see the following Table 3. If a ship moving nearly perpendicularly to the berth hits a single fender, the resulting after the impact lateral v_{y1} and yaw ω_{z1} velocities generally depend on the fender contact point in relation to the ship's midship (index '1' denotes the first impact, here the bow impact, '2' refers to the second impact i.e. by the stern). To be more precise one should refer the fender position to the ship's radius of gyration r_z - see also the early works of Vasco Costa (Vasco Costa, 1964, 1968). The instant pivot point position x_{PP} during the fender compression decreases from the infinity up to the convergence with the fender position Δx_c at the moment of maximum deflection t_{max}. For the chemical tanker in concern with a berthing speed of 0.25m/s this is presented in Figure 2, where both magnitudes are expressed in units of the ship's length (the value +0.5 coincides with the ship's bow).

It is evident from Table 3 that the highest contribution to the residual total kinetic energy after the first impact, as actually coming from the ship's rotation, is gained for a fender close to the midship section - the parameter $\%E_1(\omega_z)$ represents the ratio of yaw-related energy to the total remaining energy E_1. The difference between E_1 and the initial energy E_0 (here arising from the pure lateral motion) is represented by dE_1. Furthermore, the quantity $\%dE_1$ means the ratio of just absorbed energy dE_1 to the initial energy E_0, while the expression dE_1/E_F indicates the absorbed energy as compared to the fender specific maximum energy E_F that can be safely absorbed (here E_F=98.1kJ). Values of dE_1/E_F in Table 3 higher than unity, specifically for fenders close to the midship, are rather theoretical ones (although of some practical implication), since the assumed linear fender was allowed to be compressed outside the limit of 20cm, which was necessary to completely stop the ship and transfer her full kinetic energy to the fender. It must be well understood that for the mostly forward fenders the absorbed energy is essentially lower, but the rest of initial energy still remains on the ship and increases the risk of second impact.

Table 3. Motions and energy absorption - analytical study

	fender abscissa (in ship's length from amidships)					
	0.0	**+0.1**	**+0.2**	**+0.3**	**+0.4**	**+0.5**
t_{max} [s]	3.0	2.8	2.3	1.9	1.5	1.3
v_{y1} [m/s]	0.0000	-0.0382	-0.1047	-0.1547	-0.1856	-0.2046
ω_{z1} [°/min]	0.00	13.47	18.48	18.19	16.38	14.44
$\%E_1(\omega_z)$	0.00	0.85	0.58	0.38	0.26	0.18
E_1 [kJ]	0	86	235	347	416	459
dE_1 [kJ]	560	475	326	214	144	102
$\%dE_1$	1.00	0.85	0.58	0.38	0.26	0.18
dE_1/E_F	5.7	4.8	3.3	2.2	1.5	1.0

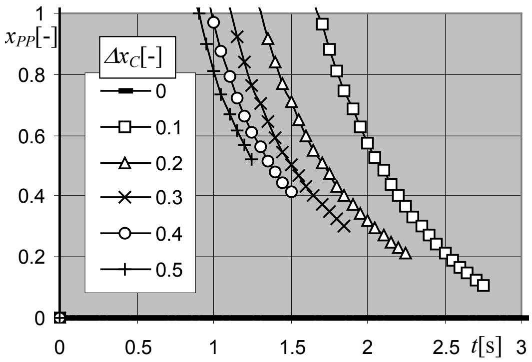

Figure 2. Ship's pivot point during the work of fender.

The ship's kinematic behaviour during berthing as experienced within the scope of the simulation experiment (see Section 2) is summarised in Table 4a and 4b, except for the run R0 that is similar to R1 in output. The subscripts '0' and '1' relate to the condition before and after the first impact, the indices '2' and '3' deal with the second impact accordingly (if applicable). Time t_2 is the moment of beginning the second impact as counted from the start of the first impact. The parameter dE_3 stores the released (absorbed) energy during the second impact. Though the first impact in the bow-in berthing can affect up to maximum three particular forward fenders, see the last row in Tables 4a and 4b, the second impact is somehow a continuous pressing of all fenders in sequence (strictly related to the hull parallel body), as installed on the berth, commencing from the fenders of the first impact. In this context t_2 indicates the point of time when the ship activates the first aft (negative) fender, see Figure 1. The meaning of other symbols in both Tables is identical to that of Table 3.

Table 4a. Motions and energy absorption - simulation.

	Run no.						
	R1	***A0***	***B0***	***C0***	***D0***	***E0***	***F0***
v_{y0} [m/s]	- 0.1475	-0.1460	-0.1433	-0.1409	-0.1386	-0.1313	-0.1232
ω_{z0} [°/min]	0.00	0.03	0.13	0.33	0.44	0.84	0.83
$\%E_0(\omega_z)$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E_0 [kJ]	195	191	185	181	179	167	162
v_{y1} [m/s]	0.0167	-0.0631	-0.0693	-0.0802	-0.0871	-0.0883	-0.0938
ω_{z1} [°/min]	-2.43	11.86	11.66	11.11	10.74	10.37	9.54
$\%E_1(\omega_z)$	0.49	0.61	0.56	0.46	0.40	0.38	0.29
E_1 [kJ]	5	92	97	107	114	113	124
dE_1 [kJ]	190	99	88	74	65	54	39
$\%dE_1$	0.98	0.52	0.47	0.41	0.36	0.32	0.24
dE_1/E_F	1.94	1.01	0.89	0.76	0.67	0.55	0.39
t_2 [s]	-	11	28	62	100	146	255
v_{y2} [m/s]	-	-0.0505	-0.0597	-0.0406	-0.0366	-0.0303	-0.0268
ω_{z2} [°/min]	-	11.99	10.06	9.78	8.72	7.61	5.93
$\%E_2(\omega_z)$	-	0.72	0.56	0.72	0.72	0.74	0.69
E_2 [kJ]	-	80	72	53	42	31	20
v_{y3} [m/s]	-	0.0287	0.0252	0.0273	0.0241	0.0213	0.0159
ω_{z3}[°/min]	-	2.71	1.69	2.65	2.43	2.08	1.70
$\%E_3(\omega_z)$	-	0.28	0.17	0.30	0.31	0.30	0.34
E_3 [kJ]	-	10	7	9	8	6	3
dE_3 [kJ]	-	70	66	43	35	26	17
$\% dE_3$	-	0.87	0.91	0.82	0.82	0.82	0.83
dE_3/E_F	-	0.71	0.67	0.44	0.35	0.26	0.17
fenders of 1st impact	from -6 to +4	+3, +4, +5	+4, +5	+5, +6	+6	+ 6, +7	+8

The second impact, though very important in certain circumstances, has received in the literature rather less interest so far. (Vasco Costa, 1964, 1968, 1987) gives only some general shiphandling conclusions, probably due to the lack of appropriate simulations tools to perform such a research.

As shown in Table 4a, the higher angles of approaching the berth, while maintaining the same normal velocity, lead to significant drops in the energy dE_1 absorbed by fenders and rotation-related contribution $\%E_1(\omega_z)$ to the remaining energy. Also proportionally lower energy is absorbed within the second impact, see dE_3. The latter is always weaker than the first impact - the hydrodynamic damping of hull motions during a period till the ship is finally reaching the alongside position seems to be responsible for that.

Table 4b. Motions and energy absorption - simulation.

	Run no.						
	B1	***B2***	***B3***	***G0***	***G1***	***G2***	***G3***
v_{y0} [m/s]	0.0000	0.1464	-0.2471	-0.1475	0.0000	0.1485	-0.2486
ω_{z0} [°/min]	-20.13	-39.25	13.53	-0.04	12.77	25.30	-8.54
$\%E_0(\omega_z)$	1.00	0.76	0.12	0.00	1.00	0.56	0.05
E_0 [kJ]	162	807	621	195	65	453	583
v_{y1} [m/s]	0.0671	0.2089	-0.1546	-0.1077	0.0357	0.1828	-0.2010
ω_{z1} [°/min]	-8.71	-24.76	26.28	-10.31	3.31	15.21	-19.53
$\%E_1(\omega_z)$	0.43	0.38	0.56	0.29	0.28	0.24	0.30
E_1 [kJ]	71	636	490	146	16	392	515
dE_1 [kJ]	91	171	130	49	49	61	69
$\%dE_1$	0.56	0.21	0.21	0.25	0.76	0.14	0.12
dE_1/E_F	0.93	1.75	1.33	0.50	0.50	0.63	0.70
t_2 [s]	-	-	11	31	-	-	16
v_{y2} [m/s]	-	-	-0.1095	-0.0787	-	-	-0.1546
ω_{z2} [°/min]	-	-	25.41	-11.25	-	-	-20.60
$\%E_2(\omega_z)$	-	-	0.71	0.48	-	-	0.44
E_2 [kJ]	-	-	365	106	-	-	384
v_{y3} [m/s]	-	-	0.0663	0.0311	-	-	0.0584
ω_{z3}[°/min]	-	-	5.57	-5.02	-	-	-7.75
$\%E_3(\omega_z)$	-	-	0.24	0.54	-	-	0.44
E_3 [kJ]	-	-	52	19	-	-	55
dE_3 [kJ]	-	-	314	87	-	-	329
$\% dE_3$	-	-	0.86	0.82	-	-	0.86
dE_3/E_F	-	-	3.20	0.89	-	-	3.36
fenders of 1st impact	+5	+5,+6	+4,+5	-8	-8	-8	-7,-8

However, when it comes to fender loads the situation is somehow indefinite - dependent on the number of fenders in contact with the ship's hull, the maximum loads (kN) experienced in fenders are approximately as follows: 790(420), 940(400), 680(350), 800(300), 530(280), 620(210) for runs A0÷E0 correspondingly. The first value regards forward fenders during the first impact, while a value in parenthesis refers to aft fenders in the second impact. Some of the these results will be supported later with figures. With reference to the less dangerous second impact similar but only qualitative issues have been known in the literature.

It is worthwhile to report that in all the runs the ship, though keeping its almost parallel position very close to the berth, is unnoticeably and slowly losing the contact with fenders that can be called a slight rebound. It also happens in the parallel approach R1. This effect, basically recognizable by the positive lateral velocity v_{y3} after the second impact (or v_{y1} if only the first impact exists), is surprisingly mostly produced by the implementation of the decompression reaction, though very small as mentioned before. The ship's parallel body over its full length namely collects reactions from a number of fenders that give pretty high force in the aggregate. The induced yaw motion in the berthing R1 is due to the asymmetry of fenders around the midship as simultaneously acting on the ship's parallel body.

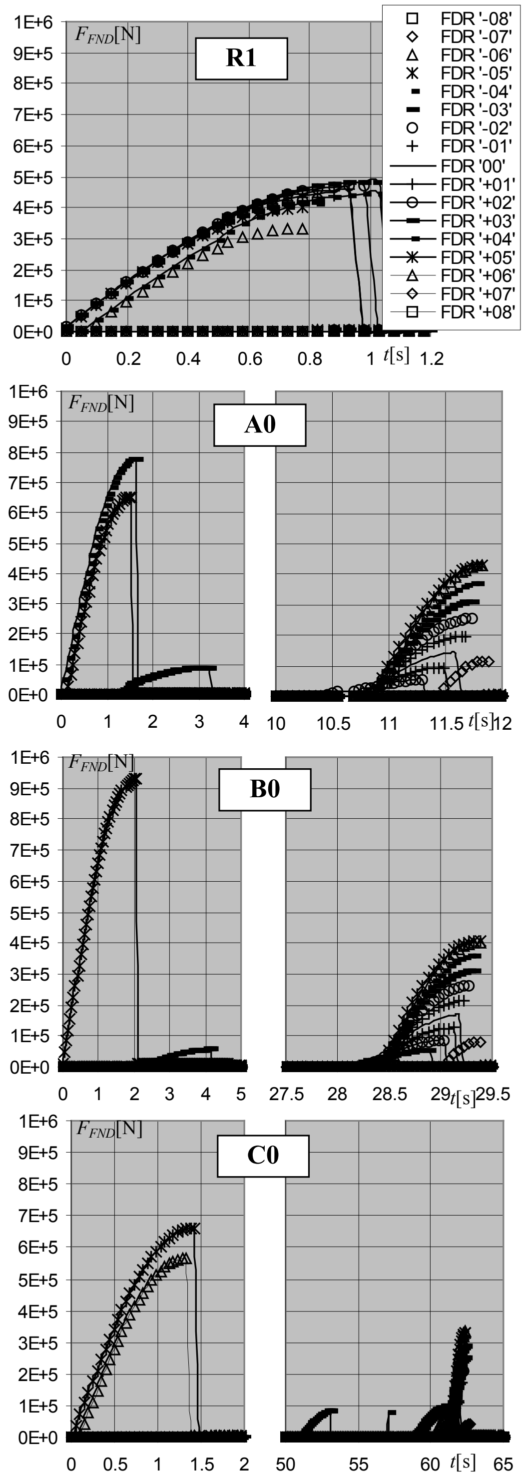

Figure 6. Fender local loads for constant heading parallel and bow-in berthing.

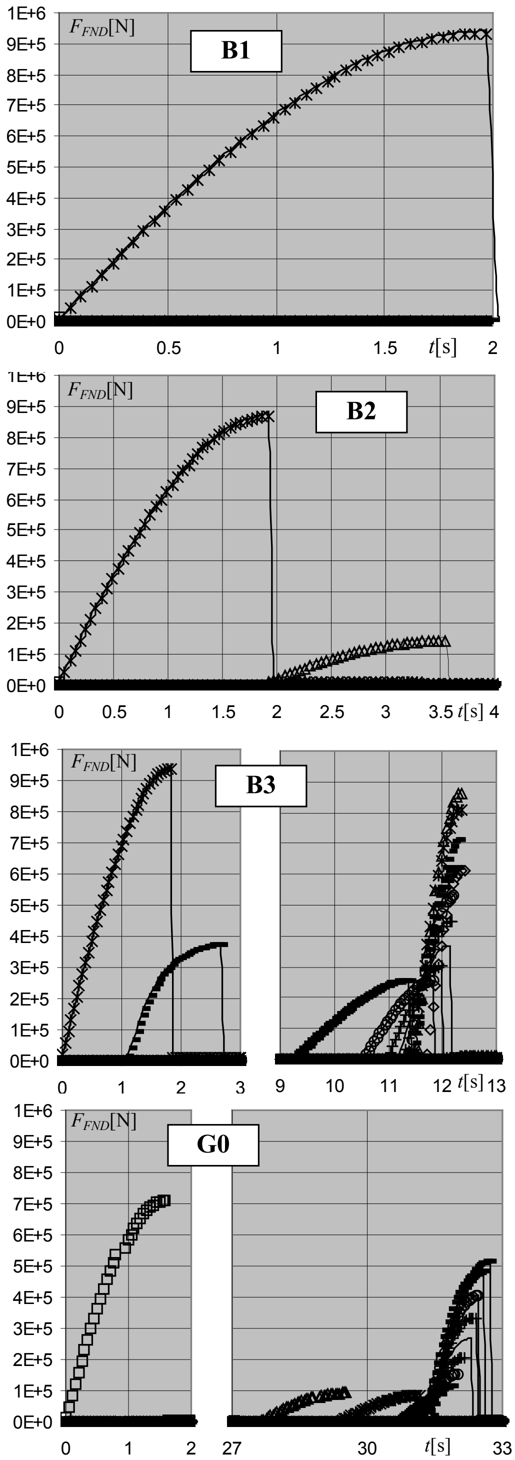

Figure 7. Fender local loads for bow-in berthing with turning and the constant heading stern-in berthing (G0).

It is very interesting that for runs B1 and B2, see Table 4b, dealing with the negative yaw velocity (i.e. turning the bow towards the berth), there is no second impact and the ship leaves the berth with 45% and 80% of the initial energy accordingly. Anyhow in the case of B3 simulation (positive angular movement i.e. the bow tends out of berth) the stern impact in terms of the energy is almost 2.5 times stronger than the bow impact. This is an essential quantitative improvement over the Vasco Costa guidance.

The stronger second impact, as compared with the first one, also arises for the stern-in berthing in variants G0 (a constant heading, oblique approach) and G3 if we are of course considering the energy.

It shall be underlined that the second impact measurement in terms of the absorbed energy is not a reliable and comprehensive indication of the ship-berth interaction, since the number of activated fenders is often unknown if they are continuously (close to each other) distributed along the berth. This is partially shown in subsequent Figures 6-8 where the maximum value 1x10^{6}N at the scale of vertical axis F_{FND}, representing the fender reaction, is nearly the breaking strength of the fender. The general pattern of fender loads in the time domain as presented agrees with the investigations of (Fontijn, 1988).

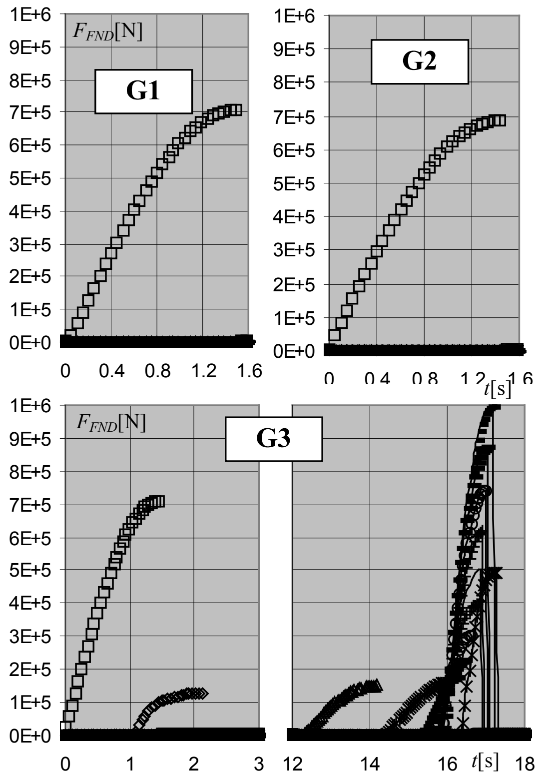

Figure 6. Fender local loads for stern-in berthing with turning.

For the aforementioned run B3 (Fig. 7) the very high reactions in the aft fenders are really very similar in magnitude to those of the first (bow) impact - both take about 90% of the breaking strength, however the stern impact involves quite a large number of fenders that allows to essentially 'resist' the second impact. Moreover, the nearly twice higher absorbed energy in the second impact is even accompanied by 50% reduction of fender loads. Additionally, the five times higher energy of the second impact in run G3 (here made by the bow), Fig. 8, is just connected with 50% increase of the fender load, though in our particular case the latter assumes nearly breaking value.

The maximum lateral speed for parallel berthing in deep water is the speed of run R0, see also Table 4a, that is equal to 0.3m/s(0.6kt). For the assumed fender arrangement this ensures fender loads nearly at the level of their breaking strength. When someone wants to introduce shallow water conditions, the mentioned limit speed is being reduced to 0.52kt, 0.48kt, or 0.42kt if multipliers of order 1.5, 2.0, 3.0 are accordingly applied to the sway added mass. The selected 'reference' velocity for all the peformed simulation runs, see Section 2, at the level of 0.15m/s just ensures the safe berthing under any tested circumstance i.e. without damage to fenders.

4 FINAL REMARKS

The performed research has proved a great potential of simulating the fender local loads, even in real-time, and demonstrated a ready-for-use software environment serving this purpose.

This study has among others revealed that some meaningful discrepancy between the impact (absorbed) energy and local loads in fenders appears. This shall be taken into account when attempts or efforts are made to establish the best shiphandling guidance with reference to the most favorable combination of lateral (linear) and angular velocity for a given ship, fendering system, depth and weather conditions. Such recommendations, if properly applied, should ease both the first and second impact in terms of local loads. Though the latter is often mitigated by the wheel order.

To quantify the observed rebound phenomenon, that is also of practical importance, further investigations have to be planned, where the fully nonlinear real-world fenders are programmed.

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