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Durability evaluation of adhesive tapes for buildings applications

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Abstract

In the building sector, various adhesive materials are experiencing an increased usage for sealing of overlaps and joints between most commonly used building materials, around penetrations, pipes and windows for increasing the moisture and airtightness of buildings. Among the adhesive materials are adhesive tapes that are used to ensure adequate air tightness of a building and thus must be able to withstand severe environmental conditions without significant long-term deterioration. Durability test methods are needed to evaluate whether the tapes fulfill their performance requirements for the service life of the whole building. However, there is a lack of reliable test methods and evaluation procedures for tapes used for building applications. This study was performed to evaluate tape durability testing and evaluation methods, which hence form a basis for further improvements of the existing methods.

Keywords: Air tightness; Accelerated ageing; Building; Durability; Digital image correlation; Joint; Adhesive; Tape

1. Introduction

Adhesive materials, mainly tapes, and sealants, are becoming increasingly popular for maintaining and/or increasing the moisture and air-tightness of buildings [1]. These products are used to seal joints and overlaps in the wind- and vapour barrier layers, to repair damages, and to tighten ducts (see Figure 1). One benefit is the practical application of adhesive joints, which is simple and quick compared to mechanical tightening solutions. Most importantly, the application of adhesive tapes is essential in order to meet increased airtightness requirements. Both the air tightness of the wind barrier layer on the outside and the vapour barrier on the inside of the building play indeed a major role for the energy efficiency of state of the art buildings. For example, in Norway, since January 2017, the requirement in the Norwegian building regulation (TEK 10) for the infiltration rate at 50 Pa is set to 0.6 h^{-1} for residential buildings, and 1.5 h^{-1} for apartment buildings [2]. Compared to the previous regulation, ,the current required infiltration rate for residential buildings corresponds to about 25% of the original requirement. Hence, adhesive joints have a double role: they ensure both energy efficiency and protection of the building (e.g. avoiding moisture damages).

Adhesive tapes should adhere satisfactorily to the surfaces of end use materials , they should remain unaffected by temperature extremes and the presence of moisture and they should tolerate surface contaminants. As adhesive tapes are concealed in the building envelope and hence less accessible, they need to maintain their sealing function for the intended service life of the envelope (e.g. 50 years, 100 years or longer). The influence of cyclic and climate exposure conditions such as temperature, liquid water and humidity on durability of adhesive tapes used in the building industry is obvious. It is important to identify the adequate properties with their corresponding requirements for specially formulated and targeted adhesive tapes which are able to withstand these exposure conditions and thus are suitable for their intended applications.

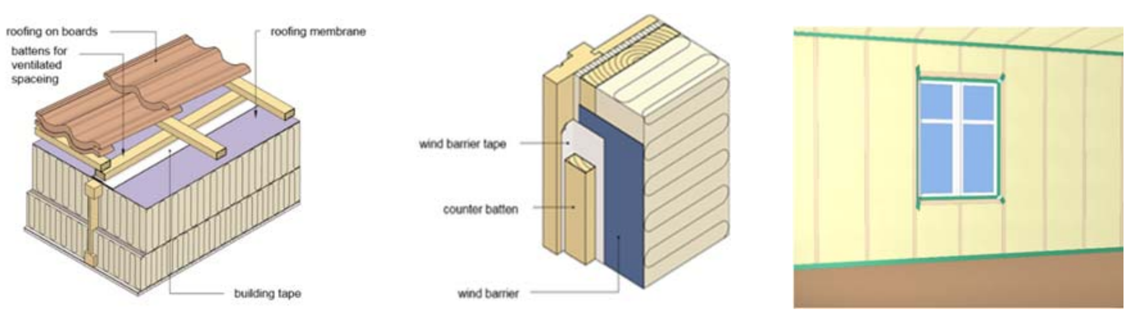


Figure 1 Examples for the use of tapes to increase air tightness in the building envelope. Left: seal an overlap in the roofing membrane. Middle: Seal between the wind barrier and a window frame. Right: vapour barrier tape for sealing of vapour barrier and a window frame (figure adapted from SINTEF).

Durability of joints is therefore important, and accurate and reproducible test methods should evaluate their adhesive properties. Small-scale and large-scale accelerated climate laboratory ageing are widely used as durability evaluation methods. With such methods, main properties of building components or systems and their durability towards climate strains can be investigated within a relatively short period of time. Thus, various accelerated ageing apparatuses are utilized in the laboratory according to different ageing methods and standards. The selection of the apparatuses depends on a number of factors including the type of product or material to be tested, the end-use application, the main degradation modes, and budgetary restrictions. For adhesive tapes, UV resistance, moisture resistance, and thermal resistance properties are important to withstand degradation during the actual construction period and use phase of the building. Thermal resistance is of special importance when adhesive tapes are to be subjected to high temperatures, which may be the case during the construction period or around windows and the roof area [3]. Accelerated ageing experiments may provide information related to the expected service life, the deterioration processes and maintenance schedules of the new systems during their real applications.

To the authors knowledge, such reliable durability test methods (e.g. accelerated ageing procedures and long-term performance prediction methods) are lacking for adhesive tapes used for outdoor building applications [4], despite the existence of different standards [5-8] relevant to tapes used for other application areas. There is only one standard, DIN 4108-11 [9], recently developed by German Institute for Standardization, which describe the minimum requirements to the durability of adhesive tapes used for buildings. However, this national standard is used only for adhesive tapes applied for sealing of vapour barrier layers.

SINTEF Building and Infrastructure (SINTEF) evaluates and documents the performances of building materials, components and construction systems used in Norwegian buildings. This is a requirement given by the Norwegian building authorities (Direktoratet for Byggkvalitet) in the building engineering regulation[2], for building materials used in Norwegian buildings. Among others, SINTEF has performed testing and evaluation of the durability of tapes used in buildings according to SINTEF guidelines for tapes used in buildings [10], in order to evaluate the suitability of the tapes for the use in buildings exposed to the harsh Norwegian climate.

SINTEF guidelines for tapes used in buildings provide test methods for tapes used for sealing both wind barrier and/or vapour barrier building layers. The guideline is based on the standard test methods used for testing roof membranes [11-13], considering the tapes are expected to be exposed to similar climate conditions like the roof membranes. According to the guideline, the durability of the adhesive tape joints is evaluated by exposing the test specimens to main environmental conditions (i.e. water, UV, freeze/thaw and heat) in accelerated laboratory ageing. The durability of the adhesive tapes and adhesive joints is evaluated using two weeks of accelerated ageing in a climate simulator with four repeated cycles, according to NT Build 495 [14], and 24 weeks of heat aging at 70 ^{o}C in accordance with NS-EN 1296 [15]. The tensile strength of the tape and the shear and peel resistance of the adhesive joints are evaluated before and after ageing, and for different tape/substrate interfaces. However, the test is time-consuming (e.g. accelerated ageing tests need 24 weeks), and expensive (e.g. testing of one tape with two end-use substrates leads to testing of more than 30 test specimens). In addition, there is uncertainty on the exposure condition of vapour barrier tapes and wind barrier tapes in the accelerated ageing chamber. The objective of this study is twofold, i.e. to evaluate existing tape durability test methods and explore possible future research perspectives. These results from this work are expected to help establishing guidelines for a new testing scheme. Possible future perspectives are also discussed.

2. Methodology

The methodology section of this paper is divided into two parts. The first part outlines the durability test and evaluation methods, designed and performed. It includes the description of materials used for testing, accelerated aging test method used to evaluate the effect of different weathering factors and description of the test methods used to evaluate the performance of the adhesion bonds. This first part also describes the statistical and sensitivity analysis used for the evaluation of the adhesion test results.

The second part outlines the test method used to quantify the effect of wind load on the adhesive properties of wind barrier and adhesive tape joints.

2.1 Test methods

2.1.1 Materials

Adhesive tapes are viscoelastic materials (i.e. have both viscous and elastic properties) that adhere to a surface only by applying a light pressure [16]. Because of their viscous properties, they can flow easily and be able to dissipate energy during the adhesive bonding process to the substrate. They also resist separation under stress due to their elasticity. The degree of wetting is one of the criteria for good adhesion and it mainly depends on the difference between the surface energy of adhesive and substrate. Surface energy is sensitive to the surface chemistry and the morphology of the surface. For example, metals and glass have a high surface energy and are easier to bond; whereas plastics have a lower surface energy and are harder to bond. Wood fiberboards concrete, bricks and certain types of oriented strand boards (OSB) require a high quality primer in order to improve adhesion as the surfaces of these materials may delaminate when the adhesive tape is applied. For adhesive tapes applied to rough and textured surfaces, the ability of the adhesives to flow and fill out different textured surfaces is crucial. When dealing with difficult-to-bond substrates and critical applications, use of primer or special adhesive enhancing formulations may help to ensure predictable adhesion conditions.

The surface of the substrate where the adhesive tape is glued must be clean, dry, grease- and solvent-free for a good adhesion. Besides the properties of the adhesive and the substrate characteristics, stress conditions (e.g. weathering) and end use environment (e.g. indoor use or outdoor use) are other factors which affect the performance of the adhesive tape.

Four types of single-sided acrylic tapes and seven types of substrates were selected to evaluate the adhesion and cohesion performance of adhesive tapes. Two of the tapes are designed for indoor applications and the other two are designed for outdoor applications. The seven substrates used represent typical materials in which the tape is applied. The description of the test specimens along with the notation system used in this study are presented in Table 1.

The four tapes (S, E, I and W) were applied on the selected substrates (WT, WI, VT, S, CS, G, GS) and preconditioned at a temperature of (23 ± 2) ºC and a relative humidity of (50 ± 2) % for 48 h before the test.

Table 1 Tapes and substrates used in the experiments.

Description of the acrylic tapes and substrates used in the test			
Tapes	**Description**		**Notation**
	Adhesive	Backing	
Tapes for indoor applications	Modified acrylic adhesive	PE coated paper backing	S
	Modified acrylic adhesive	PE film backing	E
Tapes for outdoor applications	Modified acrylic adhesive	Grid fabric of PE film backing	I
	Modified acrylic adhesive	Polyolefine backing	W
Substrates	**Description**		**Notation**
Wind barriers	PE based wind barrier		WT
	PP based wind barrier		WI
Vapour barrier	PE based vapour barrier		VT
Uncoated spruce	Planed wood		S
Coated spruce	Wood coated with water based paint		CS
Glass	-		G
Galvanized steel	-		GS

2.1.2 Accelerated ageing

Accelerated ageing tests are used to predict the long-term performance of joints. Two different accelerated ageing test series were selected**:**

- In the first ageing test series, the materials were first exposed to two weeks of climate ageing in a vertical climate simulator, according to NT Build 495 [14]. In the vertical climate simulator, the samples are subjected in turns to four different climate exposure conditions; ultraviolet (UV) and infrared irradiation (black panel temperature of 63 °C), water spray (15 $dm^3/(m^2\ h)$), freezing (−20 °C) and ambient laboratory conditions. The exposure time is 1 h for each climate condition. The samples are then subjected to 24 weeks of heat ageing at 70 ºC in heat chamber, according to NS-EN 1296. The temperature of 70 °C was used since the maximum temperature of 60 °C to 70 °C is the normally accepted upper safe temperature limit for accelerated ageing of polymers [17]. However, also note that higher temperatures may occur for shorter period at extreme conditions, e.g. up to 90 °C under dark coloured roof tiles.
- In the second ageing test series, the test specimens were directly exposed to 24 weeks of heat ageing at 70 °C in a heat chamber according to NS-EN 1296 [15].

The two weeks of climate ageing test (in the first ageing test series) are used to simulate the potential maximum outdoor climate exposure of tapes during the construction period, whereas the 24 weeks of heat ageing (in the first and second ageing test series) simulate the potential ageing of the tapes during their intended use.

Untreated (fresh) test specimens and aged specimens, after 2, 8, 12 and 24 weeks of ageing, were evaluated. Untreated (fresh) test specimens were used as a reference for comparison of the ageing result with aged specimens. The notation system used for the two ageing series and test intervals is summarized in Table 2.

Table 2 Accelerated ageing and test intervals (with notation system used)

Ageing	***Test interval***					
Test series 1: Climate and heat ageing	Fresh (f)	After 2 weeks climate ageing (c)	After 2 weeks heat ageing (1)	After 8 weeks heat ageing (2)	After 12 weeks heat ageing (3)	After 24 weeks heat ageing (4)
Test series 2: Heat ageing		After 2 weeks heat ageing (1h)	After 8weeks heat ageing (2h)	After 12 weeks heat ageing (3h)	After 24 weeks heat ageing (4h)	

2.1.3 Test methods for determination of the performance of adhesive joints

Adhesion to a surface and cohesion or internal strength properties of adhesive tapes determine the sticky nature of adhesive tapes. Adhesion is the binding force between two different materials, whereas cohesion is the binding force between two similar materials. Peel and shear resistance test methods are used to evaluate the adhesion and cohesion performance of adhesive joints.

Peel resistance is the force required to peel an adhesive tape from a specified substrate at a specified angle and speed. The peel resistance gives information about the bond strength between the adhesive tape and the substrate. The peel force measured is not an inherent property of the adhesive, but depends on many variables such as the test method, temperature, peel rate, adhesive chemistry, adhesive thickness, ageing, the stiffness and thickness of the adhesive backing and properties of the substrate [18].

180 degree peel test, 90 degree peel test and T-peel test are the three main types of peel tests. The 90 and 180 degree peel tests are commonly used when an adhesive tape is adhered to a more rigid substrate (e.g. wood) while the T-peel test is used for tape applied to thin, flexible substrates (e.g. polyethylene vapour barrier). Even if both 90 degree and 180 degree peel tests are peeled at the same testing rate, the peel rate for 90 degree is greater than for the 180 degree [18].

The shear resistance is a measure of the internal strength or cohesiveness of an adhesive. For tapes sealing joints, they will be exposed to sustained forces caused by different rates of expansion and contraction of the surfaces on both sides of the joint. High shear resistance of the adhesive tapes used to cover joints is thus important to create an air and/or moisture seal which absorbs stress and movement to help structures stay strong and safe [3, 19].

In this work, the peel and shear resistance of adhesive tapes glued to essential end-use substrates were evaluated before and after accelerated ageing according to NS-EN 12316-2 [12] and NS-EN 12317-2 [13], respectively (see Figure 2). The tests were carried out using a universal testing machine (Zwick MT-411).

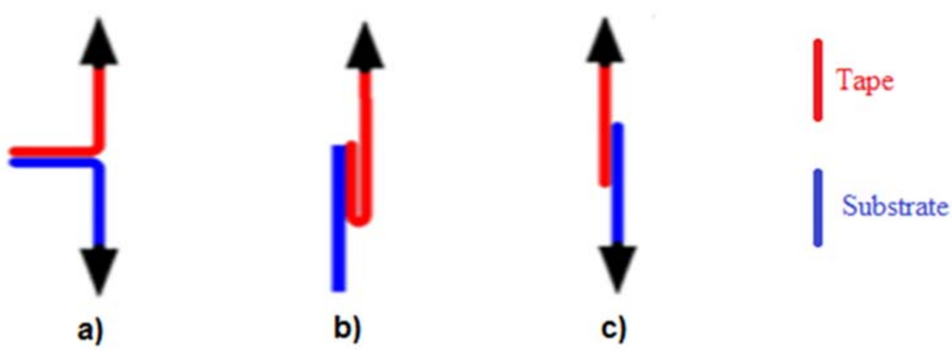


Figure 2 Schematic diagram of peel resistance tests (T-peel resistance test of tape adhered to flexible substrate (a) and 180 degree peel resistance test of tape adhered to rigid substrate (b)) and shear resistance (c) tests, adapted from [4].

The test methods, test specimen dimensions and the number of test specimen's replicate used are summarized in Table 3.

Table 3 Test methods,test specimen sizes and number of test specimen's replicate.

	Peel resistance test	

	T-peel (for tapes applied to flexible substrates)	***180 degree (for tapes applied to rigid substrates)***	***Shear resistance test***
Standards	NS-EN 12316-2 [12]	NS-EN 12316-2 [12]	NS-EN 12317-2 [13]
Grip distance (mm)	100 ± 2	200 ± 2	120 ± 2
Grip separation speed (mm/min)	100 ± 10	100 ± 10	100 ± 10
Sample size (width x length) mm, for tapes	(50 x 300) ± 0.5	(50 x 300) ± 0.5	(50 x 220) ± 0.5
Sample size (width x length) mm, for substrates	(70 x 220)±0.5	(70 x 220) ± 0.5	(70 x 220) ± 0.5
Number of test specimens replicas used for Test series 1	5	5	3
Number of test specimens replicas used for Test series 2	3	3	3
Total number of test specimens tested	990		594

2.1.4 Statistical treatment of the results

A total of 1584 evaluations were performed and are classified into different *configurations* and different *evaluations*. A *configuration* is defined by a tape: *t*, a substrate: *s*, and an exposure: *e*. An *evaluation* X can be either peel resistance: PR or shear resistance: SR. For each evaluation, between three and five replicates were used. The replicate number is referred to as *i*, and the number of replicates is referred to as *n* in the following.

It is assumed that most of the evaluations *X* collected under a given configuration are representative of a unique population. Evaluations are identified that are collected under a given configuration, but do not belong to the assumed population, e.g. external perturbation during the test.

The criterion for identifying an evaluation *X* not belonging to the assumed population for a given configuration is adapted from Minitab statistical software (2010), and is defined as follows:

$$\begin{cases} \text{If } X \in \left[Q_1 - 1.5\left(Q_3 - Q_1\right); Q_3 + 1.5\left(Q_3 - Q_1\right)\right], \text{ then } X \text{ belongs to the population} \\ \text{If } X \notin \left[Q_1 - 1.5\left(Q_3 - Q_1\right); Q_3 + 1.5\left(Q_3 - Q_1\right)\right], \text{ then } X \text{ does not belong to the population} \end{cases} \quad (1)$$

where Q_1 and Q_3 are the lower and upper quartiles [20], respectively. The following statistical indicators are computed. The mean value $\overline{X}$ is defined as:

$$\overline{X} = \sum_{i=1}^{n} \frac{X_i}{n} \quad (2)$$

The standard deviation S^2 is defined as:

$$S^2 = \sqrt{\sum_{i=1}^{n} \frac{\left(X_i - \overline{X}\right)^2}{n-1}} \quad (3)$$

2.1.5 Sensitivity analysis

The statistical design of experiments (DOE) methodology [20] was used for identification and correlation of the significant factors that affect the mechanical properties of the taped joints. Three general factors: exposure times, substrates, and tapes, were selected as input variables, and two adhesive properties: peel resistance and shear resistance, were selected as output variables. The three factors and their levels are shown in Table 4.

Table 4 Factors and levels used for the full factorial design.

Factors	***Levels***
Exposure time e	c, 1, 2, 3, 4, f, h2, h8, h12,h24
Substrate s	GS, G, S, CS, WT, WI,VT

Tape t	I, W, E, S

Statistical evaluation of the data was performed using Minitab 17 software. The main response value compares the relative strength of the various factors on a selected response. For example, the main effect of a given tape t_1 is defined as:

$$\bar{\bar{X}}_{t_1} = \bar{X}_{\text{for } t=t_1} \quad (4)$$

The interaction value quantifies the interaction of two factors at all possible combinations on the mean response. For example, the interaction of a given tape t_1 and a given substrate s_1 is defined as:

$$X_{t_1 s_1} = \bar{X}_{\text{for } t=t_1 \text{ and } s=s_1} \quad (5)$$

2.2 Digital image correlation

Digital image correlation (DIC) was employed for measuring full-field displacements of wind-barriers membrane (WT) joined by adhesive tapes (W) under wind loads. Wind loads were applied according to the experimental protocol described in standard EN 12211:2000 [21]. Two loading protocols were followed, according to the wind resistance method given in Annex B of the standard EN 12211:2000:

- Loading protocol 1: a maximum dynamic pressure equivalent to a strong breeze (P_1 = 40 km/h, positive pressure) is progressively applied from the inside of the test specimen. A negative pressure is then progressively applied to the inside of the test specimen in order to reach - 40 km/h ($-P_1$) wind speed in the opposite direction (from outside to inside).
- Loading protocol 2: a maximum dynamic pressure equivalent to a violent storm (P_1 = 113 km/h, positive pressure) is progressively applied from the inside of the test specimen.

The test specimen construction corresponds to a typical Scandinavian timber frame construction with 36 mm × 148 mm solid timber studs at a spacing of 600 mm between timber studs, as recommended by [22], and shown in Figure 3a). A two-part wind-barrier membrane of type *WT* was fixed to each studs be means of staples every 20 cm. A 50 cm wide adhesive tape of type *S* was used to join the different parts of the wind-barrier membrane. The overlapping joint was located 20 cm from the nearest timber stud, and 40 cm away from the furthest stud.

Prior to the test, a surface of approximately 30 cm x 30 cm was spray-painted with an alcohol free acrylic black paint on the outside of the test specimen. A perforated plate with a regular pattern was used to ensure a fine-grained and high contrast speckle pattern, see Figure 3b). During testing, grey-scale images of the speckle-patterned specimen surface were recorded at a framing rate of 1 Hz using two Prosilica GC2450 digital cameras equipped with a 28 – 105 mm Nikon lens, see Figure 3c). The recorded images were post-processed using an in-house three-dimensional DIC software [23] in order to compute displacement and strain fields of the specimen.

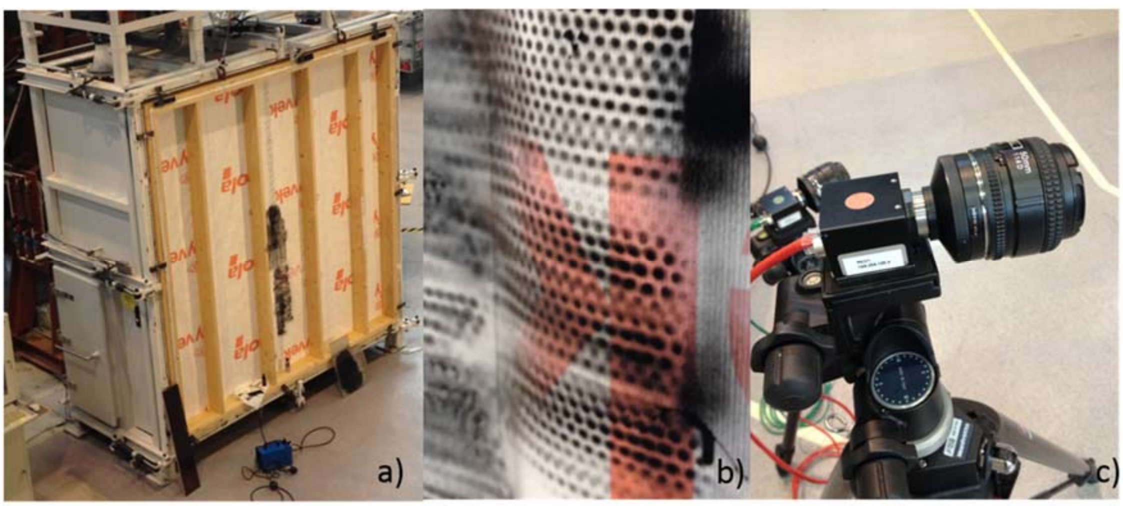


Figure 3 a) Full scale test specimen, b) Speckle pattern on both the tape (W) and the wind barrier (WT), and c) One of the digital cameras used for recording images.

3. Results

3.1 Peel and shear resistance

3.1.1 Wind barrier tapes

The mean peel resistance and shear resistance for wind barrier tapes from test series 1 (2 weeks climate ageing and 24 weeks' heat ageing) are presented in Figure 4**.**

The results show significant reduction in peel resistance with exposure time and relatively higher peel values for rigid substrates (GS, G, S and CS) compared to wind barriers (WT, WI). From rigid substrate, the lowest peel resistance for S (uncoated spruce) can be due to the effect of exposure on the adhesive-substrate interface. However, there was slight reduction in shear resistance with respect to exposure time and type of substrate. There was also significant difference in shear resistance between the two types of wind barrier tapes (I, W) with respect to exposure time and type of substrate, although the peel resistance was almost similar. The difference in the chemical composition of the two tapes can be one reason for the variation of the results. These results may be summarized as follows:

- In general, W tape is less affected by increase in exposure and type of substrates but has a lower peel and shear resistance compared to I tape.
- In particular, type of exposure and choice of substrate have a non-significant effect on shear resistance of W tape.
- The lowest peel and shear resistance of WT with respect to type of exposure and the two tapes can be due to the lower surface energy properties of the polyethylene based substrate, WT. It is also stated by Maassen et al. [24] that polyethylene, polypropylene and other commonly used polyolefines exhibit a low surface energy, and that adhesion of adhesive tape to such substrates is still a challenge.
- The effect of exposure is more significant for peel resistance: mean reduction of up to 50% of the measured performance, than for shear resistance: mean reduction of up to 30% of the measured performance. These show that the surface properties of the substrate and exposure condition have significant effect on the peel adhesion tests.
- Exposure has a less significant effect on the shear resistance, and all substrates are observed to experience a sharp reduction of performance during the last period of the aging protocol.
- The only notable exception to this pattern is the WT substrate, which exhibits a sharp reduction of performance at the very beginning of aging protocol, and then maintains an almost constant performance to the end of the aging protocol. This can be due to the substrate-adhesive interface properties.

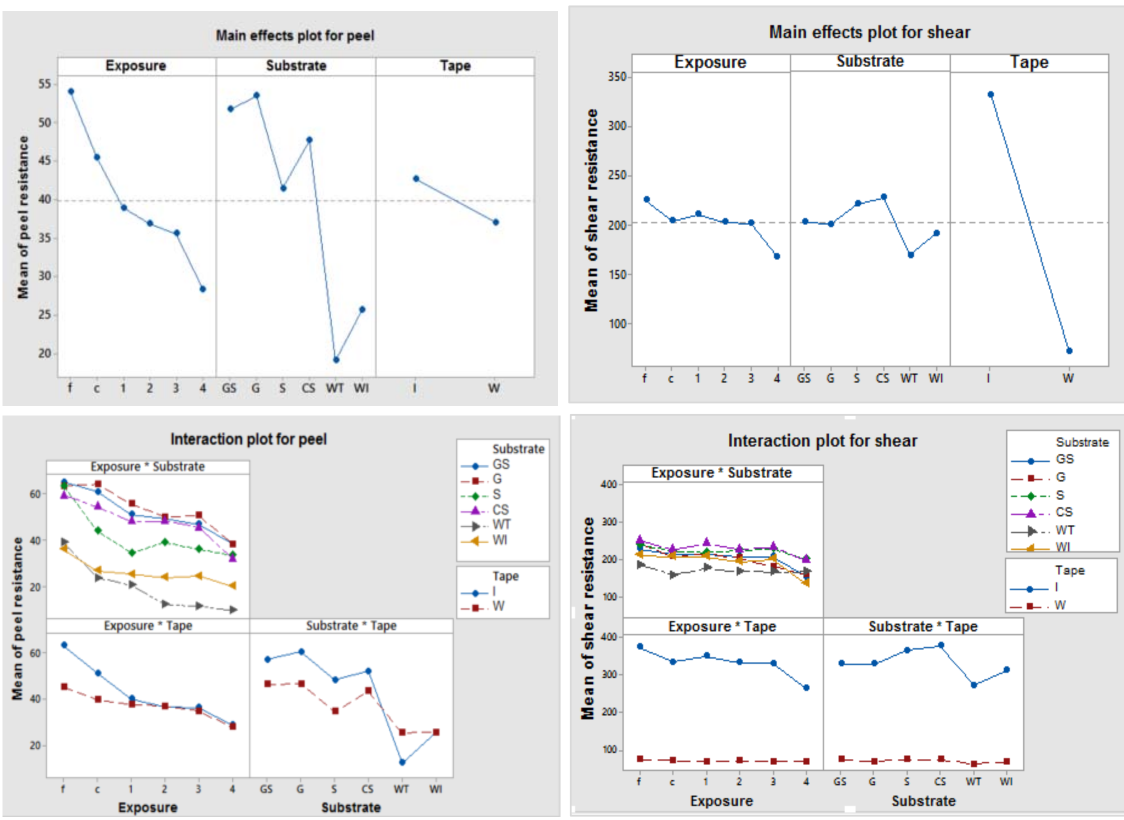


Figure 4 The main effect and interaction plot of factors on the mean peel and shear resistance for wind barrier tapes exposed to 2 weeks climate ageing and 24 weeks of heat ageing (test series 1).

The mean peel and shear resistance results for wind barrier tapes investigated in test series 2 (24 weeks heat aging) (Figure 5) were showing almost similar trends as test series 1 (Figure 4). The lack of climate aging protocol results in the following differences:

- Slightly general higher performance with respect to both peel resistance (+12%) and shear resistance (+4%).
- The effect of exposure onto peel resistance is observed to be "delayed" for tape I, since the reduction of performance is significant only from the third period of the aging protocol.

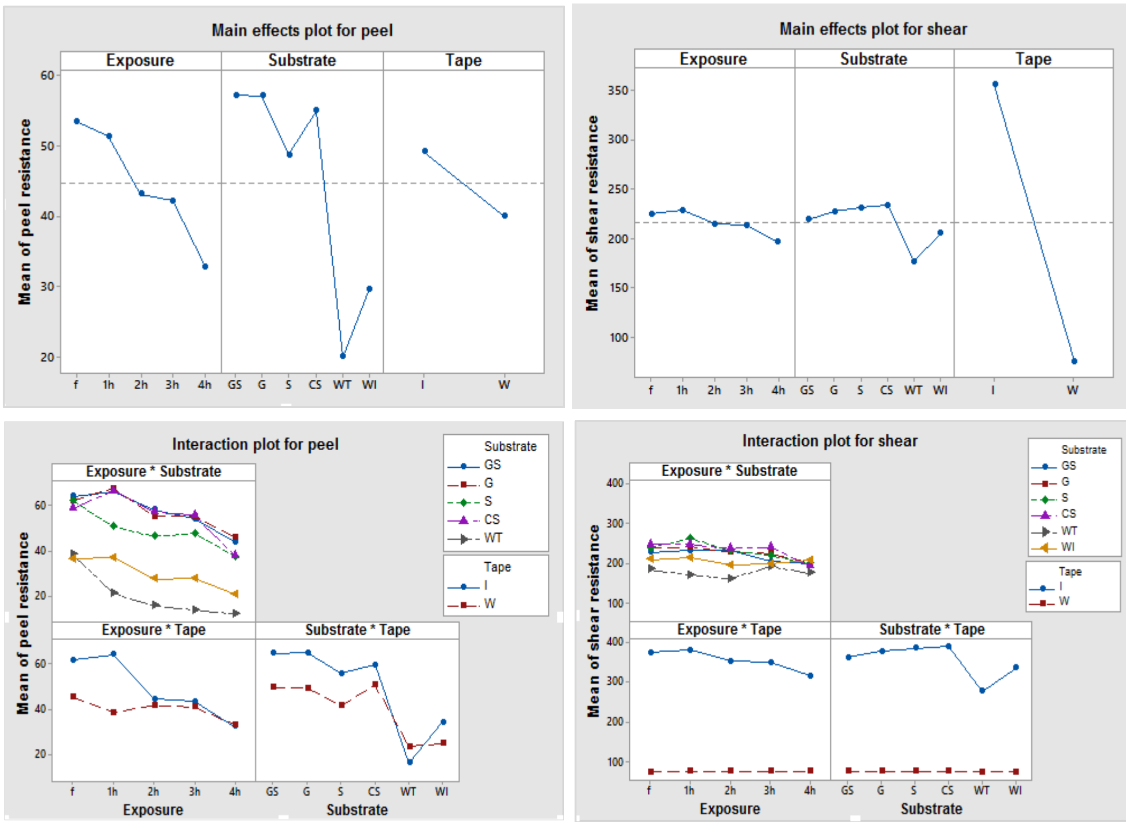


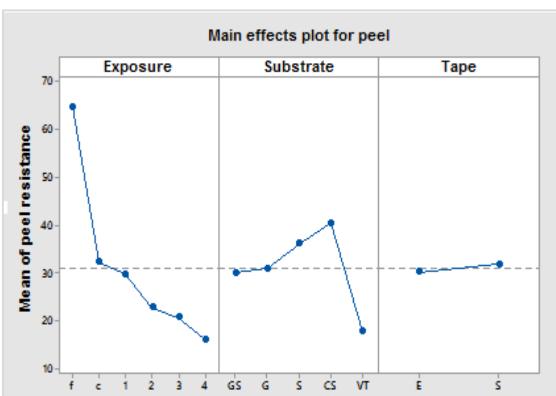
Figure 5 The main effect and interaction plot of factors on the mean peel and shear resistance for wind barrier tapes exposed to 24 weeks of heat ageing (test series 2).

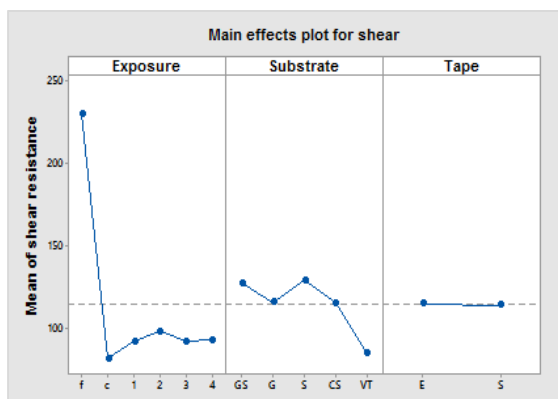
3.1.2 Vapour barrier tapes

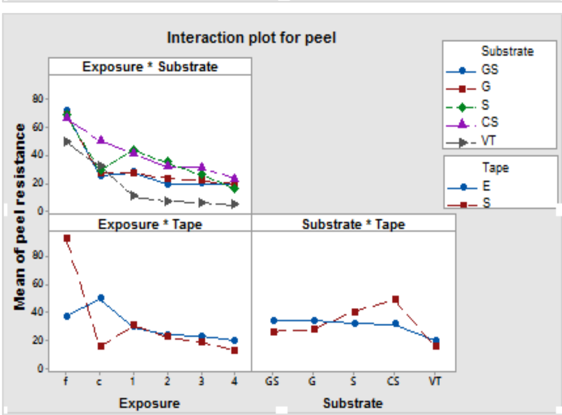
Figure 6 and Figure 7 present the mean peel and shear resistance for the vapour barrier tapes from test series 1 and test series 2, respectively.

The results from test series 1 (Figure 6) showed significant reduction in the peel and shear resistance of S tape after 2 weeks of climate ageing (c). The peel resistance keeps on decreasing with increase in exposure time while the shear resistance changes very slightly. It was also observed that the peel and shear resistance for rigid substrates (GS, G, S and CS) were higher than that for the vapour barrier (VT). However, the peel and shear resistance between the two types of vapour barrier tapes (E, S) with respect to exposure time and type of substrate (except for CS) were nearly similar. These results may be summarized as follows:

- Both peel resistance and shear resistance of S tape are substantially affected by climate ageing (c), and are slightly affected by choice of substrate. The response of S to different exposure condition can be due to the properties of adhesive and backing composition and adhesive-substrate interfaces. The significant reduction in peel and shear resistance of S tape is due to the effect of moisture on the paper backing of S tape during climate ageing. This may be due to that S tape is exposed to an environment where it was not designed. That means, S tape is designed to be used for indoor application where climate exposure is limited.
- Peel resistance of tape E increases after 2 weeks of climate ageing (c). This can be due to the effect of temperature during ageing in the heat chamber. The temperature may soften the adhesive and wet the substrate, which leads to increase in the peel resistance.
- Shear resistance of tape E is not significantly affected by exposure type or by choice of substrates. The exposure to heat ageing can reduce the shear resistance of the tape due to the softness of adhesive (which reduces the cohesion force). However, the reduction in shear resistance is very slow and steady.







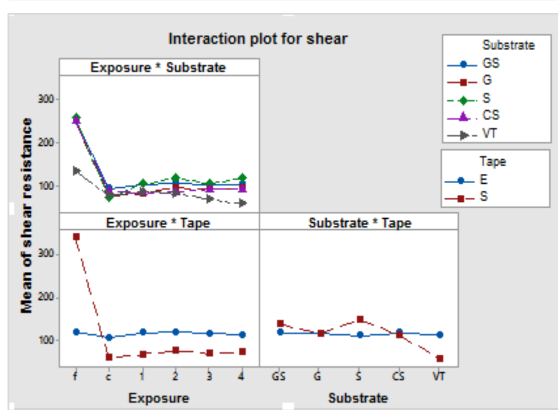


Figure 6 The main effect and interaction plot of factors on the mean peel and shear resistance for vapour barrier tapes exposed to 2 weeks climate ageing and 24 weeks of heat ageing (test series 1).

The results from test series 2 (Figure 7, 24 weeks of heat ageing) indicated that the peel resistance reduced significantly with exposure time, while the shear resistance remains similar. It was also observed that the peel and shear resistance of rigid substrates (GS, G, S and CS) were higher than for the vapour barrier (VT). In addition, the peel and shear resistance of S tape was significantly higher than E with respect to exposure time and type of substrate (except for VT). Here it should be noted that, the properties of the different backings used in adhesive tapes can influence the peel and shear resistance. These results may be summarized as follows:

- The lower peel and shear resistance of substrate VT compared to all other tested substrates may be due to the lower surface energy of VT.
- Shear resistance of both E and S tapes is not significantly affected by the type of exposure.

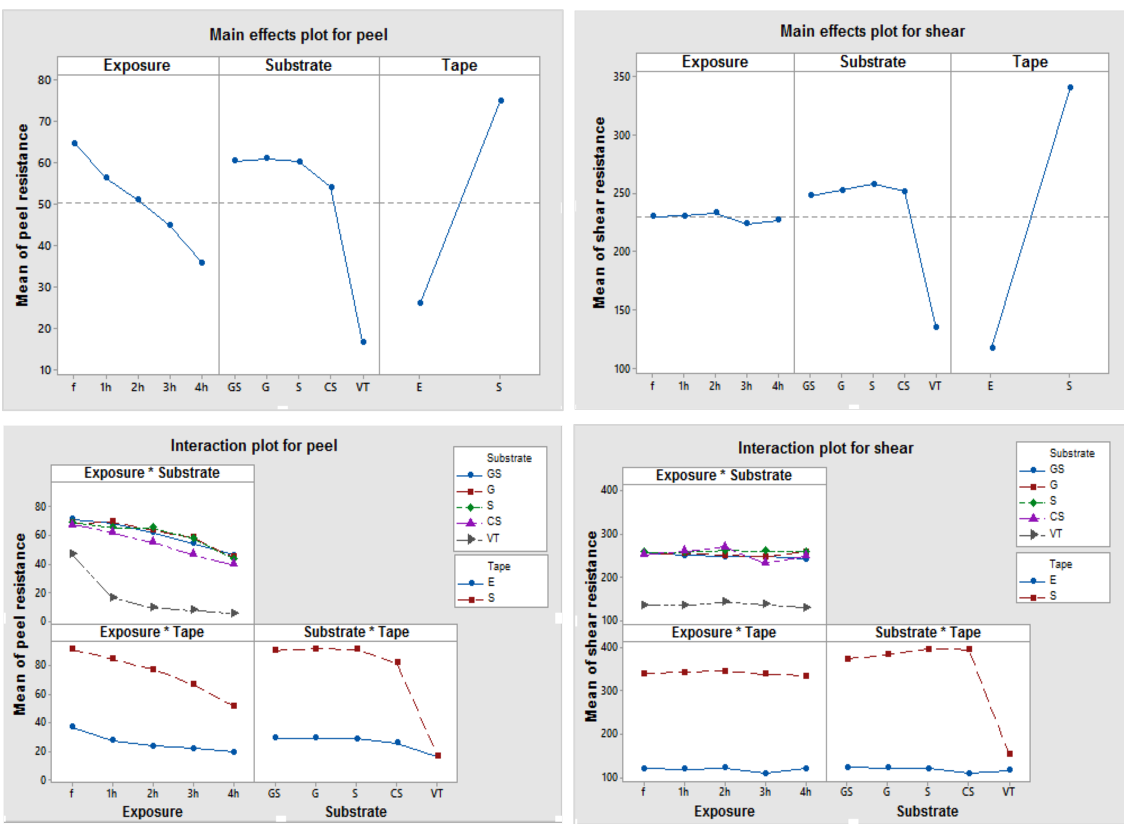


Figure 7 The main effect and interaction plot of factors on the mean peel and shear resistance for vapour barrier tapes exposed to 24 weeks of heat ageing (test series 2).

The peel and shear resistance results of vapour barrier tape joints exposed to test series 1 (2 weeks of climate ageing and 24 weeks of heat ageing) were significantly affected by climate ageing.

3.2 Digital image correlation

Results from the digital image correlation (DIC) experiments show limited permanent deformation of the test specimens after the first loading protocol, see Figure 8b, and substantial permanent deformation after the second loading protocol, see Figure 8c. The initial undeformed speckle pattern is given in Figure 8a for easy comparison.

After the first loading protocol, just a slight change in the speckle pattern is visible compared to the initial speckle pattern. At the right side of the tape the speckle pattern is hardly widened. After the second loading protocol, stronger deformation of the speckle pattern is visible at the edges of the tape. Clear white lines are observed.

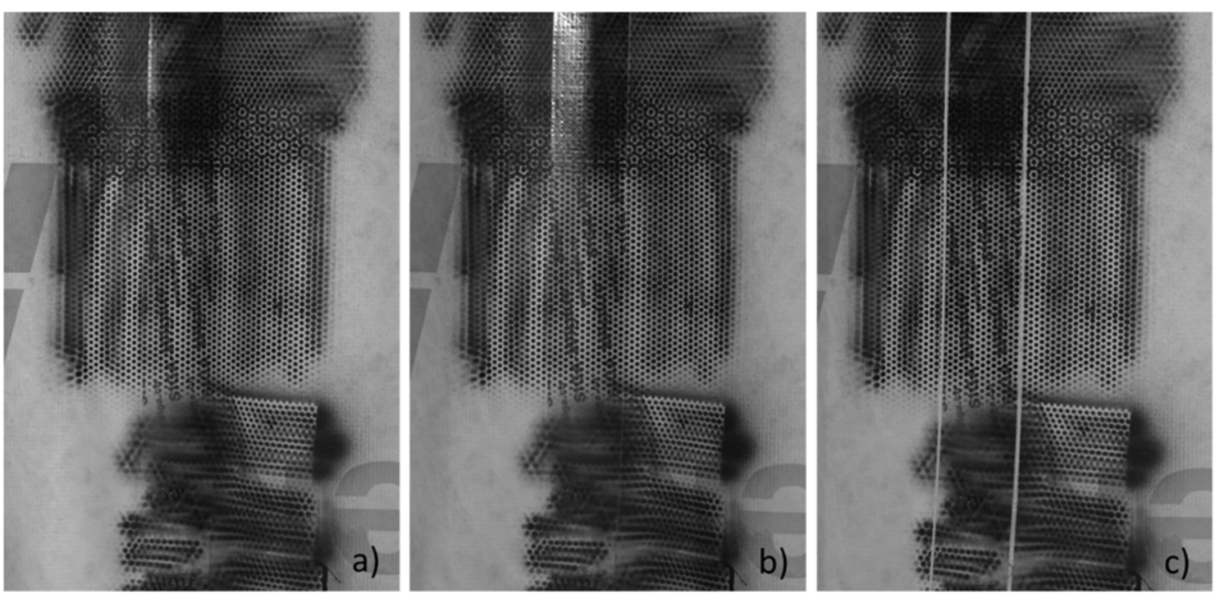


Figure 8a) Initial speckle pattern, b) deformed speckle pattern after loading protocol 1, and c) deformed speckle pattern after loading protocol 2.

Detailed analyses of the evolution of the strain field (Figure 9) suggest adhesive degradation or deformation and a consequent sliding of the tape across the wind barrier. However, the deformation and sliding of the tape is relatively small. Further analysis of the degradation processes as well as better understanding of the mechanical properties of the bonding between tape and substrate are therefore required.

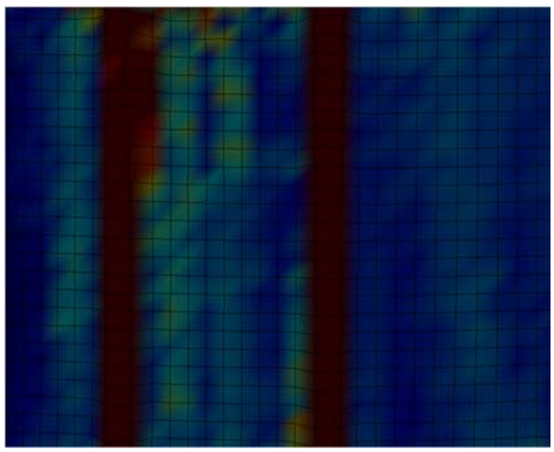


Figure 9 An example of strain field obtained from post-processing. Blue colour no movement. Green colour little movement. Red colour large movement

4. Discussions and future research perspectives

The scope of this work was limited to evaluation of the durability of adhesive joints based on mechanical tests. The chemical properties of the adhesive joints before, during and after the accelerated ageing test were not evaluated. In further work, detail investigation on the chemical properties of adhesive joints should be incorporated. Fourier transform infrared spectroscopy (FTIR) analysis can be used as a potential surface characterization technique to understand chemical composition of the adhesive tape and the chemical changes in the adhesive joints before, during and after ageing. Scanning electron microscope (SEM) is another possible method, where elemental analysis through energy-dispersive x-ray spectroscopy (EDS) embedded in the SEM can be used for extracting information about chemical changes during ageing processes.

The peel and shear resistance results of vapour barrier tape joints exposed to test series 1 (2 weeks of climate ageing and 24 weeks of heat ageing) were significantly affected by 2 weeks climate ageing. The results from test series 2 (24 weeks of heat ageing) indicated that the peel resistance reduced significantly with exposure time, while the shear resistance remains similar. In real world conditions, the probability of these joints to be exposed to rain and frost might be limited as these tapes are intended for indoor use. It was argued that the vapour barrier tapes should be exposed to only 24 weeks of heat ageing provided the tapes will not be exposed to solar radiation and moisture during the construction period of the building (for example exposure to rain or frost before the roof has been covered). However, the possibility of the vapour barrier tapes exposure to solar radiation during for example transportation, storage, or installation, was also discussed. Thus, to ensure that the vapour barrier tapes withstand any solar radiation exposures, it is recommended to expose vapour barrier tapes for three days in horizontal ageing apparatus followed by 24 weeks of heat ageing. The horizontal ageing apparatus is a non-commercial accelerated ageing apparatus, which is used for exposing materials to a combined horizontal UV, temperature and water spray on a consecutive basis according to EN 1297[17]. Due to the possibility of exposure of the wind barrier tapes to different exterior climate conditions during the construction period (before the building is covered with cladding), it is recommended to expose wind barrier tapes for 2 weeks climate ageing before the 24 weeks of heat ageing.

Accelerated ageing experiments may provide information related to the expected actual service life of a product, the deterioration processes and maintenance schedules of the new systems during their real applications. One of the critical aspects of durability testing is prediction of the equivalent service life of products from accelerated ageing tests. That means, for example an estimation of the equivalent actual service life of adhesive tape after accelerated ageing for 2 weeks in climate simulator and 24 weeks in heat chamber at 70 ˚C (test series 1). Service life estimations are important for several reasons including for comparison of different products, giving warranties, making life time cost calculation, and establish requirements for maintenance and renovation. The rate of degradation in the accelerated ageing test chamber can be compared with actual outdoor exposure using an acceleration factor, a number correlating the ageing time in the test chamber with actual natural outdoor ageing exposure. A simplified calculation methodology has been used to calculate an acceleration factor [17, 25]. However, this methodology is developed using a number of assumptions. The calculation considered the effect from UV and temperature while the influence from other climate strains such as moisture exposure, has not been included. In addition, the calculation is very dependent on the choice of reference natural temperature. It is also difficult to give a precise comparison between artificial and natural aging. The outdoor exposure can vary a lot depending on the weather conditions where the building is situated and how strongly it is exposed for example solar radiation, rain, heat and frost. In this work, the service life estimation of the adhesive tapes is not included. It is recommended to investigate and elaborate existing service life estimation method and evaluate how accelerated ageing test results of joints simulate the actual service life conditions.

Although standard test substrates, such as glass and steel, are used as a standard test plates, glass and galvanized steel along with main end-use substrates have been tested in order to evaluate the actual substrate/interface property. The test results of peel and shear resistance of wind barrier and vapour barrier tapes adhered to hard substrates i.e. galvanized steel (GS), glass (G), coated spruce (CS) and planed spruce (S) are almost similar. This might indicate the possibility of using one of the substrate as a standard test substrate, for e.g. galvanized steel (as suggested by AFERA) or glass (as suggested by FINAT) in place of coated and uncoated wood when testing wind barrier and vapour barrier tapes. This standard test substrate can also be used in place of other materials like gypsum board or materials with delaminate surfaces such as concrete, brickwork, OSB and wood fiberboards (after the application of primers on the surface of the materials in order to improve adhesion performance of the surface).

The peel and shear resistance results of adhesive tapes adhered to flexible membranes, wind barrier membranes (WT and WI) and vapour barrier (VT), were relatively lower compared to adhesive tapes adhered to rigid substrates. This shows the importance of using a standard reference substrate from flexible membrane for testing wind barrier and vapour barrier tapes. Thus, it is suggested to test the wind barrier tapes against a standard hard or rigid substrate (e.g. galvanized steel) and polyethylene (PE) wind barrier membranes (e.g. WT), while vapour barrier tapes can be tested against a standard hard substrate (e.g. galvanized steel) and PE vapour barrier membranes (e.g. VT). Using a standard substrate can minimize the number of end-use substrates used to test the actual substrate/interface properties, which leads to reducing the time and cost of durability testing. Further investigation of the effect of surface energy of different building materials on which the wind barrier and vapour barrier tapes are applied is needed to verify these findings.

Detailed analyses of the evolution of the strain field from the digital image correlation results suggest adhesive degradation and a consequent sliding of the tape across the wind barrier. However, the deformation and sliding of the tape is relatively small. Further analysis of the degradation processes as well as better understanding of the mechanical properties of the bonding between tape and various substrates is recommended.

Here it is important to note that the performance of the adhesive tapes is also very dependent on the actual application of the tapes in buildings. First it is important to determine the adequate properties with their corresponding requirements for adhesive tape suitable for the specific application areas, e.g. identify tapes intended for indoor and outdoor applications. The condition of the surface of the substrate is another factor which determines adhesion performance. It is important to know the surface properties of the substrate and evaluate if special surface treatment is required before the application of the adhesive tapes. In order to guarantee good adhesion, the surface should also be dry and free from dust and grease. Adhesive tapes become hard and glassy with decreasing temperature and higher temperatures make the adhesive stickier and reduce their adhesive strength. Thus, tapes should not be stored and/or applied in too cold or too warm temperature. Special adhesive tapes designed for extreme temperature can be used for very high or too low temperature applications. Manufacturers or suppliers of adhesive tapes should provide technical data, instructions and information about the application area and conditions of application of the adhesive tapes, and the end users should follow the given procedures during the application of the tapes to achieve the required adhesion.

5. Conclusions

Adhesive tapes are used to maintain and/or increase the moisture and air-tightness of buildings. To the authors knowledge, adequate durability test methods (e.g. accelerated ageing procedures and long-term performance prediction methods) are lacking for tapes used for outdoor building applications. In this study, the long-term degradation mechanisms and mechanical properties of various commercially available adhesive tapes used for buildings applications were evaluated. Two wind barrier tapes and two vapour barrier tapes adhered to seven different types of substrates have been tested in order to evaluate the effect of different properties of the substrates on the durability of the joints. Two accelerated ageing test series have been used applying two different ageing procedures to evaluate the durability of the adhesive tapes used for wind barrier and vapour barrier joints. Peel and shear resistance tests were performed before, during and after accelerated ageing of the test specimens in order to evaluate the adhesion and cohesion performance of adhesive joints. The statistical design of experiments (DOE) technique was used for identification and correlation of the significant factors that affected the mechanical properties of the taped joints. Furthermore, the effects of wind load on the adhesive properties of wind barriers and adhesive tape joints were also investigated.

From the accelerated ageing test results, it was suggested to differentiate the accelerated ageing exposure of tapes used for indoor and outdoor during accelerated ageing tests.

The possibility of using standard substrates when testing the adhesive tapes instead of applying actual end-use substrates was also suggested. The study also highlights the need for further analysis of better understanding of the chemical and mechanical properties of the adhesive tapes, bonding between adhesive tapes and various substrates, the degradation processes and reliable service life prediction methods. The body of this work is expected to strengthen the further development of durability testing and evaluation methodology for adhesive tapes for building applications.

References

1. Hutchinson, A.R., A. Pagliuca, and R. Woolman, *Sealing and resealing of joints in buildings.* Construction and Building Materials, 1995. **9**(6): p. 379-387.
2. TEK 10, *The Norwegian building regulations (Byggteknisk forskrift, TEK 10).* https://lovdata.no/dokument/SF/forskrift/2010-03-26-489. 2016.
3. Moll, L., *Airtightness in buildings. Downloaded June 4, 2014 from* http://www.ecologicalbuildingsystems.com/docs/Airtightness2.pdf.
4. Fufa, S.M., M. Kvalvik, and P. Rüther. *Adhesive tapes for building purposes: Framework for evaluation of performance and durability*. in *XIII International Conference on Durability of Building Materials and Components*. 2-5 September 2014,. Sao Paulo, Brazil.
5. EN 1939, *Self adhesive tapes - Determination of peel adhesion properties*. 2003: European committee for standardization, Brussels.
6. EN 1943, *Self adhesive tapes - Measurement of static shear adhesion*. 2002: European committee for standardization, Brussels.
7. EN 12024, *Self adhesive tapes - Measurement of resistance to elevated temperature and humidity*. 1996: European committee for standardization, Brussels.
8. EN 12028, *Self adhesive tapes - Measurement of elongation under static load*. 1996: European committee for standardization, Brussels.
9. DIN 4108-11, *Thermal insulation and energy economy in buildings — Part 11: Minimum requirements to the durability of bond strength with adhesive tapes and adhesive masses for the establishment of airtight layers (In German)*. 2015: German Institute for Standardization, Berlin.
10. SINTEF Building and Infrastructure, *SINTEF Teknisk Godkjenning Retningslinjer -Tape til bygningsformål i damp- og vindsperresjiktet*. 2011.
11. NS-EN 12311-1, *Flexible sheets for waterproofing Determination of tensile properties-Part 2: Plastic and rubber sheets for roof waterproofing*. 2013: Standard Norge, Oslo.
12. NS-EN 12316-2, *Flexible sheets for waterproofing Determination of peel resistance of joints Part 2: Plastic and rubber sheets for roof waterproofing* 2013: Standard Norge, Oslo.
13. NS-EN 12317-2, *Flexible sheets for waterproofing Determination of shear resistance of joints Part 2: Plastic and rubber sheets for roof waterproofing*. 2010: Standard Norge, Oslo.
14. NT BUILD 495, *Building materials and components in the vertical position:Exposure to accelerated climatic strains*. 2000, Nordtest, Espoo, Finland.
15. NS-EN 1296, *Flexible sheets for waterproofing-Bitumen, plastic and rubber sheets for roofing - Method of artificial ageing by long-term exposure to elevated temperature* 2001: Standard Norge, Oslo.
16. Benedek;, I., *Pressure-sensitive adhesives and applications. Second edition, Revised and Expanded*. 1997, Marcel Dekker Inc, New York
17. Jelle, B., *Accelerated climate ageing of building materials, components and structures in the laboratory.* Journal of Materials Science, 2012. **47**(18): p. 6475-6496.
18. McGuiggan, P.M., et al., *Peel of an adhesive tape from a temperature-gradient surface.* International Journal of Adhesion and Adhesives, 2008. **28**(4–5): p. 185-191.
19. 475 (2014). *Adhesive Bonds and Failures: What's Going On?. Downloaded June 4, 2014 from* https://foursevenfive.com/adhesive-bonds-and-failures-whats-going-on/.
20. Ronald E. Walpole, et al., *Probability & statistics for Engineers & Scientists*, ed. U.S.R. 8th Edition. Pearson Education International. 2007.
21. EN 12211, *Windows and doors - Resistance to wind load - Test method* 2000: European committee for standardization, Brussels.
22. BKS 523.251, *Bindingsverk av tre i småhus. Dimensjonering og utførelse*. 2014: SINTEF Building and Infrastructure, Oslo.

23. Fagerholt, E., *Field Measurements in Mechanical Testing Using Close-Range Photogrammetry and Digital Image Analysis.* , in *Doctoral thesis at NTNU, Department of Structural Engineering*. 2012.
24. Maassen, W., M.A.R. Meier, and N. Willenbacher, *Unique adhesive properties of pressure sensitive adhesives from plant oils.* International Journal of Adhesion and Adhesives, 2016. **64**: p. 65-71.
25. Jelle, B.P. *Evaluation of Building Products by Conducting Accelerated Climate Ageing in the Laboratory*. in *XII International Conference on Durability of Building Materials and Components*. 12-15 April 2011,. Porto, Portugal.