ANALYSIS OF OFFLOADING OPERATIONS IN FPSO UNITS

Alexandre Teixeira de Pinho Alho
*Department of Naval & Ocean Engineering
Federal University of Rio de Janeiro
e-mail: alho@peno.coppe.ufrj.br

Fernando L. L. Prado*

Abstract. *The cargo offloading operation of tanker ships consists, basically, in a cargo transfer procedure. Since the offloading operation imposes significant effects on the weight distribution of the vessel, the cargo offloading sequence is defined in accordance to both structural and stability requirements. In this sense, the cargo offloading process represents a critical aspect related to the design and operation of tanker vessels. This paper presents the analysis of the offloading operation of a typical FPSO unit. The analysis comprehends the simulation of the operation of the cargo system during the offloading process and the evaluation of the effects on the structural loads. The results obtained indicate that the simulation of the cargo system operation is a useful tool for the analysis of the offloading process both at the design stage and during site operation.*

Keywords. *fluid, networks, design, offshore.*

1. Introduction

The offloading process of FPSO – Floating, Production, Storage and Offloading – units consists basically in a cargo transfer procedure, in which the oil stored inside the FPSO tanks is transferred to the cargo tanks of an another ship, called shuttle tanker. The cargo offloading process of FPSO units is of particular interest due to more stringent operational requirements in relation to conventional tanker vessels.

Since the offloading operation imposes significant effects on the weight distribution of the vessel, the cargo offloading sequence is defined in accordance to both structural and static stability requirements. In addition to structural and static stability requirements, the offloading operation of FPSO units should satisfy rigorous requirements related to the dynamic behaviour of the vessel. Such requirements are related to the dynamic stability of the ship and the maximum loads that can be applied to her mooring system.

Another particular aspect of the FPSO units is that the cargo offloading process is made through a single discharge line to the shuttle tanker. This characteristic imposes a restriction to the offloading flow rate value, since the maximum flow rate is limited by the maximum flow velocity allowed in the main discharge line. This stringent restriction is not observed in conventional tanker vessels since every cargo pump has its own discharge line.

The design of the cargo system of tanker vessels and FPSO units involves several distinct problems. One of them, which usually require a great effort, is related to its functioning, that means the system is able to satisfy the offloading flow rate and the pressure design specifications. Unfortunately, due to the great computation effort usually required to analyze complex pipe networks, it is not a common practice to perform the analysis of the cargo system functioning at the design stage.

This paper presents the analysis of the offloading operation of a FPSO unit. The analysis comprehends the simulation of the operation of the cargo system during the offloading process and the evaluation of the effects on the structural loads. The author adopted a new method to the analysis of pipe networks that seems to be more adequate for the analysis of fully branched systems. The results obtained indicate that the simulation of the cargo system operation is a useful tool for the analysis of the offloading process both at the design stage and during site operation.

2. Cargo System Modeling

In a recent work (Alho, 2001), the author proposes a new method to solve the problem of the analysis of pipe networks. In this method, the network topology is described using a subsystem representation that seems to be more adequate for the analysis of fully branched systems.

The proposed method is based on modeling the pipe network as a set of simultaneous subsystems. A subsystem is formed by a set of pipes, or elements. Each subsystem connects an inflow node to an outflow node of the system. A node represents the endpoints of an element.

The analysis of pipe networks is based on the simultaneous application of the principles of mass conservation and energy conservation. For any given pipe network configuration, the principle of the mass conservation establishes that the algebraic sum of the inflows and outflows at a node must be equal to zero:

$$\sum_{k=1}^{K} I_{j,k} Q_k = 0 \qquad (1)$$

where Q_k = the flow rate of the element k and $l_{j,k}$ = a constant that represents the incidence of the element k in relation to the node j.

Considering a steady state flow of an incompressible fluid, the principle of energy conservation states that the energy balance, *DE*, in a subsystem i is expressed by:

$$(\Delta E)_i = \sum_{k=1}^{K} a_{i,k} (\Delta E)_k \quad ; \qquad (2)$$
$$(\Delta E)_k = (\Delta P)_k + rg(\Delta z)_k + \frac{1}{2} r(\Delta V^2)_k + (\Delta l_T)_k - h_k = 0$$

where P = the static pressure, z = the elevation of a node, V = the flow velocity, Dl_T = the total head loss and h = the energy added by a pump. In Equation 2, r represents the fluid density and g the acceleration of gravity. The term $(DE)_k$ represents the energy balance in a single pipe element k. The coefficient ai,k is equal to unity if the pipe element k is one of the elements that forms the subsystem i. Otherwise, ai,k is equal to zero.

The total head loss load in each pipe element k can be expressed by:

$$(\Delta l_T)_k \cong C_{Dk} Q_k^m \qquad (3)$$

where C_D represents the total head loss coefficient. The values of C_D and the exponent m are obtained by appropriate formulations, based on flow characteristics. For the case of flow of liquids, the total head loss can be estimated by Darcy-Weisbach formulation:

$$\Delta l_T = f\left(\frac{L + L_E}{D}\right)\frac{Q^2}{2gA_T^2} \qquad (4)$$

where f = friction factor, L = length of the pipe, L_E = equivalent length of fittings and valves, D = internal diameter and A_T = cross sectional area of the pipe. A pipe element can be equipped with one or more pumps. The head supplied by the pump to the fluid can be appropriately represented by a function of the type:

$$h = f(Q) \qquad (5)$$

where the function $f(Q)$ and its respective coefficients can be determined from the performance curves of the pump.

Combining the equations of mass conservation, Equation 1, with the equations of energy conservation, Equation 2, a system of equations is obtained, whose unknowns represent the flow rate in each pipe element k. The solution of the system of equations represents the flow rate distribution in the system for a given operation configuration. In systems equipped with pumps, the pump flow rate is given directly by the value of the corresponding pipe element.

3. Cargo System for Analysis

The present study was developed using as reference the cargo system of a FPSO unit with 2.0 million-bbl (329,600 m^3) storage capacity. It consists of FPSO unit that has a total of 15 cargo tanks to store the crude oil production. The total volume offloaded from the vessel represents approximately 75% of the total storage capacity. The cargo system is equipped with three centrifugal cargo pumps, with a total offloading rate of 10,575 m^3/h.

The original planning of the offloading operation of the unit in study is presented in Tab. 1. The operation is divided in two sets of cargo offloading steps. Both sets consist of a 12 hour cargo transfer operation for a shuttle tanker. Each hour represents one step of the offloading operation. It was assumed that both shuttle tankers have identical storage capacity.

4. Offloading Operation Analysis

The analysis of the offloading operation was based on the modeling of the cargo system as a set of simultaneous subsystems, in which each subsystem represents a set of pipe elements that connects a cargo tank to the system manifold. In doing so, a specific model was generated for each offloading step.

The simulation results are shown in Tab. 2. Figure 1 shows the total average flow rates for each offloading step. As shown in Fig. 1, the average flow rates during the first part of offloading operation are higher than the values established in the original planning. As a consequence, the operation of some tanks finished earlier than the time scheduled. This effect is particularly significant with tanks 3P/S and 3C. In these cases, the operation time was reduced in 78 min and 125 min, respectively.

Table 1: Original offloading planning.

	Tank														
Step	1 P	1 C	1 S	2 P	2 C	2 S	3 P	3 C	3 S	4 P	4 C	4 S	5 P	5 C	5 S
1	1762	0	1762	0	1762	0	0	0	0	0	1762	0	1762	0	1762
2	1762	0	1762	0	1762	0	0	0	0	0	1762	0	1762	0	1762
3	0	0	0	1762	0	1762	881	1762	881	1762	0	1762	0	0	0
4	0	0	0	1762	0	1762	881	1762	881	1762	0	1762	0	0	0
5	0	3525	0	0	0	0	1762	0	1762	0	0	0	0	3525	0
6	1762	0	1762	0	1762	0	0	0	0	0	1762	0	1762	0	1762
7	1762	0	1762	0	1762	0	0	0	0	0	1762	0	1762	0	1762
8	0	0	0	1762	0	1762	881	1762	881	1762	0	1762	0	0	0
9	0	0	0	1762	0	1762	881	1762	881	1762	0	1762	0	0	0
10	0	3525	0	0	0	0	1762	0	1762	0	0	0	0	3525	0
11	1175	1175	1175	0	0	0	1175	1175	1175	0	0	0	1175	1175	1175
12	0	0	0	1175	1175	1175	0	0	0	1175	1175	1175	0	0	0
13	1762	0	1762	0	1762	0	0	0	0	0	1762	0	1762	0	1762
14	1762	0	1762	0	1762	0	0	0	0	0	1762	0	1762	0	1762
15	0	0	0	1762	0	1762	881	1762	881	1762	0	1762	0	0	0
16	0	0	0	1762	0	1762	881	1762	881	1762	0	1762	0	0	0
17	0	3525	0	0	0	0	1762	0	1762	0	0	0	0	3525	0
18	1762	0	1762	0	1762	0	0	0	0	0	1762	0	1762	0	1762
19	1762	0	1762	0	1762	0	0	0	0	0	1762	0	1762	0	1762
20	0	0	0	1762	0	1762	881	1762	881	1762	0	1762	0	0	0
21	0	0	0	1762	0	1762	881	1762	881	1762	0	1762	0	0	0
22	0	3525	0	0	0	0	1762	0	1762	0	0	0	0	3525	0
23	1175	1175	1175	0	0	0	1175	1175	1175	0	0	0	1175	1175	1175
24	0	0	0	1175	1175	1175	0	0	0	1175	1175	1175	0	0	0

Table 2: Simulation Results.

	Tank															
Step	1 P	1 C	1 S	2 P	2 C	2 S	3 P	3 C	3 S	4 P	4 C	4 S	5 P	5 C	5 S	Dif (%)
1	1815	0	1815	0	1815	0	0	0	0	0	2110	0	2022	0	2022	9,67
2	1804	0	1804	0	1838	0	0	0	0	0	2027	0	1955	0	1955	7,65
3	0	0	0	1831	0	1831	1297	1840	1297	1989	0	1989	0	0	0	14,16
4	0	0	0	1815	0	1815	1281	1759	1281	1930	0	1930	0	0	0	11,69
5	0	3603	0	0	0	0	1924	0	1924	0	0	0	0	3603	0	4,54
6	1787	0	1787	0	1845	0	0	0	0	0	1962	0	1895	0	1895	5,63
7	1766	0	1766	0	1839	0	0	0	0	0	1908	0	1839	0	1839	3,61
8	0	0	0	1778	0	1778	1223	2575	1223	1857	0	1857	0	0	0	16,23
9	0	0	0	1763	0	1763	1214	2051	1214	1817	0	1817	0	0	0	10,05
10	0	3505	0	0	0	0	1286	0	1286	0	0	0	0	3505	0	-9,40
11	1053	1117	1053	0	0	0	0	0	0	0	0	0	514	1117	514	-49,22
12	0	0	0	1038	888	1038	0	0	0	632	218	632	0	0	0	-36,92
13	1653	0	1653	0	1700	0	0	0	0	0	1973	0	1840	0	1840	0,79
14	1642	0	1642	0	1722	0	0	0	0	0	1891	0	1773	0	1773	-1,25
15	0	0	0	1651	0	1651	1169	2602	1169	1791	0	1791	0	0	0	11,82
16	0	0	0	1641	0	1641	1158	2237	1158	1739	0	1739	0	0	0	6,97
17	0	3360	0	0	0	0	1744	0	1744	0	0	0	0	3484	0	-2,30
18	1624	0	2031	0	1726	0	0	0	0	0	1827	0	1306	0	1713	-3,29
19	1600	0	1658	0	1718	0	0	0	0	0	1774	0	1600	0	1658	-5,34
20	0	0	0	1609	0	1609	1104	2694	1104	1674	0	1674	0	0	0	8,47
21	0	0	0	1591	0	1591	1094	693	1094	1633	0	1633	0	0	0	-11,80
22	0	3263	0	0	0	0	1649	0	1649	0	0	0	0	3258	0	-7,15
23	1705	1602	1240	0	0	0	307	0	307	0	0	0	1705	1483	1240	-9,31
24	0	0	0	1734	1359	1734	0	0	0	1387	760	1387	0	0	0	18,59

The effects of these discrepancies on the cargo weight distribution are showed in Fig. 2. As can be noted, the total accumulated difference in cargo weight during the first part of the offloading operation is always negative (Steps 1 to 12). This fact indicates that the cargo weight at the end of each step is always lower than the planned values. The most critical situation occurred in Tank Region #3. In this tank region, it is observed an accumulated cargo weight of 7,482 t lower than the expected value at the end of step 9.

The opposite situation is verified during the second part of the offloading operation (Steps 13 to 24). The results obtained for these steps indicate a clear trend of reducing average flow rates, as can be seen in Fig. 2. A negative accumulated difference in cargo weight during this second part is only observed in Tank Region #3, which showed again higher average flow rates. The lower flow rates observed during the second part of the offloading operation result in a longer operation time for some cargo tanks. This is the case of cargo tanks 1P/S and 2 P/S. Theoretically, the operation of these tanks demands more than 12 hours to be finished. These effects are somewhat expected, and can be explained by the variation of the cargo level inside the tanks during operation. In the first part of the operation, the high liquid column decreases the total head of the cargo pumps, which results in higher pump flow rates. However, during the second part, the lower liquid column heights cause an opposite effect.

The simulation results indicate minor discrepancies in the accumulated difference of cargo weight at the tank regions #1 and #2 when compared with the others tank regions. This can be explained as a consequence of the higher distance between these tanks and the pump room. The larger the length of a pipe, the higher its head loss will be. Consequently, the tanks located at these regions operate at lower flow rates. Therefore, the effect of increasing the flow rate as a result of a high liquid column at pump suction is somewhat minimized by the higher head loss observed between the tanks located at regions #1 and #2 and the pump room.

The results obtained with the analysis of the cargo offloading operation showed significant differences in relation to the flow rate distribution established in the original planning. Since the weight distribution of the vessel is directly influenced by the offloading flow rates, the effect of these discrepancies is that the original structural loading and stability analysis is no longer valid. The effect of the discrepancies in flow rate distribution on the structural loads of the vessel is illustrated in Fig. 3 and Fig. 4. Figures 3 and 4 show, respectively, the bending moment and the shear force diagrams related to the weight distribution at the end of step 9. It can be observed a difference of approximately 13% between the maximum value of bending moment expected by the original structural analysis and the one obtained based on the simulation results.

These results indicate that the flow rate of the system should be balanced so that the offloading operation can be executed as originally planned. A solution for this problem is to control the flow rate of each tank by valve stroking. This alternative represents a simple and effective solution to this problem. However, the adjustment of the flow rate by valve stroking represents a loss of energy. Another alternative to solve this problem is to control the flow rate by changing the cargo pump speed. Although this is a possible alternative, it demands higher skills to the operators and it depends on system resources to be an effective solution. On the other hand, with the aid of a simulation tool, it is possible to optimize the offloading operation. Also, a simulation tool can be used to optimize the design of the cargo system itself, seeking to minimize the discrepancies between the original planning and the results observed in site operation.

5. Conclusions

In this paper, a proposed pipe network analysis method was applied for the analysis of the cargo offloading operation of a FPSO unit. The results obtained indicate that the simulation of the offloading operation can be used to find possible discrepancies between the original planning and the real behavior of the cargo system during site operation. In this sense, a simulation tool is particularly useful for the planning of the cargo offloading sequence, as well as for the design of the cargo system itself.

In addition, the resources offered by a simulation tool can be also used for the analysis of the cargo system under new operational conditions. An offloading simulation tool can be also applied to the development of specific training software.

6. References

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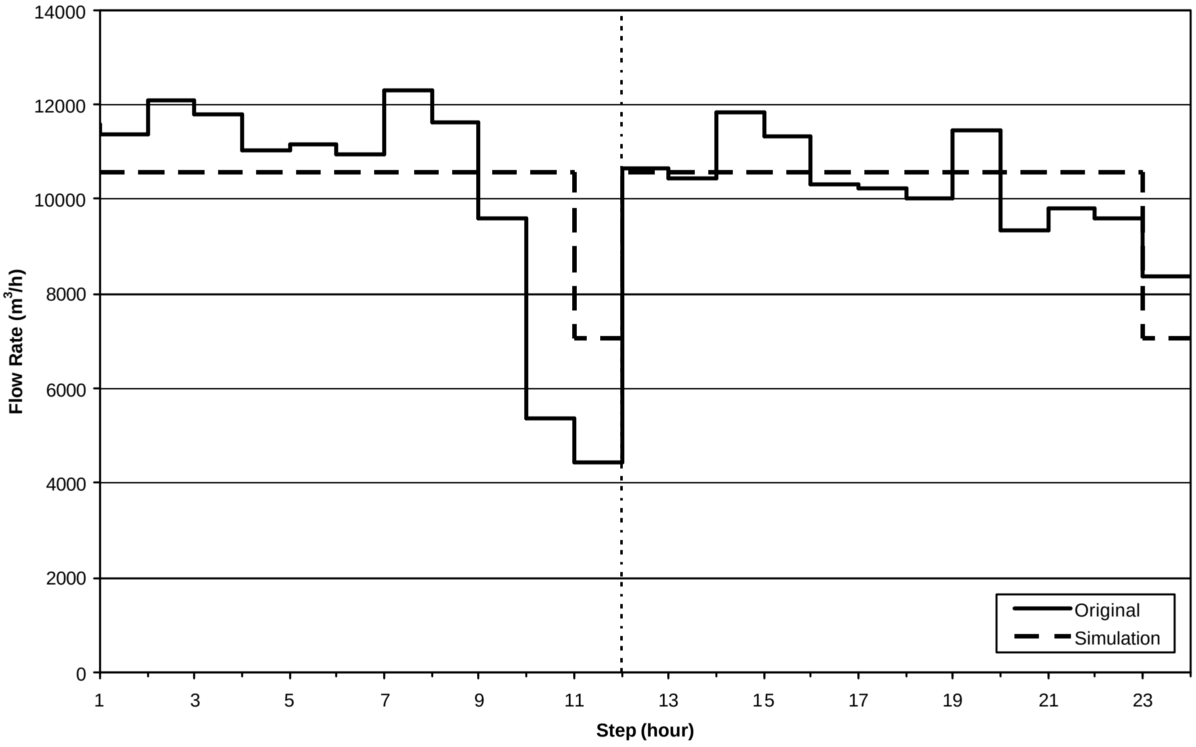

Figure 1: Average total flow rate in each offloading step.

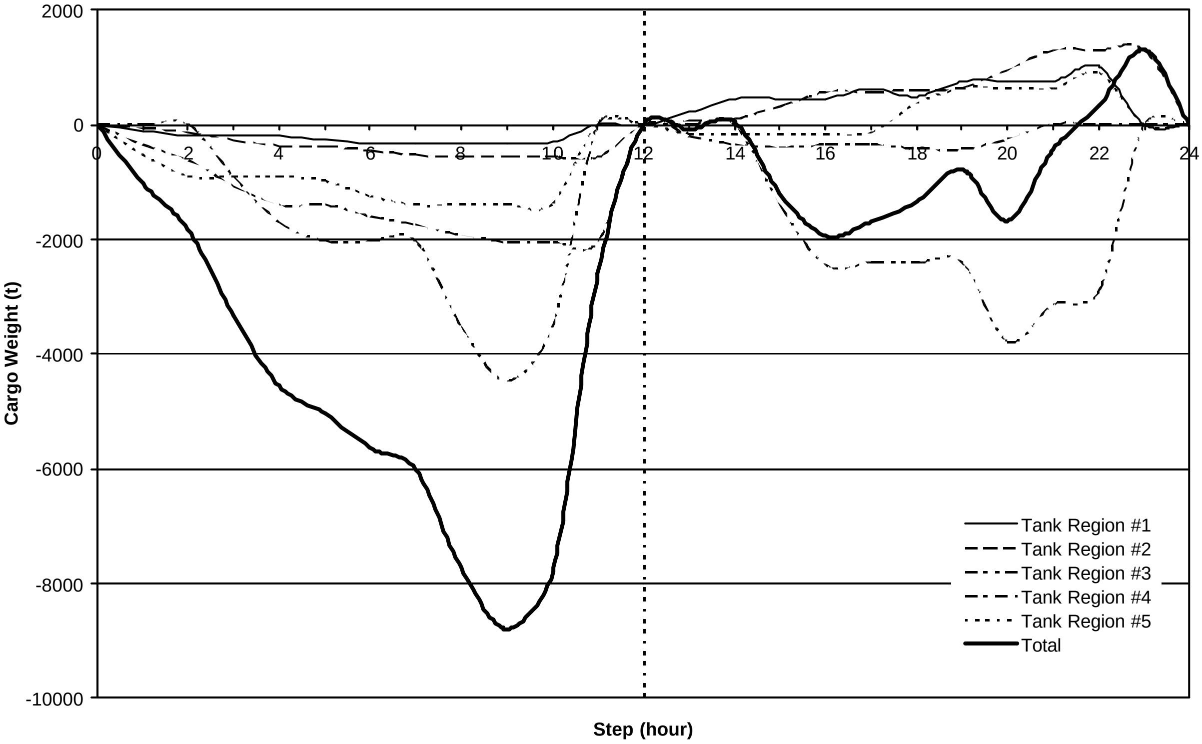

Figure 2: Accumulated difference in cargo weight.

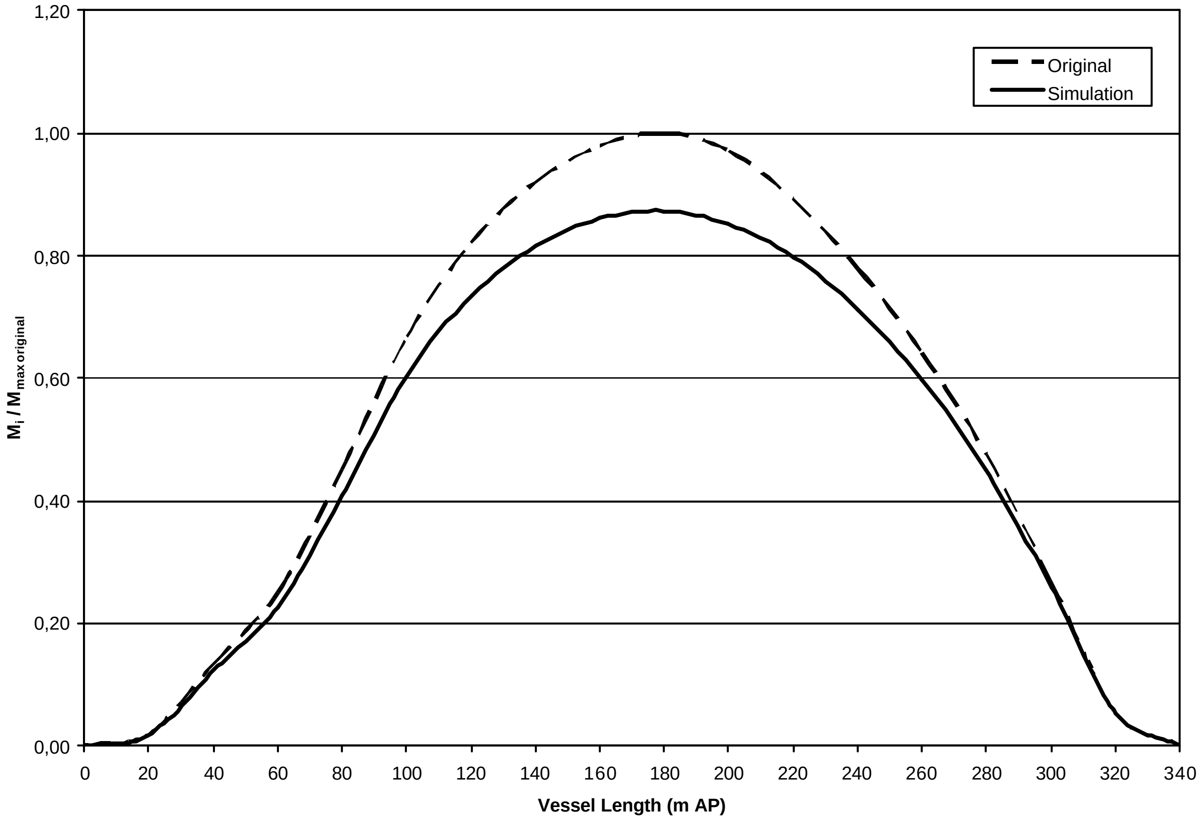

Figure 3: Bending moment after step 9.

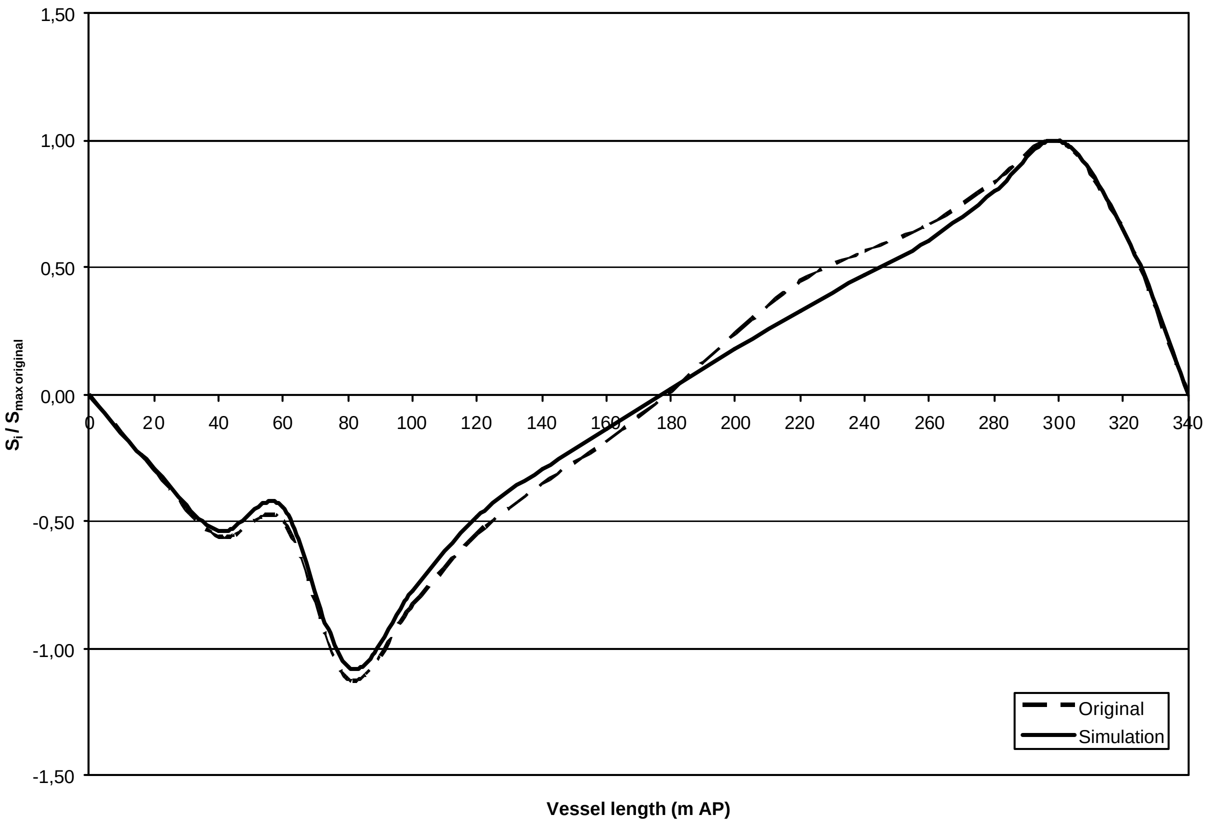

Figure 4: Shear force after step 9.