BIRCH PLYWOOD SAMPLE CYCLIC BENDING PROPERTY INVESTIGATION AND ANALYSIS

Agris Zalcmanis[1], **Karlis Abols**[2], **Kaspars Zudrags**[2], **Andrejs Krasnikovs**[2]
[1]JSC “Latvijas Finieris” , Latvia; [2]Riga Technical University, Latvia
agris.zalcmanis@finieris.lv, andrejs.krasnikovs@rtu.lv

Abstract. In the present research several thicknesses sanded birch (*Betula sp.*) plywood samples were tested, having fiber directions of surface veneer both in longitudinal and transverse directions, in order to investigate dynamic strength, stiffness and damage accumulation properties. Sample dimensions were according to EN310 for static and also dynamic tests. Low Cycle Fatigue (LCF) 3-point bending tests with single cycle amplitude value not less than 85 % of specimen ultimate bending strength were carried out. Each cycle was characterized by “Quazi” linear load increase and decrease (saw type) and R value close to zero. Experimentally numbers of cycles up to rupture were obtained and corresponding stiffness degradation S-N curves were plotted. Analysis of the results indicates that stiffness degradation is a noteworthy factor to be taken into account when designing plywood structures. The experimental data show – when stiffness degradation occurs, remaining deformation also appears due to damage accumulation. It also shows that when the bending stress is approximately 85 % of ultimate strength, mean numbers of cycles up to rupture vary between 123 and 3490 cycles depending on thickness and lamina lay-up. If the stress level is lowered to 80 % ultimate bending strength, fatigue life should extend to 10000 cycles. Average stiffness degradation varies from 8.9 % to 20.0 % depending on thickness and lamina lay-up.

Keywords: plywood, stiffness degradation, fatigue, bending.

Introduction

Through the last decade, interest has grown to birch (*Betula sp.*) plywood as a material for different structural applications. In automotive industry plywood is commonly used in trailer floors and wall linings, in construction industry in concrete formworks as insulation panels in liquid natural gas tankers and in numerous other structures. Many industry branches need high performance plywood products with high strength to weight ratio.

Speaking about trailer floors, for manufacturers it is especially important to carry out an analytical approach for plywood load bearing capacity and stiffness estimation, in order to minimize mass and maximize static and dynamic load resistance. Plywood floor during exploitation is bearing static anddynamic loads. Static loads arise from weight of the cargo products in situation when the trailer is not moving. One type of the dynamic loads are rising inertia forces of the cargo products in situation when trailer is accelerating or breaking, or riding over uneven surface. Another type of the dynamic loads is created by the forklift truck when it is loading or unloading the cargo container. Latter is the subject of investigation in the present research. Up to 40000 N are transferred from each front wheel of the forklift truck to plywood floor, which is resting on steel crossbars mounted into the chassis of the trailer. Typical span/thickness ratio varies from 12 to 18. After certain cycles of loading and unloading, floor plates are accumulating ultimate level of internal damages, high enough for the necessity to change material preventing a sudden failure.

Manufacturers are specifying simple analytical assumptions for design of plywood constructions subjected to static load conditions. Load duration and service classes, as well as partial safety factors for fatigue verification for different material groups can be found in the Eurocode 5 [1]. Unfortunately, such approach is restricting application of plywood as a contemporary construction material, lifetime evaluation at different stress levels, depending on the plywood internal architecture (lay-up).

To obtain a reliable fatigue curve, it is necessary to determine dynamic strength and stiffness properties of plywood experimentally. J. Zhang et al. [2] carried out fatigue tests with constant displacement with a specially designed air cylinder and pipe rack set-up. Use of multiple cylinders would allow to test multiple specimens simultaneously, thus reducing the total test time. In a particular cases use of constant displacement would not match the actual load case and would not allow to gather information about remaining deformation, also such set-up restricts stiffness degradation estimation, because it is not possible to control the applied force during the experiment. An alternative method, presented by Hiroshi Yoshihara [3], suggested that the compression bending test proved to be effective for measuring the MOE when the length/thickness ratio was larger than 33, because the test method

DOI:10.22616/ERDev.2020.19.TF312

minimizes deflection caused by the shearing force. This method is applicable for quite thin specimens, thus the elastic phenomena can be easily introduced. The authors of the present research are concerned on the thick specimens due to high buckling load, to onset flexure and testing equipment ability to adapt the sudden drop of the applied force (up to2.5 times [3]), failure can occur already in the first cycle. In the present research samples of sanded birch plywood of several thicknesses, with fiber direction of surface veneer in the longitudinal and transverse directions, were tested. Static bending tests were conducted according to EN310 [4]. Low Cycle Fatigue (LCF) 3-point bending tests were conducted with sample dimensions also corresponding to EN310. Analysis of the obtained data indicates that stiffness degradation is a noteworthy factor to be taken into account when designing plywood structures.

Materials and methods

There are two main testing methods used for plywood strength and stiffness determination – EN310 (3-point bending tests) and EN789 (4-point bending tests).S.F. Tsen and M. Zamin Jumaat [5] state that the strength properties obtained using different testing methods are considered to be equivalent. However, the different in test set up may affect the strength properties of the wood-based panel. When testing specimens according to EN789, there is no shear force between loading bars comparing [5] to EN310, where maximum shear force and bending moment concentrate in the middle of the specimen (under the loading bar) [5]. It is expected that fractures will happen there.

According to EN310, the span length/thickness ratio is 20, while for EN789 [6] the distance between an inner load point and the nearest support shall be 16 times nominal thickness, but not more than 400 mm and not less than 240 mm (a – where the shear force is present, Figure 1, right image). The ratio varies from 40 for 12mm samples to 32 for 21 mm samples and decreases with increasing the sample thickness – the ratio is 16 for 50 mm thick plywood. Average planar shear strength of birch plywood depending on the thickness varies from 2.07 MPa to 2.81 MPa [7], while the transverse strength of veneer varies from 2.31 MPa [8] to 4 MPa according to factory production control. The authors are concerned that shearing effect cannot be neglected due to low planar shear and transverse strength. Since the ratio for EN789 is considerably high and thickness dependant, is it assumed that loading conditions according to EN310 with smaller and constant span/thickness ratio are more relevant to actual load case in trailer plywood floors.

In order to determine the plausible starting point for fatigue tests, standard deviation for the ultimate bending strength obtained according to EN310 was calculated for different batches for all panel thicknesses in the range from 4 to 50 mm manufactured from birch (*Betula sp.*) and glued with phenol formaldehyde resin glue. Calculations show that, depending on the batch, all results are within one or two standard deviations. The bending strength varies from 80 % to 85 % of the ultimate bending strength. Higher value in our research will be used as a reference point. Table 1 shows thicknesses and lay-ups of test specimens (12-0, 21-0 – longitudinal and 12-90, 21-90 – transverse) used in the experiments.

Table 1

Lay-up and dimensions of specimens

Specimen designation	Lay-up	Average actual thickness (sanded), mm	Nominal thickness, mm	Span length, mm
12-0	I-I-I-I-I	11.46	12	240
12-90	-I-I-I-I-	11.38	12	240
21-0	I-I-I-I-I-I-I-I	19.84	21	420
21-90	-I-I-I-I-I-I-I-	19.72	21	420

Thirty two (4 groups, 8, 10 and 7 specimens in group) bending test specimens from birch plywood were tested. Samples with same thickness and outer veneer fiber orientation were cut from the same panel to ensure homogeneity of material properties. Specimens were visually checked for defects (boughs, missing veneers) and sanding symmetry. Samples, regardless of the test type, were put in machine jaws with the thinner outer layer facing downwards. Static bending tests were conducted according to EN310. Low Cycle Fatigue (LCF) 3-point bending tests were conducted with sample dimensions also corresponding to EN310. Span length is calculated according to nominal thickness regardless of the surface condition.

Tests were carried out on ZwickRoell Z600 testing machine. During the static and dynamic test deflection on the compression side of the panel (top) was measured with a crosshead travel sensor. MOE and MOR in bending were calculated according to EN310 and processing of the obtained data was performed. Stress-deflection curves were plotted. Reference value for LCF tests was obtained (85 % of average ultimate bending strength). Each LCF cycle was characterized by linear load increase and decrease (saw type) and the R value close to zero (due to preload) to prevent sample unloading during the experiment. Test speed was 150 mm·min^{-1}. Force control in the peak of the cycle and cycle end was used to maintain constant stress and capture rising remaining deformation. In the experiments numbers of cycles up to rupture were obtained and stiffness degradation curves were plotted.

Results and discussion

Figure 1 and Figure 2 show stress-deflection curves for samples 12-0, 12-90 and 21-0, 21-90. It is clearly visible that all lay-ups and thicknesses have elastic region followed by elasto-plastic. It is noticeable that 12-90 and 21-90 exhibit more elasto-plastic deflection before the specimen collapses. Markers show 85 % of average ultimate bending load. Deflection in this stress state is elasto-plastic. It is also visible that the elasto-plastic region grows with specimen thickness, particularly for transverse specimens.

The results of the static bending tests are shown in Table 2 and Table 3. The coefficient of variation (CV) is within the range of 4.75 % to 7.48 %, what is considerably small. Two samples (series 12-90*, samples 12-90-3, 12-90-4) were taken out of calculation, as they had boughs visible from side that could influence determination of the plausible starting point. MOE was calculated for each specimen to validate, if samples subjected to LCF tests fall in the same scattering field.

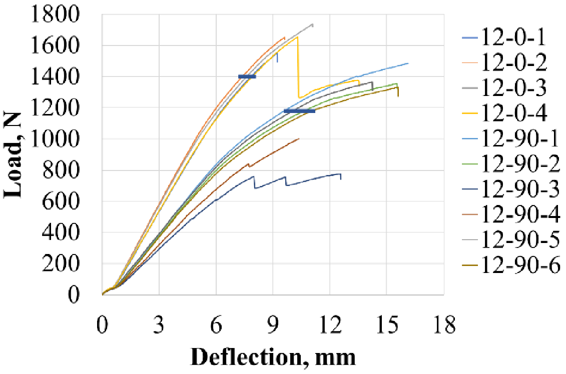

Fig. 1. **Load-deflection curve for 12-0 and 12-90 sanded plywood**

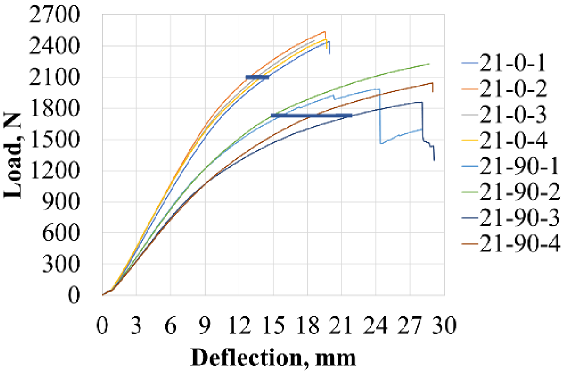

Fig. 2. **Load-deflection curve for 21-0 and 21-90 sanded plywood**

Table 2

Results of static bending test

Specimen designation	Average breaking force $F_{br;avg}$, N	Average stress σ_{avg}, MPa	Standard deviation s, MPa	CV, %
12-0	1650	88.9	4.61	5.18
12-90	1380	74.8	3.56	4.75
12-90*	1220	65.9	14.6	22.17
21-0	2470	76.5	1.40	1.83
21-90	2030	62.8	4.70	7.48

Figure 3 shows the load-deflection curve for the first 50 cycles for 12-0 sanded plywood sample. The curve of the first cycle is similar to the static stress-deflection curve with elastic deflection followed by elasto-plastic. From the relief curve it is visible that the sample obtained permanent (plastic) deflection. An increase in remaining deflection continues up to rupture.

Table 3

Results of static bending test

Specimen designation	Min stress, MPa	Max stress, MPa	Average modulus of elasticity E_{avg}, MPa	Min modulus of elasticity E_{min}, MPa	Max modulus of elasticity E_{max}, MPa
12-0	82.8	94.0	9750	9350	10200
12-90	72.1	80.1	6820	6680	7030
12-90*	42.0	80.1	6360	5210	7030
21-0	75.7	78.6	8970	8660	9250
21-90	57.7	69.0	6550	5980	7080

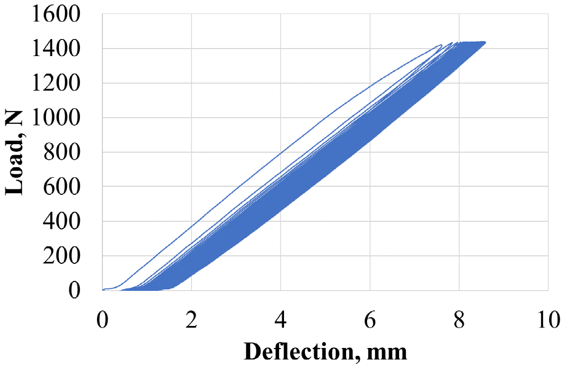

Fig. 3. **Load-deflection curve for first 50 cycles for 12-0 sanded plywoodsample**

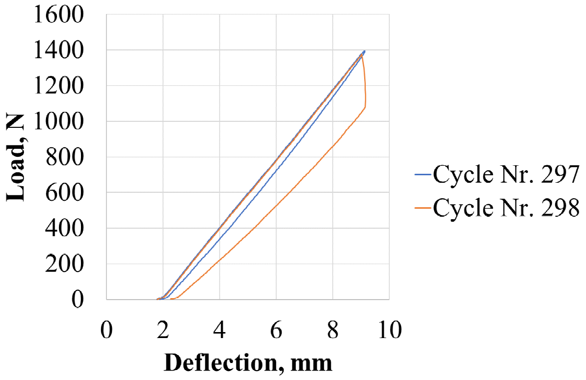

Fig. 4. **Load-deflection curve for last cycles before fracture for 12-0 sanded plywood**

Figure 4 shows that MOE for both cycles is nearly identical during the loading phase. The material exhibits rapid stiffness degradation. In the next few cycles, delamination and crack on the outer surface appear. Rupture can be classified as “avalanche type”. Growth of deflection is shown in Figure 5. It is uniform or slowly decreasing up to rupture. At some point (approx. 1000cycles) for all specimens, except 12-0, growth of deflection comes close to zero. The hysteresis loop is shown in Figure 6. Damage accumulation and stiffness degradation take place and are followed by “avalanche type” collapse.

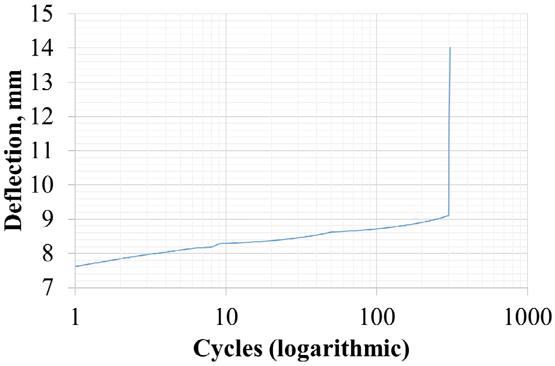

Fig. 5. **Deflection-cycle (logarithmic) curve for 12-0 sanded plywood**

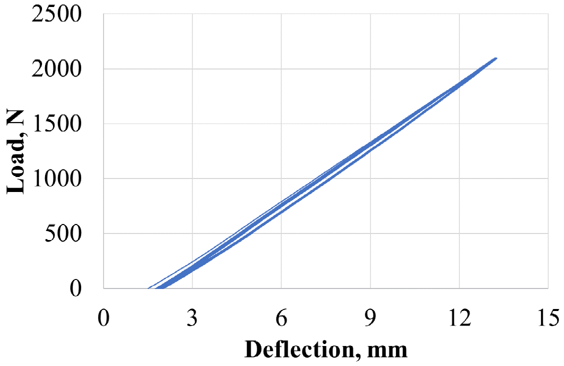

Fig. 6. **Load-deflection curve for cycles 1050 to 1200 for 21-0 sanded plywood**

The results of the dynamic 3-point bending test are presented in Table 4. CV_{force} varies from 0.16 to 0.27 %. It means that the test parameters are chosen right, and they have no negative influence on the test results. Fatigue testing is a time consuming process. Due to the low amount of samples being tested, no characteristic values for certain stress levels will be defined in this paper. J. Zhang et al. [2] used the coefficient of variation (CV_{cycles}) to describe dispersion around the mean value.Although, for static tests CV is very small and inhomogeneity of material is insignificant, for fatigue tests it is the reason for enormous disparity with CV_{cycles} values for all specimens, except 21-0, being greater than 100 %. Individual static strength (load durability 1 cycle) and cycle count up to fracture at certain stress level (85 %) will be used for the regression analysis to enlarge the number or data points. Otherwise total of 2points per specimen group – mean static strength and mean cycle count up to fracturecould be used and latter having dispersion more than 100 % would not give usable information even for roughlifetime evaluation. The results show that for lengthwise specimens mean of cycles rises 28 times and CV_{cycles} drops 2 times at the same stress level, meanwhile for transverse specimens mean of cycles rises 1.5 times and CV_{cycles} drops 1.1 times. The actual CV_{cycles} of 12-90 is yet to be determined. The results correlate with similar studies [2], CV_{cycles}decrease when the stress level is reduced.

Table 4

Results of dynamic three-point bending test

Specimen designation	**Average stress $\sigma_{dyn;avg}$, MPa**	**Average load $F_{dynlavg}$, N**	**CV_{force}, %**	**Cycle range**	**Mean of cycles**	**CV_{cycles}, %**
12-0	76.3	1400	0.22	15-298	123	104.8
12-90	64.9	1180	0.16	4-5400*	1840	132.1
21-0	66.7	2100	0.27	1462-4689	3490	50.6
21-90	55.8	1730	0.21	433-5224	2829	119.8

*sample not broken yet.

The experimental data for stiffness degradation are shown in Table 5. For all lengthwise sample dynamic test $E_{avg'}$ is in the same scattering field as E_{avg}. Despite that, 12-0 sample with the highest cycle durability exhibited 38 % of stiffness degradation while having the lowest $E_{avg'}$. If the average value for all specimen groups is taken, MOE of the material degrades by 13.4 % before it collapses. For transverse samples more samples should be taken for both static and dynamic tests, as only some of $E_{avg'}$ are in the same scattering field as E_{avg}.

Table 5

Results of dynamic three-point bending test

Specimen designation	**Average modulus of elasticity (first cycle) E_{avg}, MPa**	**Average modulus of elasticity (cycle before fracture) $E_{fract;avg}$, MPa**	**Stiffness degradation, %**	**Degradation range, %**
12-0	9977	7931	20.0	6.3-38.0
12-90	6653	6064	8.9	5.6-13.8
21-0	8860	7819	11.7	8.9-13.5
21-90	7300	6379	13.0	4.7-21.3

S-N curves were plotted and built-in MS Excel trendlines were used for data approximation. The curves are shown in Figure 7 and Figure 8. Prediction is made that for fatigue resistance 10000 cycles bending stress for 12-0 specimens should not exceed 70 MPa, for 12-90 62.5 MPa, for 21-0 65 MPa and for 21- 90 54 MPa. If the average value for all specimen groups is taken, to meet or exceed the predicted stress level should not be greater than 75 % to 80 % of the ultimate bending strength.

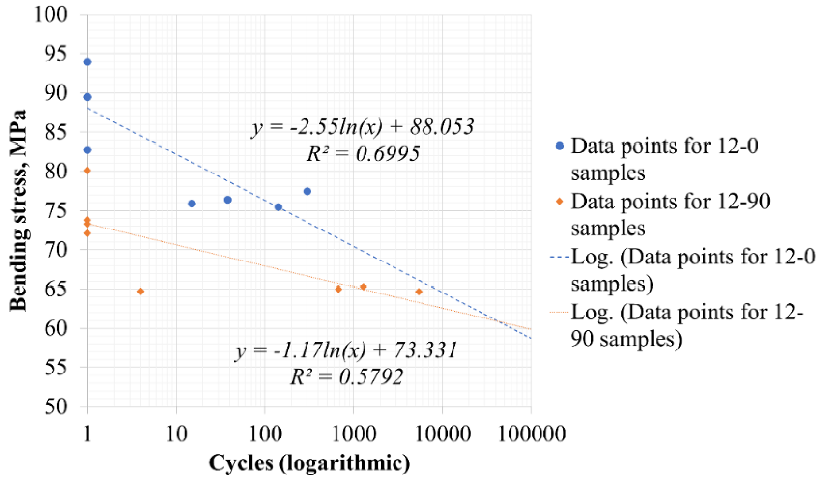

Fig. 7. **Stress -cycle (logarithmic) curve for 12-0 and 12-90 sanded plywood**

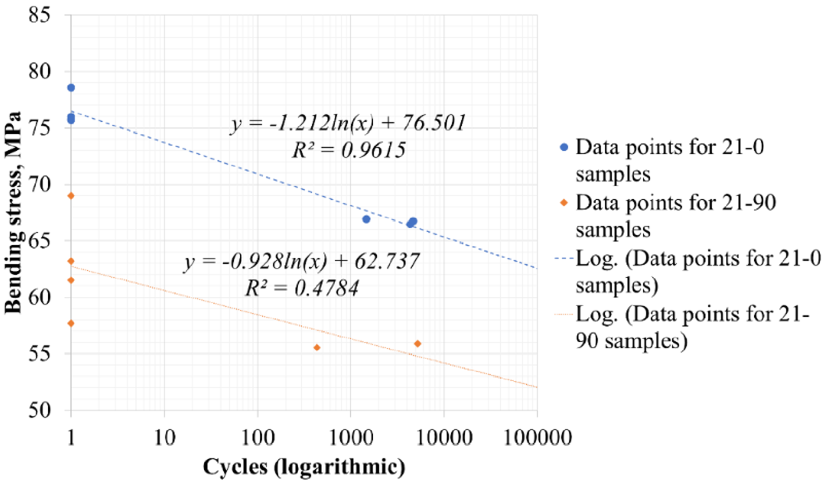

Fig. 8. **Stress -cycle (logarithmic) curve for 21-0 and 21-90 sanded plywood**

Conclusions

1. Data gathered in the experiment can be used for rough fatigue life prediction. For 12 mm lengthwise samples R^2 = 0.69, for transverse R^2 = 0.58. For 21 mm lengthwise samples R^2 = 0.96, for transverse R^2 = 0.48.
2. More tests with more samples in series need to be performed to evaluate fatigue life predictions and CV_{cycles} at a lower bending stress level.
3. The test methods described in this paper prove that stiffness degradation and fatigue are noteworthy factors to be taken into account when designing plywood structures. Fatigue life of plywood is dependent not only on the stress level, but also on the lay-up and general inhomogeneity of wooden materials. In further experiments microscopic analysis of plywood structure and damage accumulation must be carried out.

Acknowledgements

In accordance with the contract No. 1.2.1.1/18/A/004 between “Forest Sector Competence Centre” Ltd. and the Central Finance and Contracting Agency, concluded on 17th of April, 2019, the study is conducted by the JSC Latvijas Finieris with support from the European Regional Development Fund (ERDF) within the framework of the project “Forest Sector Competence Centre”.

References

[1] LVS EN 1995-2:2005 A standard “Eurocode 5 - Design of timber structures - Part 2: Bridges”

[2] Zhang J., Chen B.,Daniewicz S.R. Fatigue performance of wood-based composites as upholstered furniture frame stock. Forest Products Journal, vol. 55(6), 2005, pp. 53–59. [online] [27.04.2020] Available at: http://primolatvija.hosted.exlibrisgroup.com/permalink/f/l4e486/TN_gale_ofa133644480

[3] Yoshihara H. Bending Properties of Medium-Density Fiberboard and Plywood Obtained by Compression Bending Test. Forest Products Journal, vol. 61(1), 2011, pp. 56-63. [online] [27.04.2020] at: http://primolatvija.hosted.exlibrisgroup.com/permalink/f/l4e486/TN_gale_ofa261386510

[4] LVS EN 310:2001 standard “Wood-based panels; determination of modulus of elasticity in bending and of bending strength”.

[5] Tsen S.F., Zamin Jumaat M. Comparison of Eurocodes EN310 and EN789 in Determining the Bending Strength and Modulus of Elasticity of Red Seraya Plywood Panel. [online] [27.04.2020] Available at: http://doi.org/10.5281/zenodo.1070417

[6] LVS EN 789:2005 standard “Timber structures - Test methods - Determination of mechanical properties of wood based panels”.

[7] Latvijas Finieris. Plywood Handbook. 2017. [online] [27.04.2020]. Available at: https://www.finieris.lv/docs/Produkti/Bukleti/Handbook_2017.pdf

[8] Labans E., Kalnins K., Bisagni C. Flexural behavior of sandwich panels with cellular wood, plywood stiffener/foam and thermoplastic composite core. Journal of Sandwich Structures & Materials, vol. 21(2), 2019, pp. 784-805. [online] [27.04.2020] Available at:http://primolatvija.hosted.exlibrisgroup.com/permalink/f/1kvrd97/371KISC_AlephTUA01-000067140