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A pilot study on the use of the heavy/soft impact source for building acoustic impact measurements in housing

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ABSTRACT

About half of all Danish dwellings in Multi-Storey housing have timber floor constructions with impact sound insulation performance far below regulations for new housing. Jumping/running children is a major source of annoyance and complaints in such housing. According to building regulations in Europe and most countries worldwide, impact sound is tested using a standardized tapping machine (with steel hammers and total weight ~10 kg) defined in building acoustic ISO standards for laboratory and field measurements. However, in Japan and Korea, they traditionally used a softer impact source like a rubber ball (2.5 kg), which according to research projects and experience provide a better correlation with annoyance from jumping/running children. Recently, the rubber ball has been implemented in ISO standards as an additional/alternative impact source and is thus available for use in acoustic regulations and classification. In a Danish pilot project the rubber ball has been tested as an impact source in laboratory and field measurements and compared to tapping machine results for traditional Danish timber floor constructions before and after sound insulation improvement. The results and use in practice will be evaluated and results sent to the ISO WG having developed the specification ISO/TS 19488 for acoustic classification of dwellings.

Keywords: Building regulations, requirements, sound insulation, airborne, impact, measurement methods

1. INTRODUCTION

Most countries in Europe have building regulations, which include limit values for acoustic qualities for housing, including airborne and impact sound insulation between dwellings. An overview of such requirements in 35 countries in Europe is found in [1], and limits are field values with reference to ISO 16283 [2] and ISO 717 [3]. For impact sound, the source is the tapping machine. However, the rubber ball has recently – initiated by Korea and Japan – been implemented in ISO standards as an additional impact source, cf. ISO 16283 and ISO 717 as well as the laboratory methods in ISO 10140 [4]. Outside Europe, the tapping machine is also the most well-known impact source in relation limits for housing.

Several acoustic classification schemes exist in Europe with acoustic quality classes for the same performance areas and methods, see [1] and [5], and an international classification method for housing has been defined in ISO/TS 19488:2021 [6], being prepared in ISO/TC 43/SC 2/WG29. The ISO/WG currently discusses revisions of ISO/TS 19488. Korea and Japan want the impact ball method included in ISO/TS 19488, since their experiences show better simulation with sounds from jumping children, which is a major source of annoyance worldwide, also in Europe. In Denmark, neighbour noise also annoys many people, see [7] and [8], and especially in housing with old light-weight timber floors.

This paper deals with sound insulation of floor constructions between dwellings with focus on impact sound, including results from a pilot study with both the tapping machine and the rubber ball as impact sources. The pilot study became possible due to interest in cooperation from two BSc students [9] making a bachelor thesis at DTU about laboratory tests of a typical, old Danish light-weight timber floor and potential for improvements of sound insulation. Due to constraints in the BSc thesis time period and availability of lab facilities, we had limited options for tests, but nevertheless we succeeded to get insight in the challenges, when trying out the new alternative test with the rubberball as the impact source.

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2. THE MULTI-STOREY HOUSING STOCK IN DENMARK

In Denmark there are in total about 2.7 mio dwellings, of these almost 1.1 mio dwellings in multi-storey (MS) housing. In Figure 1 is shown the number of dwellings in multi-storey housing according to construction year. Especially for old housing with timber floors, footsteps and jumping/running children are major sources of annoyance and complaints. The pilot study is based on such constructions.

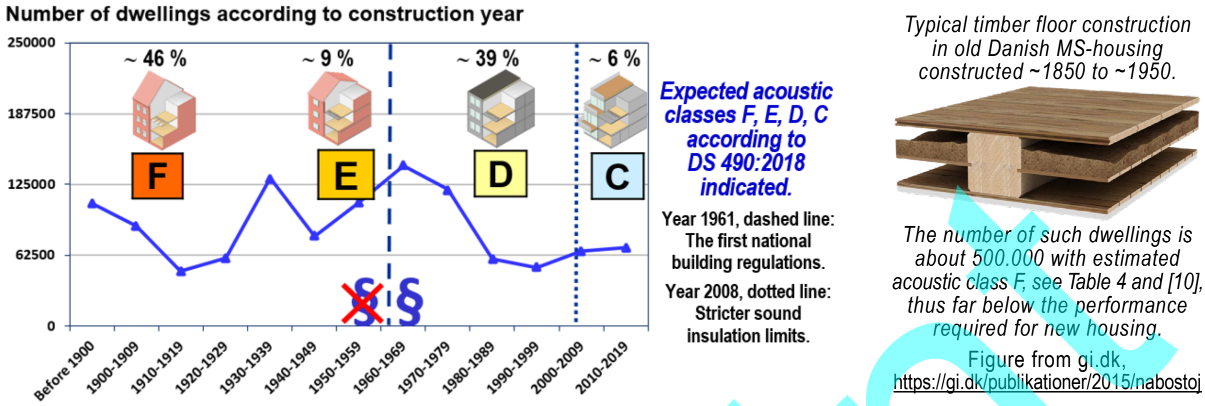


Figure 1 – Dwellings in multi-storey housing in Denmark according to construction year. The diagram is from [5], which includes more information about the Danish multi-storey housing stock.

3. MEASUREMENT METHODS & PROCEDURES: LABORATORY & FIELD

Measurements were carried out according to ISO methods, i.e. for laboratory tests the ISO 10140 standards [4] and for field tests the ISO 16283 standards [2]. For both laboratory and field tests, the rating methods in ISO 717 [3] were applied. Measurements were made for both airborne sound insulation and impact sound insulation (tapping machine) as well as impact sound using the rubber ball, being the key focus of the pilot study, fully implemented in the ISO standards "recently", inspired by experience from especially Japan and Korea and already standardized in those countries previously. The latest standards from Japan and Korea are [11] and [12] with the same impact ball characteristics as in the ISO standards.

The laboratory measurements were carried out in the DTU test facilities (complying with the ISO 10140 series) in building 355 for test of airborne and impact sound insulation of building constructions. Test specimen size was 10 m^2.

The following test equipment was applied: Sound level meter B&K 2270, tapping machine B&K 3207, B&K microphones, an old impact ball (Japanese protype, probably from before year 2000) and a new rubber ball Nor279. The tapping machine and the impact balls are shown in Figure 2.

Figure 2 – Left: Tapping Machine B&K 3207; Middle: Impact Ball Nor279; Right: Impact Ball (Old Ball)

The reason for using two rubber balls was that we started out using FORCE's old rubber ball, being unaware of the physical characteristics not complying with the new standards, and it was only in the middle of the test series, when discussing verification checks of equipment, we became suspicious, and rented (later bought) a new ball to check that the old ball could still be used. However, this turned out to be impossible for standardized measurements since the results for the two balls were very different. Nevertheless, we continued to use both impact balls, hoping to see systematic differences and to learn something about these two balls.

Dr. Hiramitsu [13] from Japan explained about the development of the rubber ball (extract mail): "*The actual impact noise of child jumping and running around had been a problem in apartment buildings around 1970s. Since the noise generated by the actual impact was lower in frequency range than that of the tapping machine, there was an argument that a different impact source should be used. Coincidently, the sound generated by car-tire impact (Bang machine) was similar to the sound of child jumping and running around. However, the impact force of Bang machine is too excessive (especially for lightweight construction buildings), and the* *development of impact ball began in the 1990s. During the development phase, prototypes of various impact balls are being made. Since these were made from rubber (e.g., natural rubber), the impact force characteristics varied greatly depending on the environmental temperature. (For example, at higher temperatures, the rubber became softer, thus extending the impact time and reducing the peak impact force value.) – After that, the impact ball material was reviewed and made from silicone rubber, resulting in an impact source with temperature-independent impact force characteristics. This background may result in the existence of impact balls (prototypes) that are not suitable for the impact force exposure levels specified by JIS and ISO.*

Calibration is recommended to check the impact force characteristics using a force plate. However, the impact force characteristics of the impact ball are rarely checked. This is because there is no change over time and no temperature dependence."

Some physical parameters of the impact balls are shown in Table 1. Compared to the tapping machine, the ball has approximately ¼ weight and ½ price.

Table 1– Some physical parameters of the impact balls

	Weight (kg)	Hardness Shore A*
Old Japanese prototype (assumed to be a Japanese prototype, probably from before year 2000)	2,55	76
Norsonic (Impact Ball Nor279) – calibrated from factory)	2,45	39
* We did not have access to a force plate for check of impact force characteristics and applied a test method inspired by ISO/TS 11819-3:2021 [14]		

The measurement procedures applied fulfil the requirements in the ISO test standards. Concerning the pilot study, the positions of the tapping machine and the impact balls are most important. The standards specify minimum 4 positions of the impact source for both laboratory and field tests with instructions concerning positions related to joists/beams and direction for the tapping machine. – The tests were made with 6 source positions for the laboratory tests and 5 for the field tests. Concerning the impact ball tests in the laboratory, 6 stationary microphone positions were used for each source position, e.g. in total 36 combinations, and correspondingly 5 for the field tests, e.g. in total 25 combinations.

4. LABORATORY TESTS: CONSTRUCTIONS AND RESULTS

The pilot study was made possible due to cooperation with the BSc students and their flexibility. After mounting of the basic laboratory timber floor ("original slab") simulating as far as possible and practical a timber floor as constructed in the field, se Figure 1, there were in total about three weeks for all tests, including complicated construction changes between some of the tests. Highest priority for testing was of course given to the BSc students.

The pilot study included laboratory tests of 6 different floor constructions, see Table 2, four of them (P0, P0C, P1, P1C) installed by the BSc students. The results below are however from new tests made with FORCE Technology equipment, see Section 3. In the end of the test period, two additional constructions, P5 and P6, were tested. They are similar to P1, but with a new parquet floor of known type as typically applied by the building association, when a new floor is needed. Two different interlayers were used under the floor. The intention was to make a field test with a parquet floor like P5 or P6 for comparison with the laboratory tests, but unfortunately access to relevant apartments could not be organized within the relevant time period. Thus, comparisons between the "same" constructions in the laboratory and field are pending and waiting for an opportunity in the future.

An overview of tests for the pilot study is described briefly in Table 2 below and results found in Table 3.

Table 2 – Tested constructions in the pilot study. Sketches based on drawings from [9].

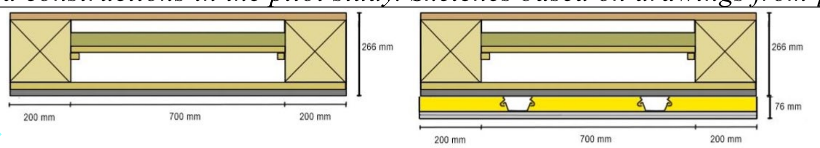
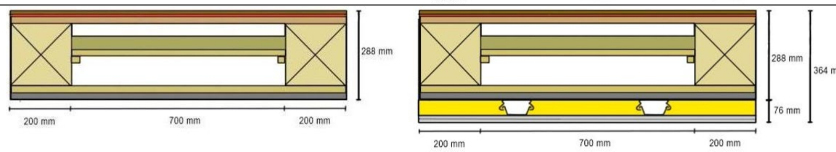
P0 + P0C **Floor heights** **P0: 266 mm** **P0C: 342mm**	
P1 + P1C **(P5), (P6)** **Floor heights** **P1: 288 mm** **P1C: 364mm**	
P0	The basic laboratory timber floor "original slab" simulates as far as possible and practical a timber floor as constructed in the field, but with clay replaced with sand.
P0C	P0 with added ceiling mounted at P0. The ceiling consists of 2 two gypsum plates mounted on profiles fixed at P0, mineral wool in spacing. Ceiling height 76 mm.
P1	Like P0, but with a parquet floor and a 2 mm foam interlayer on top of the basic floor. The parquet floor was of unknown origin, but available from previous tests, probably some years ago. Test specimen prepared by the BSc students.
P1C	P1 with added ceiling mounted like P0C.
P5	Similar to P1, but with a new parquet floor, same type as applied by the building association, when installing a new floor in an apartment. Thin interlayer (grey) aiming at reducing impact sound.
P6	The same parquet floor as for P5. Thin foam interlayer (blue).

Table 3 – Laboratory measurements for timber floor with and without additional ceiling: Airborne sound insulation, Impact sound level and Impact ball.

WITHOUT additional ceiling				WITH additional ceiling			
Construction	R_w / R_w+C_{50} (dB)	$L_{n,w}$ / $L_{n,w}$ + C_{50} (dB)	Ball (Old / Nor) $L_{iA,Fmax}$ (dB)	Construction	R_w / R_w + C_{50} (dB)	$L_{n,w}$ / $L_{n,w}$ + C_{50} (dB)	Ball (Old / Nor) $L_{iA,Fmax}$ (dB)
P0*	53 / 50	63 / 64	73 / 63	P0C	61 / 57	56 / 59	68 / -
P1	57 / 54	61 / 63	74 / 61	P1C	62 / 58	56 / 59	74 / -
P5	59 / 56	63 / 65	74 / 62				
P6	59 / 56	63 / 66	75 / 62				

Test constructions P0 is the basic construction, P1, P5, P6 has a parquet floor
* During all tests, a load 25 kg/m2 was applied, except for P0, which was tested without load.

In Figure 3 are shown laboratory measurement results for timber floor with and without additional ceiling. Table 3 and results in Figures 3a and 3b show improved results with the ceiling installed. In Fig. 3c for the rubberball measurement, it is not possible to interpret why the blue dashed line for P0C is higher (worse) than the others in the upper frequency range.

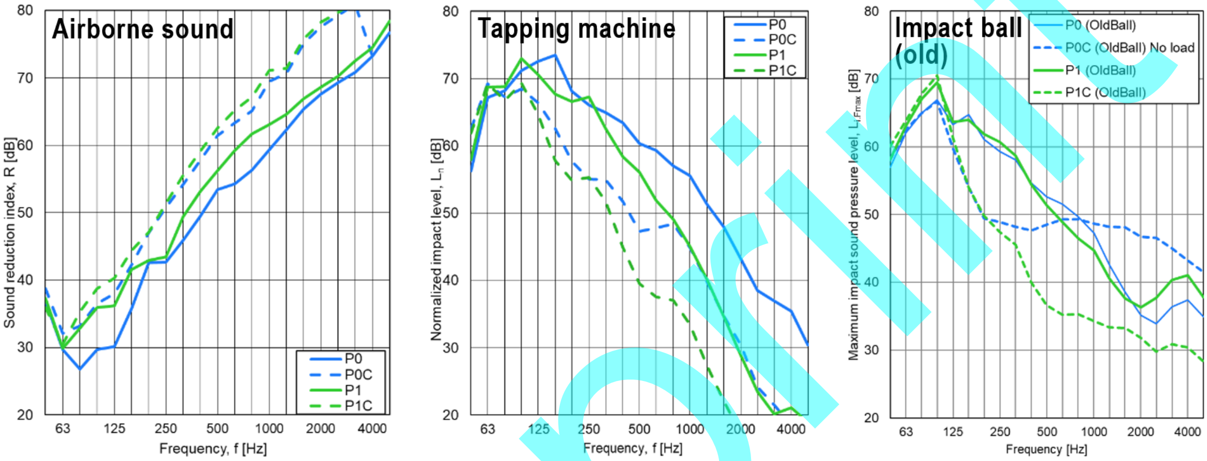


Figure 3 – Laboratory measurement results for timber floor with and without additional ceiling: (3a) Airborne sound insulation R; (3b) Impact sound level L_n; (3c) Impact ball (Old Ball) $L_{i,Fmax}$. Legends: Solid lines for construction without ceiling; Dashed lines with ceiling.

In Figure 4 are shown results for P0 (basic timber floor) and the timber floor with three parquet floor solutions. Results for P5 and P6 are as expected almost identical, and results for P1 slightly different. The reason for P5 and P6 was to test very basic floor solutions as typically applied in practice, when replacing a worn out floor. Note different dB axes in (4a) and (4b).

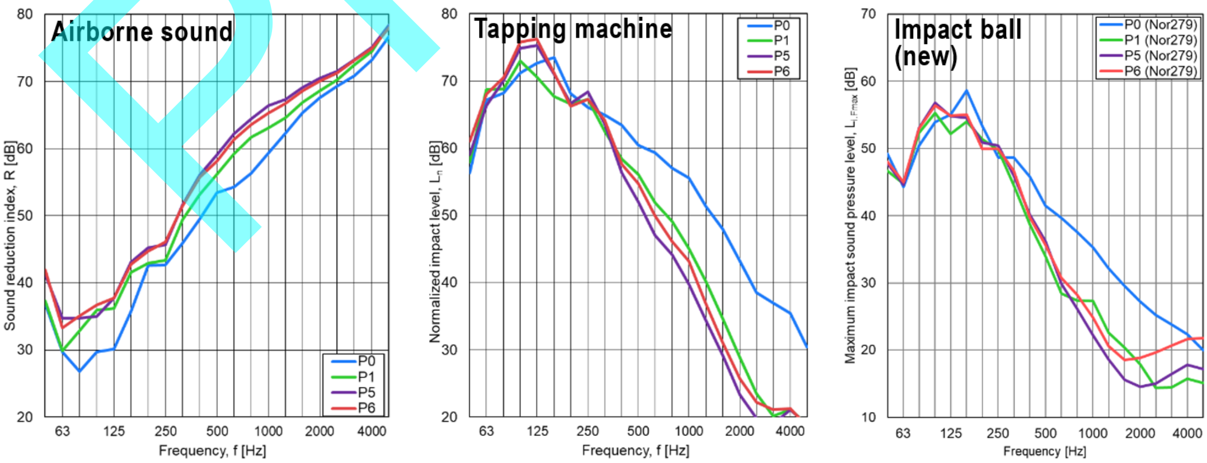


Figure 4 – Laboratory measurement results for timber floor with and without additional flooring: (4a) Airborne sound insulation R; (4b) Impact sound level L_n; (4c) Impact ball (Nor279) $L_{i,Fmax}$.

5. FIELD TESTS: CONSTRUCTIONS AND RESULTS

Field tests were made in a housing block built before 1920, 2200 Copenhagen N, G121, 3rd and 4th floor. Timber floor as shown in Fig. 1, but with additional ceilings installed in the 3rd floor rooms, height ~ 120 mm, two gypsum plates mounted on profiles fixed to room walls, i.e. independent from the basic floor construction (unlike P0C and P1C), mineral wool in spacing. The field measurements consisted of airborne and impact sound insulation tests being a part of another BUILD project (tests made by Rambøll A/S, project results to be published ultimo 2022) and rubberball measurements being a part of the pilot study. All measurements were made on 21 April 2022.

The airborne and impact sound insulation results are shown in Fig. 5a and 5b. The results are similar for both apartments and correspond to acoustic Class C, being the requirements for new dwellings, see Table 4. The sound insulation before mounting of the new ceilings was Class E for airborne sound and Class F for impact sound (tapping machine).

The rubberball results are shown in Fig. 5c. Ideally, the two apartments should give similar overall results, but there are obviously huge differences. The differences between the two upper and two lower curves are not due to differences in balls. The significant differences must be due to the impact ball test method characteristics and differences in constructions. In fact, for the field situation, we do not know the actual details of the timber construction or if changes have been made since the construction about 100 years ago. However, when the ball hits the floor, it is a heavy exposure in one point, and thus it was found worthwhile showing the individual curves for the five ball drops in each room, see Fig. 6.

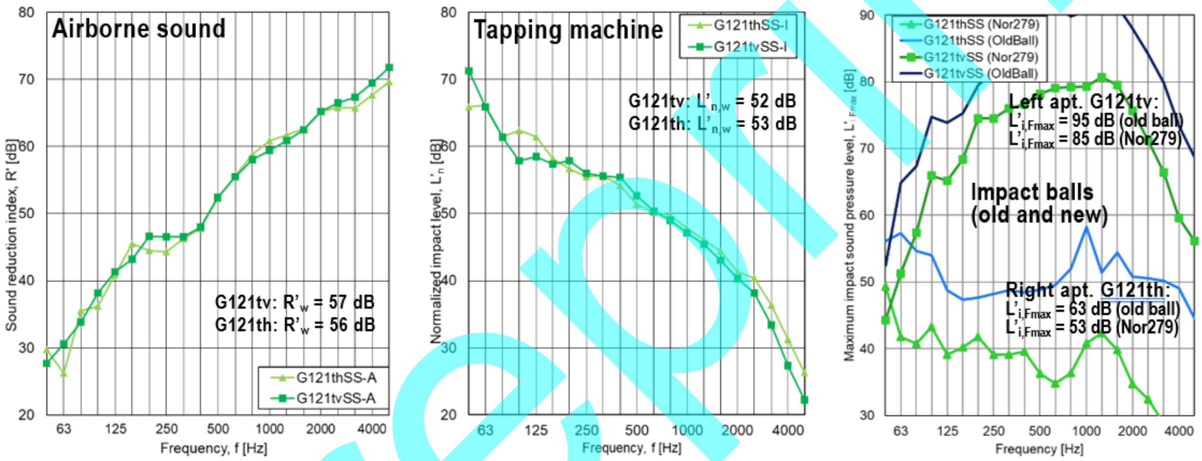


Figure 5 – Field measurement results for timber floor with additional ceiling, two apartments: (5a) Airborne sound insulation R'; (5b) Impact sound level L'n; (5c) Impact balls L'i,Fmax

Table 4 – Occupants expected satisfaction for different sound classes according to DS 490:2018. Summary based on information in DS 490 [10].

Sound insulation between dwellings Main class criteria A-F in DS 490:2018			Characteristics of DS 490 sound classes for dwellings and occupants' expected evaluation Information from DS 490:2018		
Class	Airborne	Impact	Sound class descriptions	Good or very good	Poor
A	$R'_w + C_{50\text{-}3150} \geq 63$ dB	$L'_{n,w} \leq 43$ dB and $L'_{n,w} + C_{I,50\text{-}2500} \leq 43$ dB	Excellent acoustic conditions. Occupants will be disturbed only occasionally by sound or noise.	> 90 %	
B	$R'_w + C_{50\text{-}3150} \geq 58$ dB	$L'_{n,w} \leq 48$ dB and $L'_{n,w} + C_{I,50\text{-}2500} \leq 48$ dB	Significant improvement compared to minimum in class C. Occupants may be disturbed sometimes.	70-85 %	< 10 %
C	$R'_w \geq 55$ dB	$L'_{n,w} \leq 53$ dB	Sound class intended as the minimum for new buildings.	50-65 %	< 20 %
D	$R'_w \geq 50$ dB	$L'_{n,w} \leq 58$ dB	Sound class intended for older buildings with less satisfactory acoustic conditions, e.g. for renovated dwellings.	30-45 %	25-40 %
E	$R'_w \geq 45$ dB	$L'_{n,w} \leq 63$ dB	Sound class intended for older buildings with unsatisfactory acoustic conditions.	10-25 %	45-60 %
F	$R'_w \geq 40$ dB	$L'_{n,w} \leq 68$ dB	Sound class intended for older buildings with clearly unsatisfactory acoustic conditions.	< 5 %	65-80 %
Reference: DS 490:2018 "Lydklassifikation af boliger" (Sound classification of dwellings)			**Note:** Within each sound class, the percentage of satisfied or dissatisfied occupants may depend on the type of criterion. The grouping is mainly based on the subjective assessments of airborne and impact sound from adjacent dwellings.		

Field test results for the individual rubberball impact positions in the apartments are found in Fig. 6a and 6b for the left and right apartment, respectively. Ideally, the two apartments should give similar overall results, but there are obviously huge differences between ball impact positions. Other things being equal, it seems as if much lower levels occur, when the ball hits the joists than when it hits between the joists. The apartments were occupied, and we did not have access for further measurements in the pilot study. Note different dB axes in (6a) and (6b).

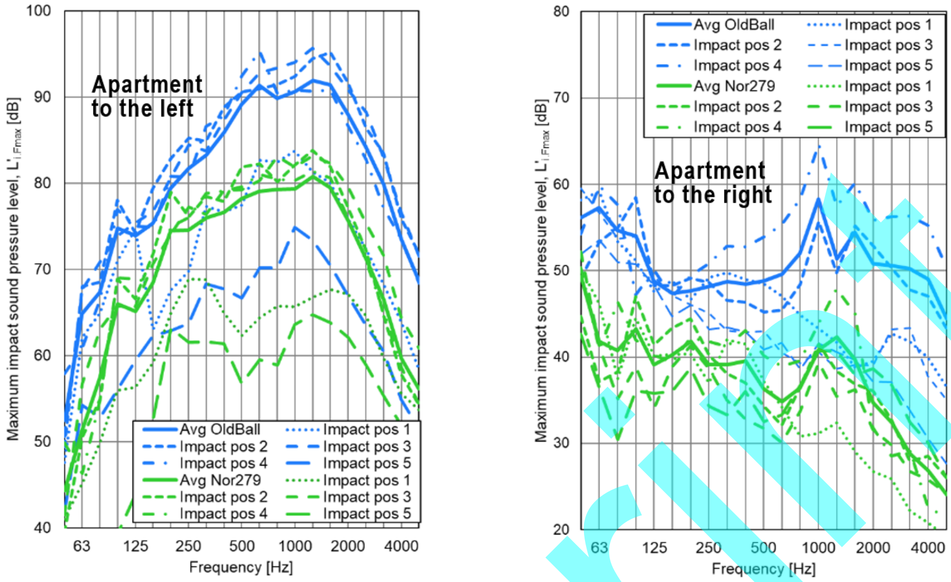


Figure 6 – Field test results $L'_{i,Fmax}$ for the impact ball method in two apartments: Individual impact positions and average results of the two impact balls, blue (old ball) and green (Nor279) respectively. (6a): Apartment to the left G121tvSS; (6b) Apartment to the right: G121thSS

6. COMPARISON OF RESULTS FOR THE TWO IMPACT BALLS

Since there is a need to understand better the behaviour of the rubberball impact results, it was found appropriate to show all results from the laboratory and field in two diagrams, see Fig. 7 with laboratory results in the left diagram and field results in the diagram to the right.

For the laboratory results, the differences between the old and new ball are similar up to about 250 Hz. However, with an additional floor, there are large differences above 250 Hz. For field results, the largest differences between the balls are found for the “th” apartment. In summary, the results show that we cannot convert results from one type of ball to the other one.

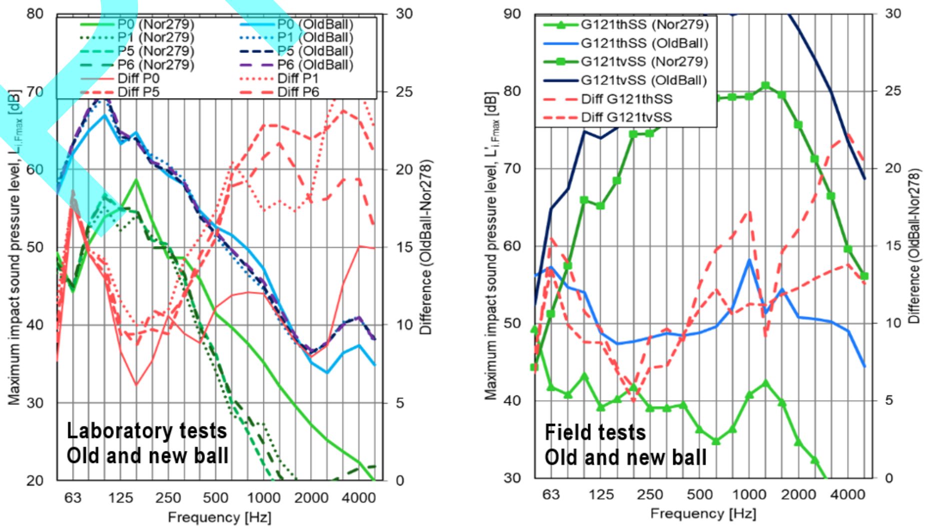


Figure 7 – Comparison of the two impact balls in laboratory $L_{i,Fmax}$ (left) and field $L'_{i,Fmax}$ (right). The red curves show the differences between the old and new ball.

Note: The two diagrams have different dB-scales (left axes). Differences between the old/new ball are in red (dB scale right axes)

7. DISCUSSION

Due to the unexpected findings during the pilot study – the major one being the awareness of the old rubberball not complying with the standards – we asked eight building acoustic experts in seven countries about their application of the rubber ball for laboratory and field measurements according to the ISO 10140 and ISO 16283 standards and about the ball types and their check of the rubber ball characteristics. The institutes asked were four in Europe, one in Canada, one in Korea and two in Japan. Some of the institutes also informed about publications related to previous studies with rubberball measurements.

The rubberball applications in these institutes are quite mixed. Some do not use the rubber ball for standardized tests, but for other building acoustic research. Some use the rubber ball for laboratory tests only, some for field tests only, and a few for both. Some institutes use the rubber ball for tests in a mock-up. In general, the rubber ball tests are mainly used for wooden constructions. – Based on responses from the institutes, it seems as if regular checks of the rubber ball characteristics are only used in a few places, but not yet implemented in most QS systems, which should be changed in the future.

During the pilot study, we discussed the details of the measurement procedures and potential benefits of using the rubber ball for impact tests. Compared to the tapping machine, the ball has approximately ¼ weight, ½ price and much less volume, and the subjective annoyance is reduced for occupants during field tests. However, considering the total test duration for a measurement, there seems to be no significant differences between the two impact sources, which is due to restrictions for e.g. number and positions of sources and microphones as well as other parts of the test procedures.

We would like to understand the reasons for the seemingly random results for some of the impact ball positions in the field, but further access to the apartments was not possible during the pilot study. A main problem for field tests in old existing housing is that construction details inside the timber floor are invisible. A possibility in further studies could be to analyze results for different ball impact positions in the laboratory tests to observe if a similar spread like in the field occurs or not. Our results indicate that rubberball impact levels are higher for the rubberball impact on the joists than between the joists.

To evaluate the potential benefits of the rubberball as an impact source, we need more laboratory and field tests as well as laboratory/field comparisons for similar constructions. Important is also to get experience for other construction types applied in old and newer/new housing.

8. CONCLUSIONS & RECOMMENDATIONS FOR FURTHER STUDIES

The pilot study included laboratory and field tests using the rubberball as impact source at old Danish timber floor constructions with and without additional ceiling and/or floor covering. Since only a limited number of tests was possible within the time frame of the study, and no other construction types than the old timber floor were tested, several needs for further studies are identified:

- Additional field measurements and/or inspections in the two apartments with lack of consistency between the rubberball results. Analysis of spread in laboratory results for different ball positions.
- More field measurements in other old apartments with rubberball tests both before and after improvement of sound insulation with ceilings and/or new floor constructions. Some of the tests could include the additional ceiling/floor constructions included in the BSc study, but not tested in the pilot study.
- Laboratory and field measurements for construction types applied in newer and new housing and comparison between results in the laboratory and field.
- More communication with the institutes having responded to request for information about their rubberball applications (see above) and study of the publications [15]-[20] from those countries.
- Study on the importance of load on floor constructions, also on light-weight reference floors.
- Check/verification procedures for rubber ball characteristics, including time intervals and ageing.

Results of the pilot study will be presented and discussed in ISO/SC2/TC43/WG29 with acoustic classes for rubberball tests currently on the agenda and in WG18 having prepared the test methods.

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REFERENCES

[1] Rasmussen, B. (2019). *Sound insulation between dwellings – Comparison of national requirements in Europe and interaction with acoustic classification schemes*. Proceedings of ICA 2019 (pp. 5102-5109). Deutsche Gesellschaft für Akustik (DEGA e.V.). https://doi.org/10.18154/RWTH-CONV-239983

[2] ISO 16283, Acoustics – Measurement of sound insulation in buildings and of building elements – Part 1: Field measurements of airborne sound insulation between rooms, 2014. – Part 2: Field measurements of impact sound insulation of building elements, 2020. – Part 3: Field measurements of airborne sound insulation of facade elements and facades, 2016.

[3] ISO 717:2020, Acoustics – Rating of sound insulation in buildings and of buildings elements. – Part 1: Airborne sound insulation. – Part 2: Impact sound insulation.

[4] ISO 10140:2021 Acoustics - Laboratory measurement of sound insulation of building elements.
– Part 1: Application rules for specific products; – Part 2: Measurement of airborne sound insulation;
– Part 3: Measurement of impact sound insulation; – Part 4: Measurement procedures and requirements;
– Part 5: Requirements for test facilities and equipment.

[5] Rasmussen, B. (2020). *Encouraging acoustic renovation of housing in Denmark by extending acoustic classification with two lower classes E and F for old housing*. In J. Yong Jeon (Ed.), Proceedings of 2020 International Congress on Noise Control Engineering: INTER-NOISE 2020 The Korean Society of Noise and Vibration Engineering, Seoul, Korea.

[6] ISO/TS 19488:2021. Acoustics — Acoustic classification of dwellings.

[7] Rasmussen, B., & Ekholm, O. (2021). Neighbour noise in multi-storey housing - Annoyance and potential health effects. Proceedings of INTER-NOISE 2021 (Vol. 263(4), pp. 2783-2792). [#2228] Institute of Noise Control Engineering. Noise-Con Proceedings Vol. 21 (Print) https://doi.org/10.3397/IN-2021-2228.

[8] Jensen, H. AR., Rasmussen, B., & Ekholm, O. (2019). *Neighbour noise annoyance is associated with various mental and physical health symptoms: Results from a nationwide study among individuals living in multi-storey housing*. BMC Public Health, 19, 1-10. [1508]. https://doi.org/10.1186/s12889-019-7893-8

[9] Melanie Førsterling Gotfredsen and Julie Bech Liengaard (2022). *Sound insulation of wooden slabs in existing buildings*. Department of Electrical and Photonics Engineering, Technical University of Denmark.

[10] DS 490:2018. *Lydklassifikation af boliger.* (Sound classification of dwellings). Danish Standards, Denmark.

[11] A 1418-2:2019. 建築物の床衝撃音遮断性能の測定方法− 第 2 部：標準重量衝撃源による方法. Acoustics - Measurement of floor impact sound insulation of buildings – Part 2: Method using standard heavy impact sources. Japan.

[12] KS F 2810-2:2012. 건축물의 바닥충격음 차단성능 현장 측정방법 – 제 2 부: 표준 중량 충격원에 의한 방법. Field measurements of floor impact sound insulation of buildings – Part 2: Method using standard heavy impact sources. Korea.

[13] Personal communication, e-mail 2022-07-15 with Dr. Hiramitsu, Building Research Institute, Ibaraki, Japan.

[14] ISO/TS 11819-3:2021 Acoustics – Measurement of the influence of road surfaces on traffic noise – Part 3: Reference tyres.

[15] Heinrich Bietz, Volker Wittstock (2015). *Vibroakustische Eigenschaften von technischen Ersatzschallquellen im Vergleich zu Gehern*. Proceedings of DAGA2015, p.1237-1240.

[16] Atsuo HIRAMITSU; Ryuta TOMITA; Susumu HIRAKAWA; Masayoshi SATO (2019). *Floor impact sound insulation of the six-story wood-frame model building.* Proceedings of ICA2019, p.5007-5012. http://pub.dega-akustik.de/ICA2019/data/articles/001442.pdf.

[17] Zeitler, B.; Nightingale, T. R. T.; King, F (2008). *Methods to control low frequency impact noise in wood frame construction.* Proceedings of Acoustics '08, pp. 5589-5594. Paris, France.

[18] Zeitler, Berndt; Sabourin, Ivan; Schoenwald, Stefan; Wenzke, Erik (2012). *On reducing low frequency impact sound transmission in wood framed construction.* Proceedings of InterNoise2012, pp. 6653-6662. New York, USA.

[19] Hiroshi SATO; Junichi YOSHIMURA (2014). *Classification scheme of floor impact sounds with the standard rubber ball in dwellings*. Proceedings of Inter-Noise 2014, Melbourne, Australia.

[20] J. H. Jeong (2021). *Background Noise, Noise Sensitivity, and Attitudes towards Neighbours, and a Subjective Experiment Using a Rubber Ball Impact Sound*. IJERPH, 2021, 18 (14).
Int. J. Environ. Res. Public Health **2021**, *18*(14), 7569; https://doi.org/10.3390/ijerph18147569