SMART SILO STRUCTURES

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ABSTRACT

To investigate the effect of silage and vehicle loads on walls of bunker silos, a smart silo, equipped with different strain and displacement sensors was constructed. Data were recorded during and after filling of the silo with chopped maize. The deformations of straight and L-shaped wall panels, measured with dial indicators and linear variable displacement transducers (LVDTs), were much higher than those predicted from load combinations mentioned in literature. The main increase in displacements, occurred after filling of the silo above a height of 1.5 m. Also the strains, measured with mechanical deformeters, fibre Bragg grating sensors and strain gauges, mainly increased during the second half of the filling process. The strains at the outer surface of the walls of the completely filled silo, evolved from around -100 microstrain at the base to +50 microstrain at the top. The negative strains at the base of the outer wall surface nearly doubled during the week after the ensilage procedure, but no further increase of strains was noticed afterwards.

INTRODUCTION

Forage such as chopped maize and grass is mainly stored in horizontal silos, existing of a concrete plate and walls up to 4 m high. Floor and wall elements can be cast in place or prefabricated. Prefabricated wall elements are supplied as (1) straight panels with holes in the lower part for positioning of reinforcement and connection to a floor plate cast *in situ* or (2) L-shaped panels. No specific Belgian or European standards are available dealing with load combinations and methods to be applied for calculation of the necessary reinforcement and dimensions of the elements. Some other national standards or guidelines (HBRM, 1991; DIN 11622, 1993; BS 5502, 1993) refer to certain research results to prescribe load combinations, but seem to have been insufficiently validated in practice. The load on the silo walls has a quite complex character: apart from the load exerted by the stored forage (which depends on the type of forage, dry matter content, compaction, etc.), also the tractors and wagons used for filling and compaction of the forage are to be taken into account. Also the unloading situation is complex, because the feed is removed in steps. The Dutch HBRM (1991) advises, based on research by ‘t Hart (1980), to simulate these effects for wall heights between 1 and 2.5 m, by a combination of a variable horizontal load of (4+5.5 z) kN/m² (z being the distance to the top along the panel height) and a horizontal line load of 2.5 kN/m acting at 0.6 m below the top of the panel. The German DIN 11622 (1993) refers to Swedish research by Kangro (1986). Here a load by the silage of (7+2.5 z) kN/m² is combined with a vehicle load represented by a linear load of 2 kN/m and 2 point loads of 6 kN at a distance of 2.8 m, both acting 0.5 m below the top of the panel (Martens, 1988 & -). Langley (2000) refers to British standard BS 5502: Part 22 (BSI, 1993). Here the load by the silage is represented by a uniformly distributed lateral load of 3.9 kN/m² and a depth dependent side loading which is not specified, but in an example is set to 11.7 kN/m² at the base of a 3 m high wall (thus 3.9 z kN/m²). The wheels of the consolidating vehicle, when adjacent to the wall, generate two

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horizontal loads acting on an area of 0.6 by 0.6 m, with centres 0.6 m below the surface and 2 m apart along the wall. In an example each of these loads is set to 4 kN.

Thus, although there seems to be a reasonable consensus about the type of loads acting on a silo wall, there are quite some differences in the actual values to be used. Different manufacturers may therefore produce panels with a totally different load capacity for the same purpose. Underestimation of the loads, and the pressure to gain an economic advantage, may result in cracking, possible leakage of silage effluent and even failure of wall elements. This does not only cause great material losses, but also impairs the safety of the farmer.

MATERIALS AND METHODS

Silo construction

To get a better insight in the loads acting on walls of horizontal silos, a new silo (length = 27 m, width = 9 m) was constructed at the experimental farm of Ghent University, with straight panels (length = 3 m, height above floor level = 2.05 m, thickness = 0.16 m) at one side and L-panels (length = 4 m, height above foot = 1.85 m, thickness = 0.10-0.15 m) at the other side. This allows analysing both panel types at the same time and under similar load conditions. The panels contained steel reinforcement as normally applied by the producers of those elements. For experimental purposes, the straight panels were constructed with concrete of a somewhat lower strength than usual. To obtain information on the real deformations and strains, a panel of each type located in the middle of the silo wall, was equipped with different sensors.

Displacement measurements

The displacements were measured with dial indicators and LVDTs (linear variable displacement transducers). The dial indicators were positioned in three vertical rows: in the middle and at the edge of the main measurement panel and at the edge of the adjacent panel (Fig.1). The indicators at the lower end of the panel had as a main objective to check if the panels could be considered as cantilever constructions. All indicators were attached to a stiff metal frame which was bolted into the floor outside the silo. To get accurate measurements which are not affected by the concrete roughness, small metal plates were glued to the concrete at the position of the indicators. As a control and to obtain continuous displacement measurements, an LVDT was positioned near the dial indicator at the top of the middle row of each panel type.

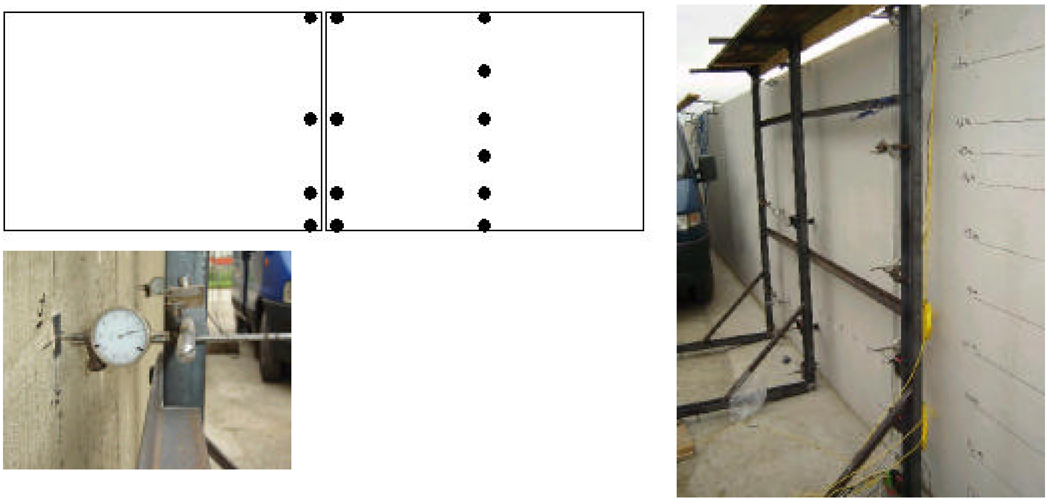

Fig. 1. Location of dial indicators on the measurement panels

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Strain measurements

Strains were measured both with traditional methods such as strain gauges and mechanical deformeters (type Demec), and with internal fibre Bragg grating (FBG) sensors. These internal fibre optic strain sensors, based on fibre Bragg gratings have been developed at the Magnel Laboratory for Concrete Research and have already been implemented in several cases for continuous monitoring of structures (Moerman, 2001; Matthys & Taerwe, 2003; Moerman et al., 2005). The strain sensor consisted of a steel rebar of 0.9 m length with a narrow groove, in which a Bragg grating sensor was glued. At the opposite side a thermocouple was attached to allow temperature compensation. When broadband light is coupled in the fibre, the grating will reflect light centred around one wavelength, called the Bragg wavelength. The Bragg wavelength depends on the average refractive index of the core of the fibre and on the period of the grating. When the sensor is subjected to strain, the period of the grating will change and hence the peak wavelength of the reflected spectrum will shift. From the measured peak wavelength, the strain applied to the sensor (and to the construction at this location) can be retrieved. Advantages of FBG sensors are the possibility of absolute strain measurements, the immunity to electromagnetic interference and corrosion and the possibility for multiplexing. Four FBG sensors were installed in the two measurement panels as show in Fig. 2. They were mainly positioned near the middle of the main measurement panels, at the internal side of the silo wall where other devices such as mechanical deformeters could not be used during forage storage, and mainly near the lower edge where the largest strains are expected.

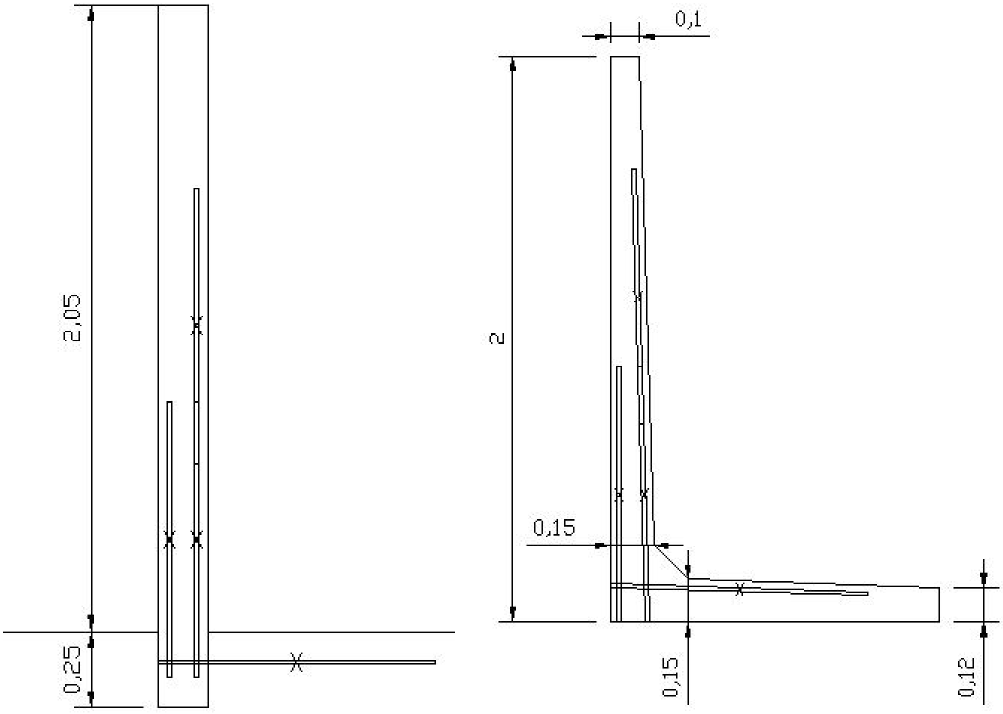

Fig. 2. Position of the FBG sensors in the measurement panels

The measurement points for the mechanical deformeters (type Demec) were glued on three vertical rows near the dial indicators (Fig. 1) and on a horizontal row at a height of 0.45 m above floor level. The gauge length of the deformeters is 0.2 m.

Strain gauges were glued on the concrete close to the FBG sensor positions and near the connection floor-wall, as well as on the FBG sensor bars in the L-panel.

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Filling of the silo

The silo was filled with chopped maize on 28 and 29 September 2004. The dry matter content of the chopped maize amounted to 30 %. Three different tractor - wagon combinations were used to fill the silo. The empty combinations weighed between 133.1 and 146.0 kN and the heaviest combination with filled wagon, was 234 to 267 kN, depending on the level of filling. A tractor of 73.6 kN was used to compact the forage. The sequences in the ensilage process are illustrated in Fig. 3. During the ensilage process, different recordings were made, called P- and R-measurements.

The P-measurements were made with the tractor plus wagon in a fixed position (Fig. 4): (a) tractor close to the wall (0.2 – 0.7 m) and the rear axle of the tractor near the middle of the measurement panel; (b) tractor close to the wall (0.2 – 0.7 m) and first rear axle of the wagon near the middle of the measurement panel; (c) same as (b) but tractor at a distance of 1.2-2.0 m from the wall. During P-measurements, all dial indicators and mechanical deformeters were measured manually and the values from FBG sensors, LVDTs and strain gauges were registered electronically. During the ensilage process, 18 P-measurements were performed, 9 at each side of the silo. Immediately after each P-measurement, a reference measurement without tractor was made. Furthermore, the time effect after filling was quantified by recording the same data (except for the dial indicator measurements) at 7/10/04 and 28/10/04.

The R-measurements (runs) included the continuous registration of data from FBG sensors, LVDTs and strain gauges, from the arrival of a tractor plus wagon, to the arrival of the next tractor plus wagon. During the ensilage process, 12 R-measurements were performed.

Fig. 3. Different stages in the ensilage process

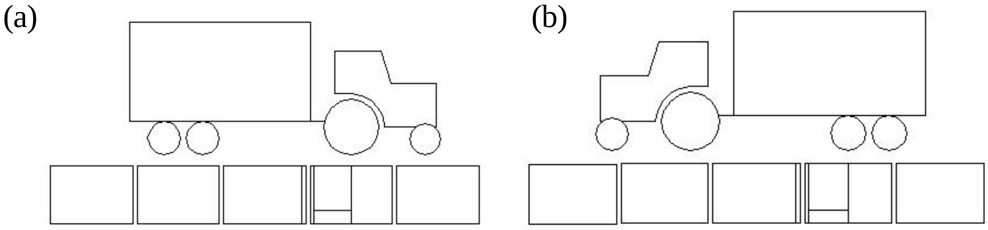

Fig. 4. Vehicle positions during the P-measurements: (a) and (b) with vehicle close to the silo wall (0.2-0.7 m), and (c) identical to (b) but with vehicle 1.2-2 m from the wall

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RESULTS AND DISCUSSION

Precalculation

The load combinations prescribed by ‘t Hart (1980) and Martens (-) were used to estimate the displacements of the considered wall panels for a completely full silo (Fig. 5). The silo wall construction was regarded as a cantilever as put forward by Langley (2000) (the construction in his example is somewhat different, namely universal beam stanchions with concrete panels slotted between them). For the E-moduli the actual values of 38110 N/mm^2 for the straight panels and 35134 N/mm^2 for the L-panels were used. Apparently the expected displacements were much higher for the L-panel (having a lower wall thickness) than for the straight panel and the prediction by Martens (-) led to 25-35% higher values than the prediction by ‘t Hart (1980). Comparing the estimated moments with the cracking moment for concrete with a flexural tensile strength f_{ctfl} = 8.73 N/mm^2 for the straight panels and f_{ctfl} = 9.19 N/mm^2 for the L-panels (actual values), it seemed that cracking of the concrete would not happen, even for a completely filled silo and when a tractor load is present (Fig. 6).

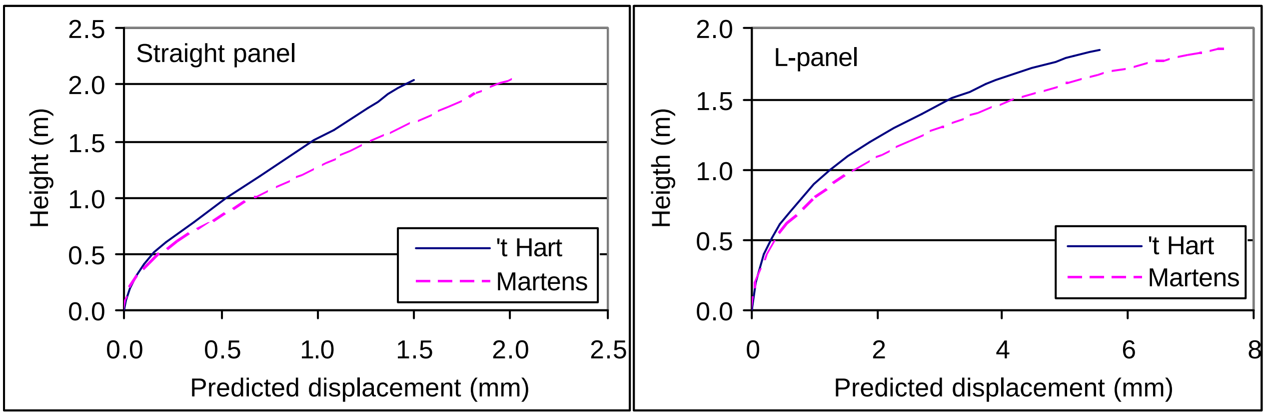

Fig. 5. Predicted displacements in uncracked condition for the two panel types using the load combinations mentioned by ‘t Hart (1980) and Martens (-), in the case of a completely filled silo

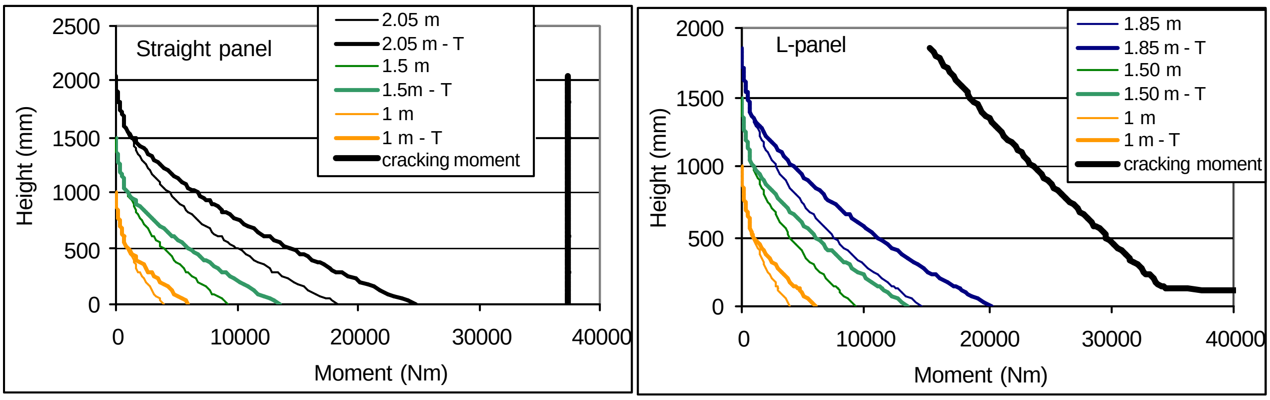

Fig. 6. Cracking moment and predicted moments for the two panel types using the load combinations by Martens (-), for different filling heights and considering the possible presence of a tractor load (T)

Displacement measurements

Fig. 7 shows the displacements recorded by the dial indicators in the middle of the two different panels for the empty to half-filled (1.1-1.2 m) silo (28/09/04) and for the half-filled to completely filled (2.1-2.3 m in the middle) silo (29/09/04). All these are displacements at times when no tractor load is present. The displacements at the two other rows were of the same order of magnitude. Only for the L-panel the dial indicators on the panel adjacent to the

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main measurement panel, showed an unexpected inward displacement during the first measurement day. This could be due to an unstable initial positioning of the L-panels, making them tilt inwards due to the load of tractor and forage. Afterwards the normal outward displacement could be observed. The displacements were much larger for the L-panels than for the straight panels: final values at the top of the panels were 12-14 mm and 3-3.5 mm, respectively. For both wall types, the displacements at the top were about 1.75 times as high as predicted by Martens (-) and 2.35 times as high as predicted by 't Hart (1980). The relatively large deformations at the lower part of the wall elements and the nearly linear change with height, indicate that the elements may act partially as cantilevers. The effect of the position of tractor and wagon and their distance to the wall was not so clear. Mostly the effect of the additional compaction by the repositioning of the tractor resulted in an increased displacement, regardless of the difference between old and new tractor position.

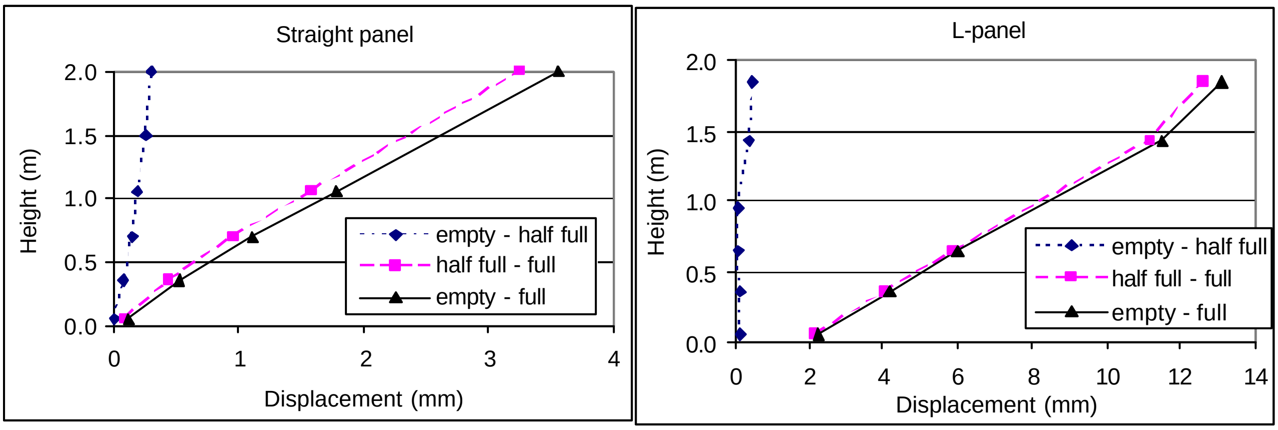

Fig. 7. Displacements recorded by the dial indicators in the middle of the two main panels

The LVDT at the top of the middle row showed values very similar to the adjacent dial indicator for the straight panels and consistently lower values than the dial indicator for the L-panels (10.5 mm instead of 13.0 mm at complete filling). Figs. 8-9 show the LVDT measurements during the different runs, with an indication of the filling height. This confirms that the displacements remain small when the filling height is less than 1.5 m, but they increase more rapidly at larger filling heights.

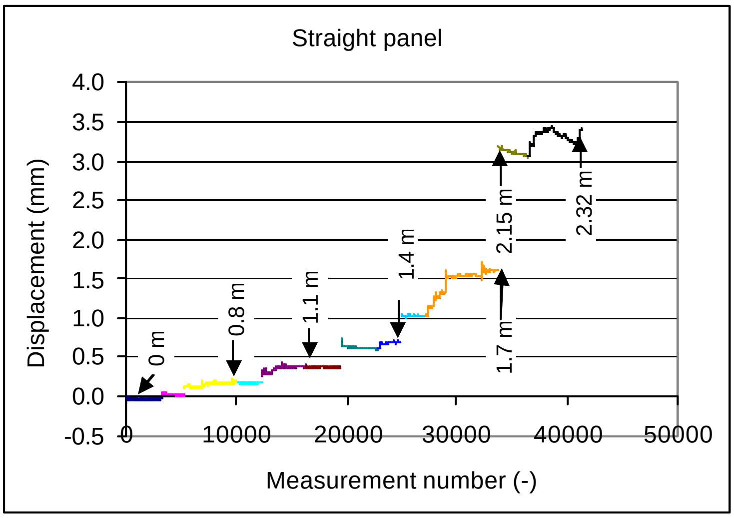

Fig. 8. LVDT measurements on the straight panel during the different runs, with indication of the filling height

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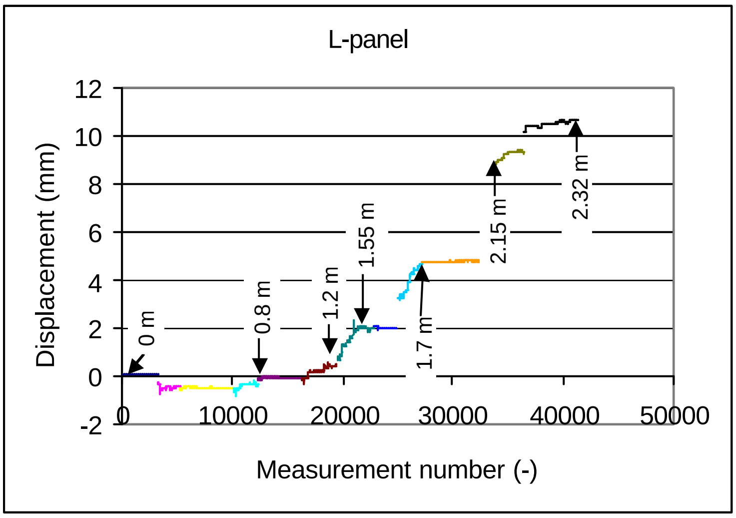

Fig. 9. LVDT measurements on the L-panel during the different runs, with indication of the filling height

Strain measurements

Giving the small strains acting in the panels, compared to the accuracy of the deformeters, the readouts are subject to a relatively large variation. Nevertheless, the overall trend is clear. The measurements for the three vertical rows on the outside of the straight panels (main panel and secondary panel adjacent to the main one) are shown in Fig. 10.

During the first half of the filling procedure, strains fluctuated around zero. Further filling and compression caused an increase in absolute strain values, going from a total strain of around -100 microstrain (compression) near the base, to +50 microstrain (tension) at the top of the wall (perhaps due to temperature change) for a completely full silo. A similar pattern could be noticed for the L-panels. Measurements one week after filling showed that strains at the outer wall surface became more negative, resulting in values of around -200 to -100 microstrain at the base to -170 to 0 microstrain at the top. Measurements one month after filling indicated no further increase in strains (in absolute values), but rather a limited release of the strains.

These observations are confirmed mostly by the continuous measurements with FBG sensors and strain gauges. Fig. 11 shows the output of the FBG sensor in the outer part of the straight panel (near the middle measurement row of the main panel; height above the floor = 0.3 m) during the subsequent R-measurements. The final value of -45 microstrain corresponds reasonably well with the deformeter measurements at this place (in fact it is expected to be somewhat lower than the deformeter measurement since the FBG sensors are located inside the concrete and closer to the neutral axis). As an example the strain gauge measurements at the inner side near the base of the L-panel are shown in Fig. 12. Here the strain at the concrete surface is clearly higher than the strain at the reinforcement level.

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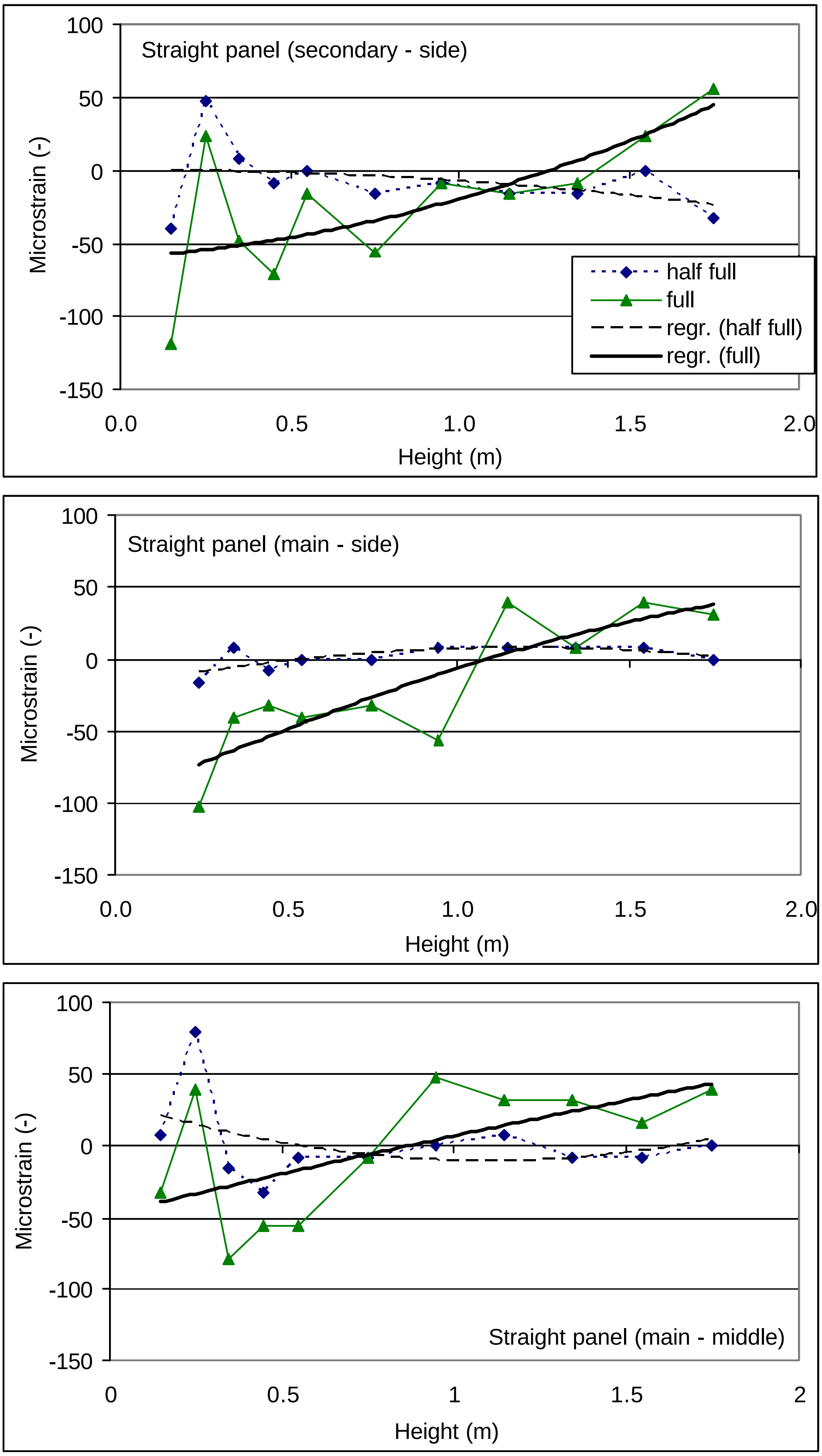

Fig. 10. Strains measured with the mechanical deformeters for the straight panels (outer side)

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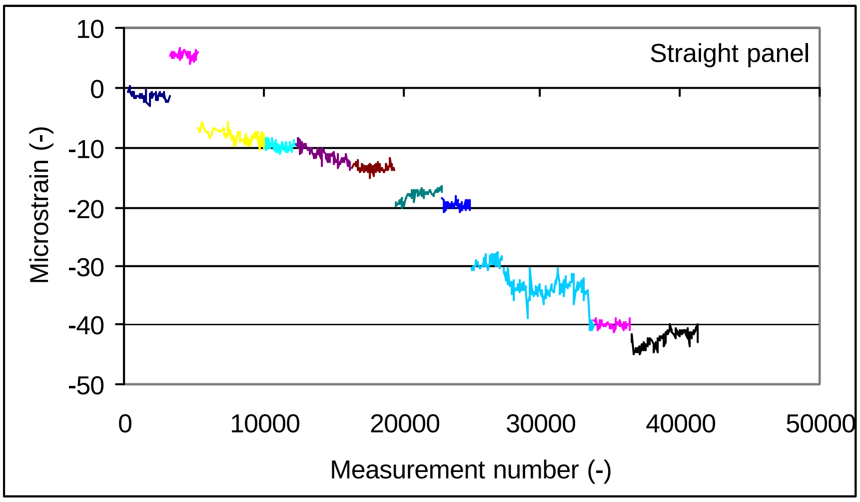

Fig. 11. Change of strain measured with a FBG sensor in the straight panel at a position located near the middle measurement line, at the outer side and 0.3 m above the floor

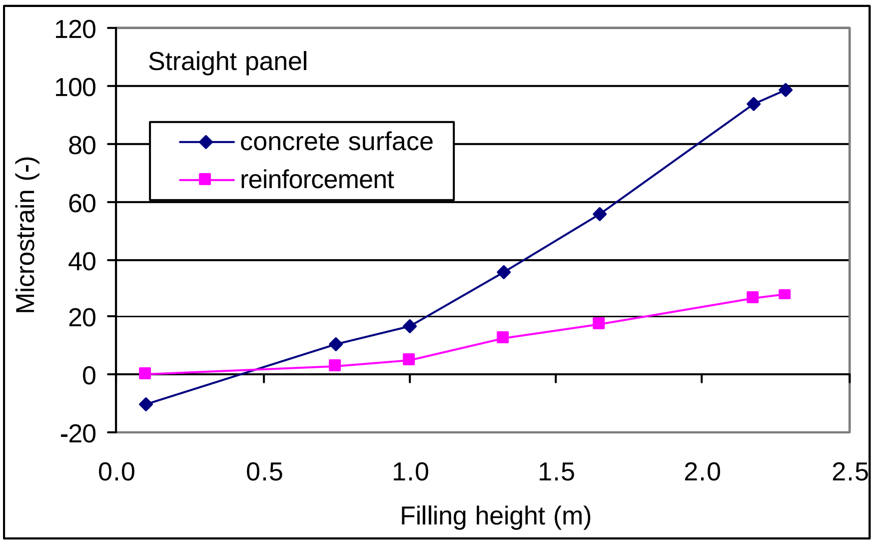

Fig. 12. Change of strain in the L-panel at a position located near the middle measurement line, at the inner side and 0.18 m above the foot

Future research

A further in depth study of the data obtained and a reversed modelling analysis, will allow finding a relation between applied loads and deformations and strains. It is aimed to propose a realistic load distribution to be used in design calculations. By investigation of the strain distribution at different points in the concrete section, the location of the neutral axis could be determined. Based on the measured displacement curves, the restrained end of the wall appears to be partially fixed. Further studies for different silo dimensions and forage types would be useful to validate the obtained results.

CONCLUSION

The deformations of the straight and L-shaped wall panels, were much higher than those predicted from load combinations mentioned by 't Hart (1980) and Martens (-). The main increase in displacements, occurred after filling of the silo above a height of 1.5 m. Also the strains mainly increased during the second half of the filling process. The strains at the outer surface of the walls of the completely filled silo, evolved from around -100 microstrain at the base to +50 microstrain at the top. The negative strains at the base of the outer wall surface nearly doubled during the week after the ensilage procedure, but no further increase of strains was noticed afterwards.

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