Airtightness assessment of single family houses in Belgium

1. ABSTRACT

Airtight construction lies at the heart of achieving high energy performance in dwellings. But how well has is it applied in new construction? This paper presents results from airtightness measurements on 44 randomly selected, standard new built single family houses in Belgium and from 4 case studies including 78 additional measurements. The houses were randomly selected after completion, to assure that standard workmanship was used during construction. Where applicable, the effect of incorporating the attic and garage in the building volume was measured by performing a series of tests in different configurations. The results are compared with those from a previous study in the early 1990's, with a database that was compiled with results from 161 air tightness reports executed on newly built dwellings by private party consultants and with the governmental EPBD-database (1884 measurements). The results show that the mean leakage rate is about 6 ACH_{50} for the randomly selected houses and 3 ACH_{50} for the houses in the databases. The houses in the databases are measured upon the initiative of the owner. Therefore, the attention to airtight workmanship is substantially higher for these cases than in the randomly selected houses. This clearly demonstrates the difference between 'mainstream' workmanship and results obtained by the 'engaged' market.

2. INTRODUCTION

Since the energy crisis of the 70's, building energy demand has been an increasingly important topic in building science. The provisional culmination of this evolution is the recast of the EU Energy Performance of Buildings Directive (EPBD), that requires all new buildings to achieve nearly zero energy demand by 2020. This strict performance objective will require high end performance of all building components, both envelope and services (HVAC, lighting…).

The passive house concept, as it was gradually introduced in the US during the 1970s (Parker, 2009) and promoted, especially in Europe, by prof. Feist (2005), focuses mainly on the quality of the shell to achieve a high energy performance, with optimized passive solar gains, thick insulation, efficient balanced mechanical ventilation with heat recovery and excellent air tightness as its main priorities, combined with well planned glazing. Within the concept, the air change rate at 50 Pa pressure difference (ACH_{50}) is required to be lower than 0.6 ACH_{50}. Although this necessitates extreme care in planning and during construction, the large number of certified passive houses all over Europe proves that this level is perfectly feasible. For example, the Passiv Haus Institut has, to date, certified 348 single family houses (PHI, 2013). Nevertheless, a number of cross-sectional case studies on dwellings in different European countries listed in Table 1 demonstrate that this high level is far from mainstream in today's construction practice, with average leakage rates at 7.5 ACH_{50} (Bossaer et al., 1998, De Gids, 2003, Van Den Bossche, 2005, Kalamees, 2007, Sfakianaki et al., 2008, Jokisalo et al., 2009, Relander, 2009). The latest studies within the series, however, suggest that new construction is increasingly airtight, e.g. Finnish massive shell houses reaching an average of 3.3 ACH_{50} in 2004-05.

Table 1. Overview of airtightness levels reported in European surveys, including country and period of the measurement campaign, number of cases included, mean leakage rate (ACH_{50})

Country and period	N°	ACH_{50}	remarks
Belgium, 1995-97	42	11.3	Corrected for net volume
The Netherlands, 2002	88	3.5-4.5	No information on flow exponent
Finland, 1979-81	16	6.0	prefabricated wood-frame
"	28	3.5	intended airtight building

Finland, 1981-98	171	5.9	Cases with complaints
Finland, 2002-03	100	3.9	Wood-frame
Finland, 2004-05	61	3.3	Massive shell
Norway, 1980	61	4.7	
Norway, 1984	10	4.0	Built 1980, low energy houses
Norway, 1990-2008	56	5.0	Wood-frame
Estonia, 1999-2000	19	9.6	Cases with complaints
Estonia, 2003-05	32	4.9	Wood- and Steel-frame
Greece, 2005	20	6.8	Passive stack ventilation
Sweden, 1978	205	3.7	
“	44	1.02	Wood-frame
UK, 1998	471	13.1	

In Belgium, the latest available information is a survey from 1997 on houses constructed between 1990 and 1995 and reports an average air change rate at 50 Pa pressure difference of 11.3 ACH$_{50}$ (Bossaer et al., 1998). Over the last 15 years, and especially due to the implementation of the first EPBD as of 2006, newly built dwellings have become increasingly well insulated and building technology has evolved a lot.

The Belgian official energy performance calculation software, throughout its different updates since the implementation of the EPBD, includes the possibility to specify the as built measured air tightness of the dwelling. To be included, the measurement has to follow the pressurization method as it is detailed in the European EN 13829 standard (CEN, 2001). If no measurement is performed a default value roughly corresponding to the mean leakage level reported in the 1997 survey is used. As a result, a database is available that lists all newly built dwellings with a reported leakage test. In this paper, this database will be referred to as the EPBD-database.

Since performing this test is not required for compliance to EPBD requirements and has to be paid for by the building owner, it is usually only executed on dwellings that aspire to reach a very good energy performance level, e.g. to obtain a passive house certificate or because financial incentives are available at high performance levels that offset the cost of the test. The latest report by the Flemish government on the energy performance of newly built dwellings in Flanders (De Baets and Jonckheere, 2013) summarizes some key data in the EPBD-database. It shows that a pressurization test is performed on only a few per cent of the dwellings close to the minimum energy performance level required by the building code, while for those dwellings with a performance level that is at least twice as good as the minimum level, more than 70% are tested. In total, for about 10% of the dwellings constructed since 2006, leakage tests have been reported in the database. This fraction is increasing every year and has now reached nearly one quarter for single family houses built after 2010.

It is reasonable to assume that since the test is mainly executed by ‘engaged’ building owners, the distribution of leakage levels that is included in the database is biased towards lower leakage levels and does not accurately represent the air tightness of the bulk of the newly built dwellings. The aim of this paper is to assess the airtightness of dwellings under current common building practice in Belgium, i.e., with standard workmanship. By comparing the results with historical data, case study data and those obtained by ‘engaged’ building owners, this work provides valuable information about the state and evolution of air tightness in single family dwellings for owners, contractors and policy makers, as well as demonstrates room for improvement in standard workmanship compared to the state of the art. The dominance of leaks in attics and garages points to targets to further improve envelope air tightness.

3. TEST CASES

For this paper, two different test groups were selected. On the one hand, 44 newly built single family houses in Belgium (constructed between 2007 and 2010, referred to below as ‘group 1’) were randomly selected after completion to assure that standard workmanship was used during construction and the results were not biased by extra efforts to reduce leakage by the contractor. These dwellings were tested by a team from Ghent University. On the other hand, a database was created with results from 109 air tightness reports executed on newly built dwellings (constructed between 2006 and 2010, referred to below as ‘group 2’) by private party consultants. The first test group represents standard practice while, since leakage testing is not compulsory in the Belgian building code; the second group is a reference for projects that are intended to perform well. Due to the fact that the database was formed with information from private party consultants, not all information, such as detailed building geometry, was available.

The data included in the created database does, however, include more detail about the test itself, compared to the data available in the EPBD-database, such as flow coefficient, flow exponent, leakage rate in both pressurization and depressurization test, and the net volume of the dwelling. In the EPBD-database only the average of pressurization and depressurization is available and the reported building volume is the gross volume. Since ACH_{50} is defined based on the net volume, the ratio of net and gross volume was estimated to be 0.75, based on the detailed geometrical data available in the 1997 survey (Van Den Bossche, 2005), to calculate ACH_{50} values for this data.

For the first test group, all relevant geometrical information (gross habitable floor area, gross heat loss area, total envelope area, net heated volume, compactness (gross volume to heat loss surface ratio)...) and technical information (ventilations system setup, type of construction, garage included in heated volume) was collected. The mean heated volume of the dwellings included in group 1 was 500 m³. The minimum heated volume was 276 m³ and the maximum was 877 m³. With a mean gross floor area of 202 m^2, the sample fits well with the average newly built single family house in Flanders between 2006 and 2010 (214 m^2 - (Defruyt et al., 2013)). The mean compactness was 1.16 m with a standard deviation of 0.14 m. 66 % were detached, 27 % were semi-detached and 7 % were terraced dwellings. Compared to the single family houses built between 2006 and 2010 (Defruyt et al., 2013), detached dwellings are overrepresented in the sample. 14 % of the dwellings had a wood-frame construction, while 84 % were massive, brick and concrete construction. All of the dwellings had a cavity wall shell with brick exterior except for 2 cases that had a single leaf wall with ETICS (External Thermal Insulation Composite System). 36 % had a balanced mechanical ventilation system, while 57 % were equipped with mechanical exhaust ventilation and 7 % had a passive stack ventilation system. This, again, is well in line with the distribution reported in the EPBD database (De Baets and Jonckheere, 2013).

All 44 dwellings in the first test group were tested in accordance with method A in EN 13829 (CEN, 2001), with the additional specifications of the Flemish government (2013). Whenever a cellar, attic or garage were included in the heated volume, multiple tests were done that respectively included and excluded these spaces.

4. RESULTS AND DISCUSSION

4.1. Leakage distribution

As can be seen in Figure 1, the distributions of the ACH_{50} results of the randomly selected test cases (group 1) and of the private party consultant cases (group 2) correspond well with a lognormal distribution, which is to be expected from a strictly positive parameter such as airtightness. The assumption of lognormal distribution of the results allows us to use bivariate t-testing to test the significance of observed results.

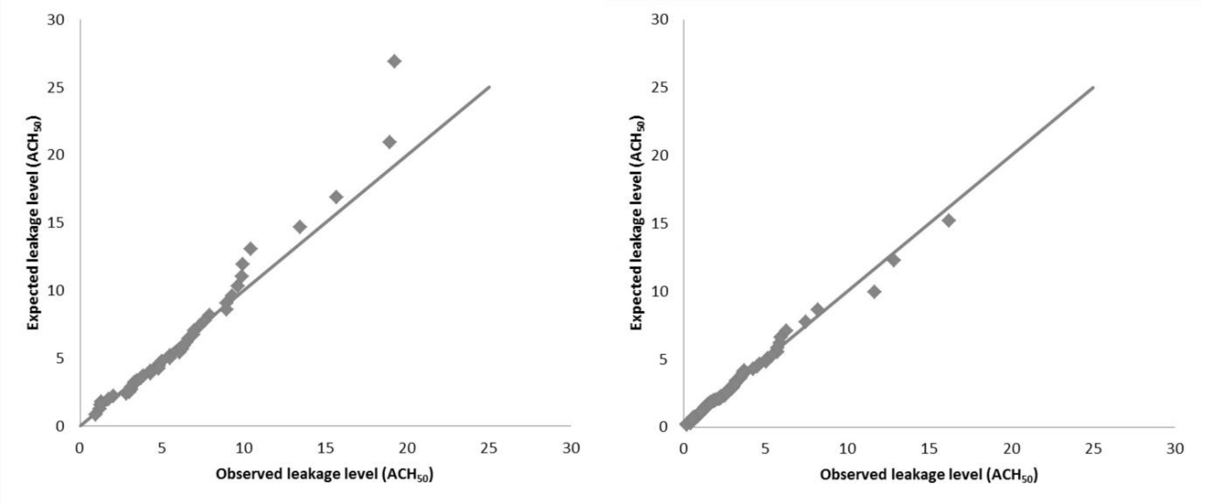

Figure 1. Q-Q' plot of the observed and expected values of the leakage level (ACH_{50}) for the randomly selected test cases (group 1, left, N = 44) and the private party consultant cases (group 2, right, N = 109), tested for log-normal distribution

As was mentioned in the section above describing the test cases, the cases in group 2 are a reference for dwellings which are intended to be airtight, assumed so due to the fact that the owner paid to do the test. As is demonstrated by the boxplots in Figure 2, the cases in this group are indeed much more airtight than those in the first test group, which is representative for standard workmanship ($p < 10^{-11}$).

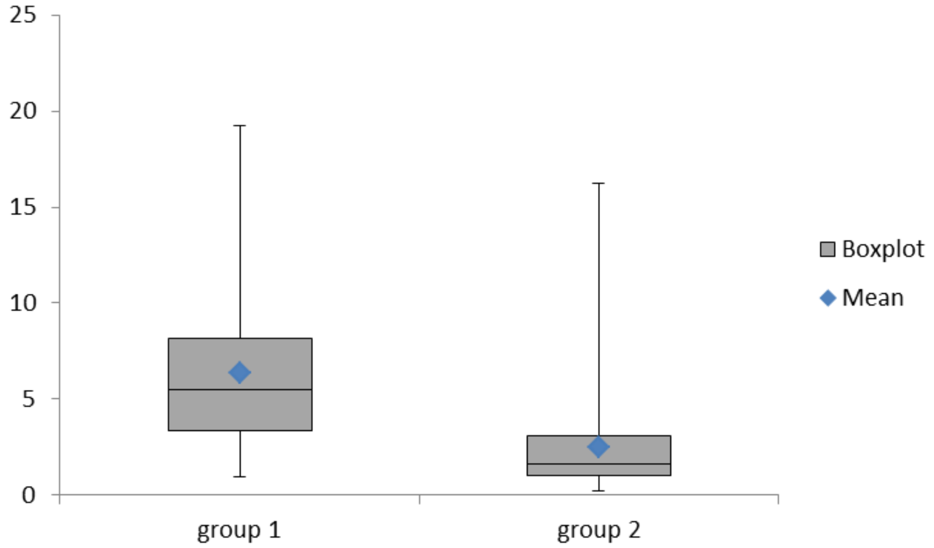

Figure 2. Boxplot of the leakage level (ACH_{50}) for the randomly selected test cases (group 1, N = 44) and the private party consultant cases (group 2, N = 109)

In the first test group, a mean air change rate at 50 Pa pressure difference of 6.4 and a median of 5.5 were found, while the second test group reached a mean ACH_{50} of 2.5 and a median of 1.6. In both test groups, high maximum values were observed (19.2 and 16.2 respectively).

Figure 3 extends the comparison of the results from both test groups with those from other databases, such as those from the 1997 survey (referred to as SENVIVV), the EPBD-database and the levels for single family dwellings found in a recent survey of 25 high energy performance dwellings in Flandres (Clean Air Low Energy project – CALE (Stranger et al., 2012)). It demonstrates that definite improvements in air tightness of standard construction have been achieved since the mid-nineties, with the mean and median leakage levels each dropping by more than 40 % from the results of the 1997 survey to those found in group 1. Standard construction, however, still lags behind the results achieved by the engaged market, represented by the entries in the EPBD-database, the dwellings tested by private party consultants (group 2) and those included in the Clean Air Low Energy project (CALE), which achieve leakage rates that are on average half, a third and a quarter of those found in group 1, respectively.

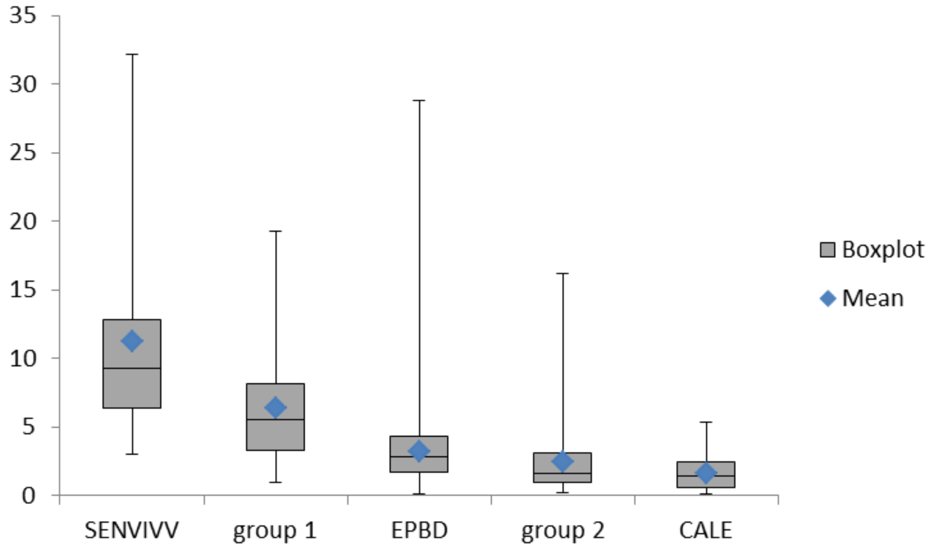

Figure 3. Boxplot of the leakage level (ACH_{50}) for the 1997 survey (SENVIVV, N = 42), the randomly selected test cases (group 1, right, N = 44), the entries in the EPBD-database (EPB, N = 1884), the private party consultant cases (group 2, left, N = 109) and the cases included in the Clean Air low Energy project (CALE, N = 19)

4.2. Leakage specifics

When pressurization and depressurization test results are compared for both groups, there seems to be a tendency for lower depressurization results, although the differences are very small and not significant (p = 0.73 and p = 0.93 for groups 1 and 2 respectively). The boxplots of the leakage rates measured during pressurization and depressurization are shown in Figure 4.

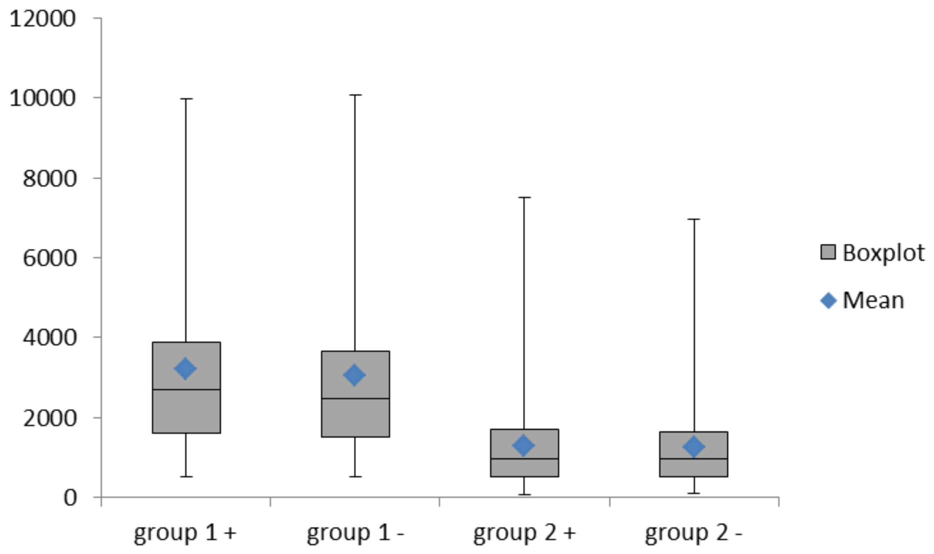

Figure 4. Boxplot of the leakage rate at 50 Pa pressure difference (m^3/h) for the randomly selected test cases (group 1, N = 44) and the private party consultant cases (group 2, N = 109) during pressurization (+) and depressurization (-) tests.

Leaks in the building envelope are usually concentrated at joints and specific details (Van Den Bossche et al., 2012, Relander et al., 2010, Relander et al., 2011a, Relander et al., 2011b, Relander et al., 2012). This was also visible during the measurements in the cases in group 1. For example, for the garage, the joints around the garage door proved to be the dominant problem, while for attics, air barriers were frequently inadequately installed and resulted in substantial leakage at the joints. In the dwellings where a garage or attic was included in the heated volume, the leakage in the houses was additionally measured with the doors towards these spaces closed. Although this is a rather crude way to demonstrate the contribution of a section of the envelope to the total leakage and the result still includes leakage through the interface between the spaces, this coincides well with the normal use condition of the dwelling. In Figure 5, the difference in leakage measured in the repeated tests with closed internal doors is shown. A garage included in the heated volume represents, on average, 30% of the total leakage (N = 15), an attic included in the heated volume on average 48% (N = 8). Since the internal doors to these spaces are usually closed in normal use conditions of the dwellings, their contribution to the infiltration rates can be largely overestimated with a standard pressurization test.

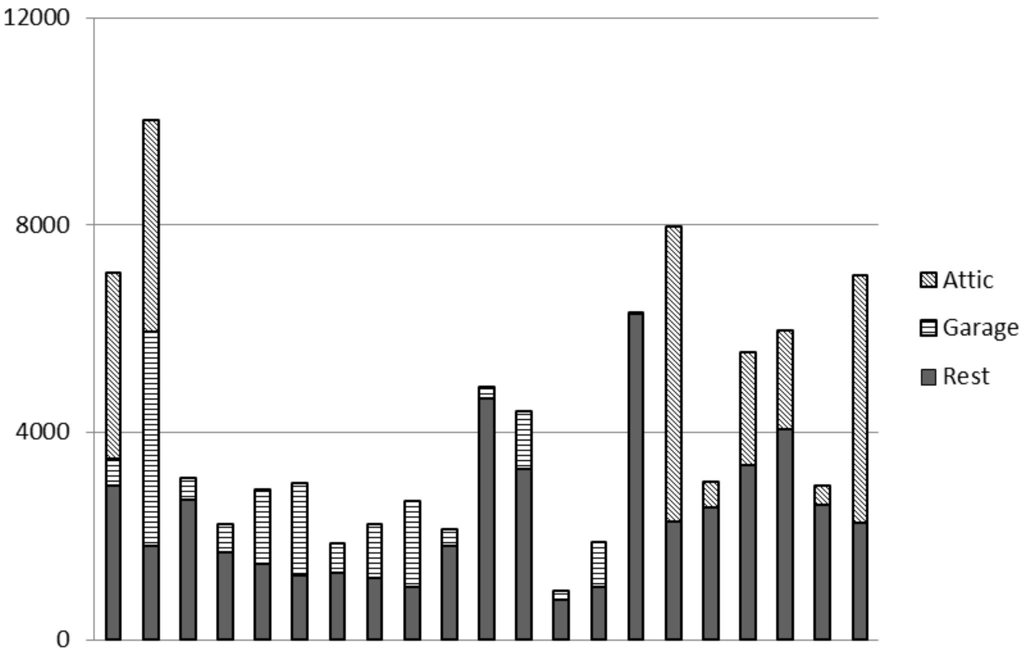

Figure 5. Leakage rate at 50 Pa pressure difference (m^3/h) for the randomly selected test cases with a garage or attic included in the heated volume, with the leakage rate measured in these individual rooms marked in horizontal (garage) and italic (attic) hatches.

Based on this assumption that the leaks are concentrated at specific joints, we can expect that the increase in the number of leaks will be less dominant than the increase in the average size of the individual leaks with increasing leakage levels (Van Den Bossche et al., 2012). This should result in an increasing flow exponent with increasing air tightness. The results of both test groups, as plotted in Figure 6, demonstrate this covariance between leakage level and flow exponent, which is most marked at low leakage levels.

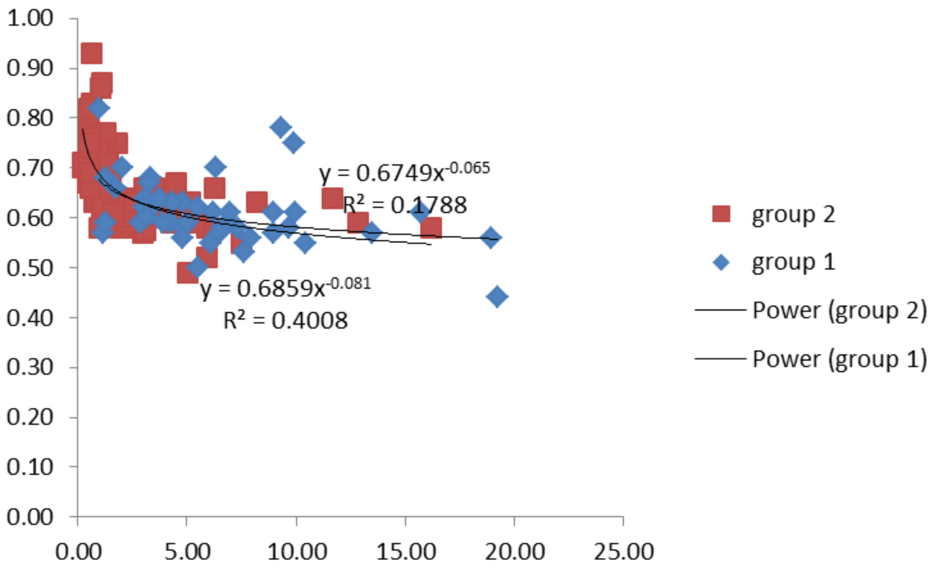

Figure 6. Leakage level (ACH$_{50}$) versus flow exponent for the randomly selected test cases (group 1, N = 44) and the private party consultant cases (group 2, N = 109)

4.3. Workmanship and building envelope design

As was demonstrated in Figure 2, a large difference in results can be associated with the quality of design and workmanship. This is further confirmed by Figure 7, which shows that large differences in leakage level were found between different contractors in the first test group. Note, however, that the number of cases for each contractor is rather small.

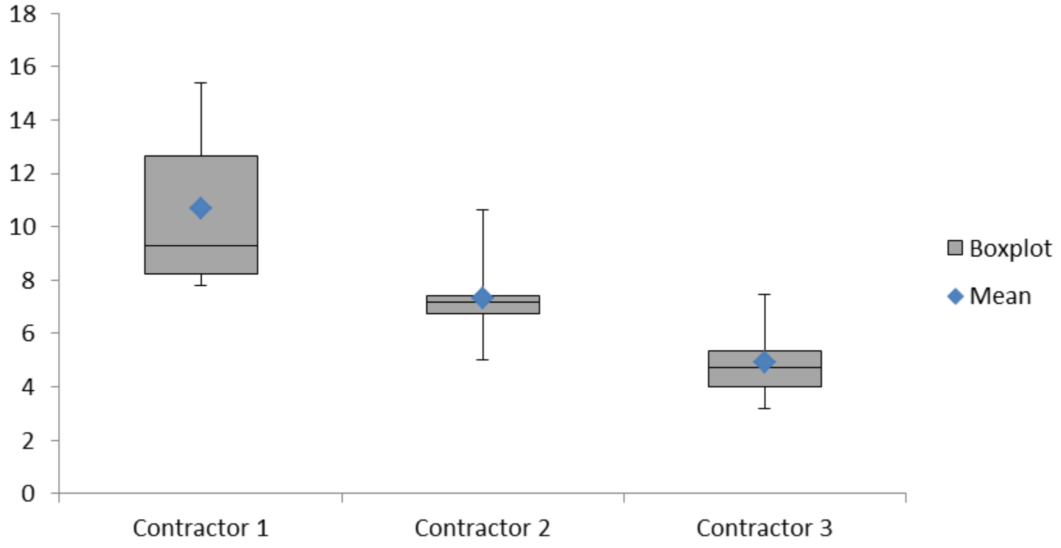

Figure 7. Boxplot of the leakage level (ACH_{50}) for the cases from 3 different contractors in the randomly selected test cases (N = 5, 7 and 6 respectively)

In addition to differences in average quality of workmanship, the results shown in Figure 7 also seem to suggest that there is a large spread in variance of the leakage level achieved by the different contractors. With variance coefficients for all 3 close to 0.3, however, this can't be confirmed. When, as was shown above, average leakage levels go down over time and this trend can be attributed to an increased level of attention to air tightness by all stakeholders in the building process, it is a logical assumption that in this process, the reproducibility of the leakage level will also improve. This was investigated by selecting a single contractor (contractor 3), and testing a number of quasi-identical dwellings built in a single neighborhood in addition to the cases described above. The results from these measurements are compared to those of similar case studies in Figure 8. Case studies 1 and 2 are neighborhoods built in the 1960's, case study 3 is the neighborhood erected by contractor 3 and case study 4 consists of dwellings constructed by a contractor specialized in the construction of passive houses. The variance coefficients decrease with decreasing average leakage from 0.4 for the first 2 case studies to 0.18 for case study 4, with that of case study 3 at 0.28. The larger spread in case studies 1 and 2 is partly caused by differences in usage and punctual retrofits. Since only passive houses are included in case study 4, and this requires a maximum leakage level of 0.6 ACH_{50}, outliers will not appear in this sample. Nevertheless, the progress in reproducibility is remarkable. Note that, although vastly improved, the reproducibility of the workmanship is still far below that of the leakage test itself, the variance coefficient of which is around 0.025 (Delmotte and Laverge, 2011).

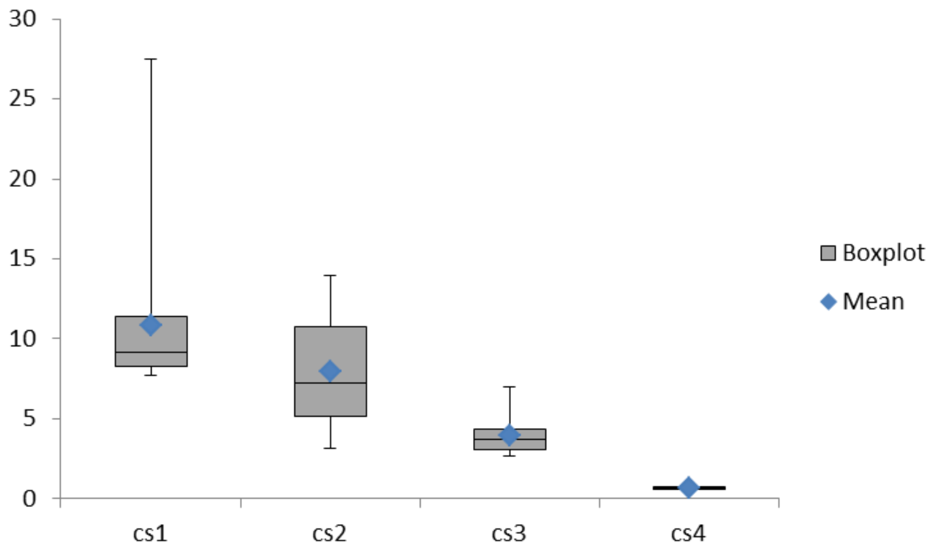

Figure 8. Boxplot of the leakage level (ACH_{50}) for the cases from 4 different case studies of quasi identical houses (N = 24, 15, 29 and 15 respectively)

The selection of a specific type of building envelope is a crucial step in the design of a dwelling. Figure 9 shows the results for different envelope types in the first test group. Although the spread in wood frame houses is larger than that in massive shell construction dwellings, the mean value in both groups is very similar, with a somewhat lower median for the massive shell dwellings. The observed difference is not significant ($p > 0.8$). Note that in this figure, the air leakage at 50 Pa pressure difference per unit of building envelope area (q_{50}) or Minneapolis leakage ratio (MLR) is used, since a unit that references the envelope area is better suited to discuss results for different shell types. Houses having exterior walls with ETICS seem to perform better with an average MLR of 3.7, but the number of test cases for this type of construction is too small for this result to be significant and are therefore not included in the comparison.

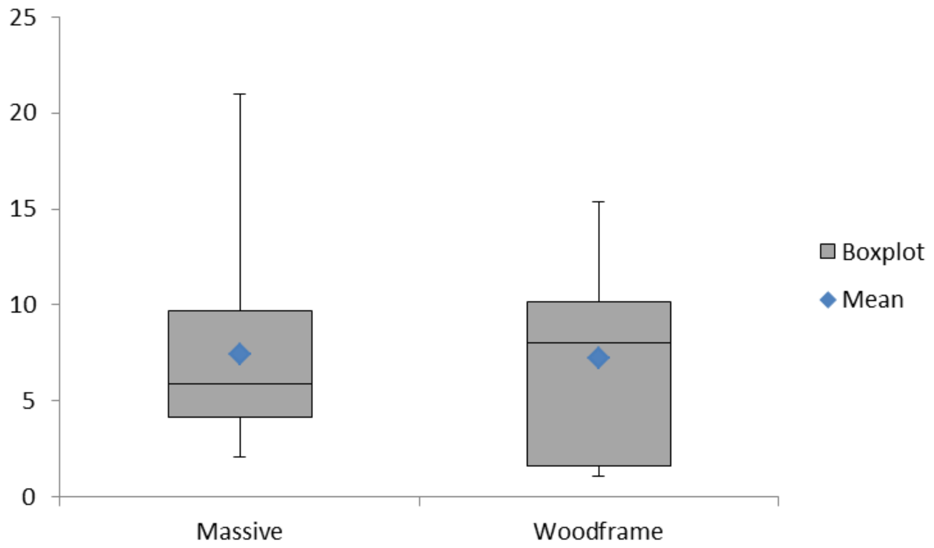

Figure 9. Boxplot of the Minneapolis leakage level (q_{50}, $m^3/(h.m^2)$) for the massive shell and wood frame cases in the randomly selected test cases (group1) (N = 34 and 8 respectively)

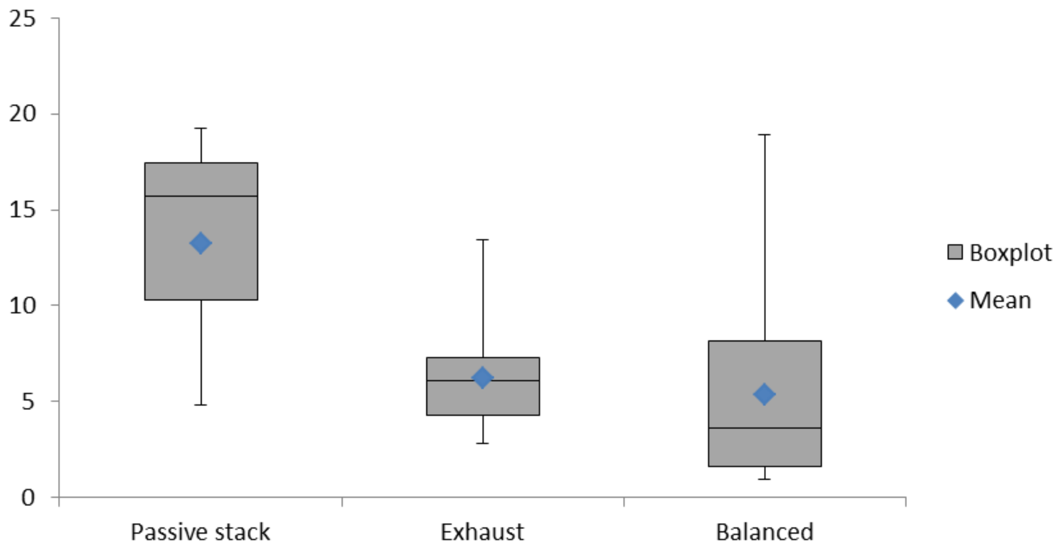

Figure 10. Boxplot of the leakage level (ACH_{50}) for the cases with passive stack ventilation, mechanical exhaust ventilation and balanced mechanical ventilation in the randomly selected test cases (group1)(N = 3, 25 and 16 respectively)

4.4. Ventilation

As can be expected, dwellings in group 1 that were fitted with passive stack ventilation proved to be less airtight than those fitted with a mechanical exhaust or balanced mechanical ventilation (Figure 10). This can easily be explained by the test method that was used. According to the standard, the stacks can only be closed with the shutters that are present (which is rarely the case), while ventilation ducts can be sealed during the test. This also explains the slightly lower flow exponent that was observed in the cases with passive stack ventilation (Figure 11). The stacks represent larger openings in the shell, causing the leakage flow to be more turbulent and thus resulting in a lower flow exponent. Due to the low number of cases with passive stack ventilation, the significance of the difference could not be tested.

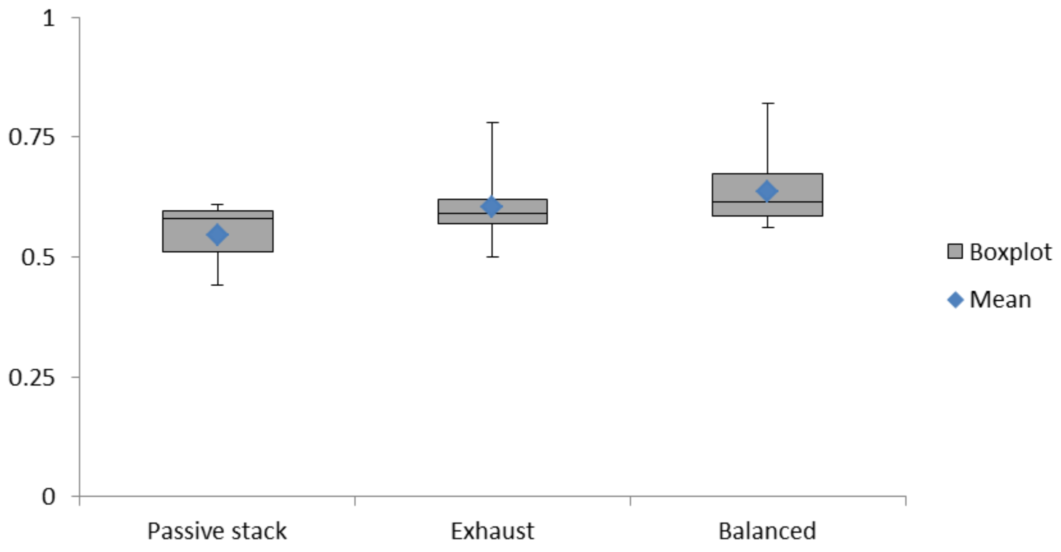

Figure 11. Boxplot of the flow exponent for the cases with passive stack ventilation, mechanical exhaust ventilation and balanced mechanical ventilation in the randomly selected test cases (group1)(N = 3, 25 and 16 respectively)

In group 1, the difference in leakage level between the mechanical exhaust and balanced mechanical ventilation cases was not significant ($p = 0.53$). The entries in the EPBD-database, however, seem to demonstrate a highly significant difference between cases with these two ventilation systems ($p < 10^{-18}$, Figure 12). This result, however, is biased by the fact that engaged owners, and especially those who aspire to obtain a passive house certificate, are much more likely to choose a balanced mechanical ventilation system (De Baets and Jonckheere, 2013). This is also reflected in the respective number of entries for each system in the database, where the balanced mechanical ventilation cases are overrepresented with an odds ratio of 9. Additionally, those projects that aspire to obtain a passive house certificate are required to combine balanced mechanical ventilation with an extremely low leakage rate ($ACH_{50} < 0.6$), which further emphasizes the bias. When the ambitious projects ($ACH_{50} < 3$) are filtered out, there is no longer a significant difference ($N = 299$ and 543 respectively, $p = 0.42$).

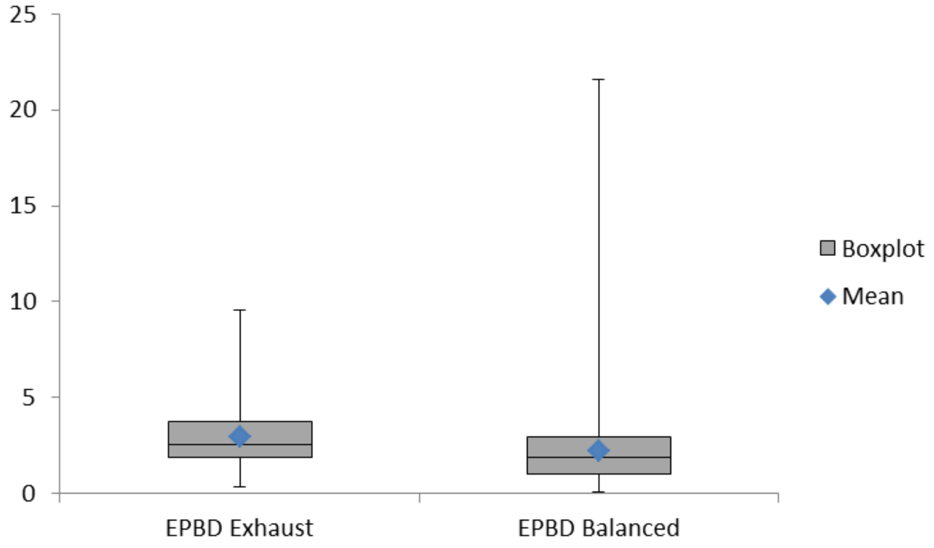

Figure 12. Boxplot of the leakage level (ACH_{50}) for the cases with mechanical exhaust and balanced mechanical ventilation in the EPBD-database (N = 491 and 1349 respectively)

5. CONCLUSIONS

Airtightness tests on two test groups and a number of case studies in Belgium were investigated. The first test group was randomly selected from newly constructed dwellings, built with standard workmanship and according to standard building practice. The second group consisted of measurements requested by the owners and are a reference for dwellings that are intended to be airtight.

Large differences in air tightness can be observed between the two test groups. The results demonstrate that a large portion of the leakage can be attributed to differences in design and workmanship and to large leaks in attics and garages, while the differences between shell types and ventilation system types are less pronounced. The observed differences match well with those observed in previous studies and with the data available in the official EPBD-database.

On the one hand, more care should be given to the sealing of secondary rooms such as garages and attics. On the other, since the access to these rooms is usually closed in normal use conditions, the leaks in these spaces will have a lower impact on total infiltration. Nevertheless, they bypass the insulation and increase transmission losses through (usually uninsulated) partition walls.

The overall air tightness of the standard workmanship test group is still high (ACH_{50} = 6) compared to other EU countries and is about 10 times higher than the passive house standard (ACH_{50} = 0.6), which can be considered to be a best practice standard.

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