AN ASSESSMENT OF THE IMPACT OF ADHESIVE COVERAGE AND WIRE TYPE ON FIXED RETAINER FAILURES AND FORCE PROPAGATION ALONG TWO TYPES OF RETAINER WIRES: AN *IN VITRO* STUDY

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A thesis submitted for the degree of Doctor of Clinical Dentistry

2022

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LIST OF ABBREVIATIONS

3D	Three-dimensional
A	Area
BR	Bonded retainer
CAD-CAM	Computer-aided design and computer-aided manufacturing
CI	Confidence interval
cm	Centimetre
h	Height
LED	Light-emitting diode
mm	Millimetre
mm/min	Millimetre per minute
n	Number
N	Newton
P	Probability value
r	Radius of a circle
R^2	Coefficient of determination
RCT	Randomised controlled trial
SD	Standard deviation
Std. Error	Standard error
STL	Stereolithographic
VFR	Vacuum-formed retainer
w	Width

ABSTRACT

Aims: To evaluate the force required to promote failure of fixed orthodontic retainers with different adhesive (composite) coverage; and to assess the presence and extent of force propagation with two different fixed orthodontic retainer wires.

Methods:

Retainer wires each of 15cm length was bonded on acrylic blocks with different adhesive surface diameters of 2mm, 3mm, 4mm, and 5mm. Two types of retainer wires were used namely, Ortho-FlexTech™ and Ortho-Care Perform™ coaxial (0.0175”). The prepared samples (n=160) were subjected to tensile pull-out test and the debonding force recorded.

Fixed retainers using two different wires and 4-mm adhesive diameter were bonded on acrylic bases resembling the labial segment of a maxillary dental arch (n=72). The retainers were loaded in an occluso-apical direction until first sign of failure while being video-recorded.

Individual frames of the video recordings were extracted every 0.2 second. Two video frames, each representing the start of load application and just before first sign of failure were compared, and their differences highlighted using an image comparison website. A force propagation scoring index was developed and used to quantify the extent of force propagation along a retainer wire when loaded.

Results: An adhesive surface diameter of 4mm required the highest debonding force for both retainer wires with significant differences in comparison to 2mm (*P*=<0.001; 95% CI: 8.69, 21.69) and 3mm (*P*=0.026; 95% CI: 0.60, 13.59). The extent of force propagation was significantly increased in the Ortho-Care Perform™ coaxial wire. A greater degree of deformation was observed for Ortho-FlexTech™ prior to failure.

Conclusion:

On the basis of this laboratory-based assessment, consideration should be given to fabrication of fixed retainers using adhesive (composite) coverage of up to 4mm on each tooth. Force appears to be propagated more readily with Ortho-Care Perform™ than with a flexible chain alternative. This may risk stress accumulation at the terminal ends of the retainer wire with the potential for associated unwanted tooth movement.

CHAPTER 1. INTRODUCTION

There is a widespread acceptance of the unpredictable nature of post-treatment and maturational changes affecting the dentition and an appreciation that lifetime permanent retention is the most reliable way to prevent relapse (Little, 2009). Notwithstanding this, studies have shown that relapse may occur irrespective of the use of fixed retainers (Steinnes, *et al*., 2017).

The tendency for genuine relapse is further compounded by the risk of unexpected tooth movement that may be associated with iatrogenic factors during retainer placement and occlusal forces post-treatment (Katsaros, *et al*., 2007). They include torque differences between two adjacent incisors (X-effect), increased buccal or lingual inclination of a single mandibular canine and opposing changes of contralateral mandibular canines. This is also known as a 'twist effect'. (Katsaros, *et al.*, 2007; Renkema, *et al*., 2011; Pazera, *et al*., 2012; Kučera & Marek, 2016). Given that these tooth movements do not resemble the pre-treatment malocclusion, they should not be termed as orthodontic relapse and have instead been describe as unwanted movement of the teeth included in the fixed retainer, even without wire fracture or bond failure (Kučera & Marek, 2016)

Detachment of the bonded retainer at the wire-composite interface is considered to be the most prevalent mechanism of failure (Bearn, 1995). Notwithstanding this, wires are also prone to fracture. In light of previous failed attempts with direct contact splinting, it is accepted that a retainer wire should be sufficiently flexible to allow for physiologic tooth movement without debonding, and still possess adequate stiffness to resist deformation from external forces (Zachrisson, 2015).

There is a need to find a balance between sufficient strength, adequate flexibility and the risk of force propagation. Whilst the association between thickness of composite and magnitude of debonding force had previously been investigated (Bearn, *et al*., 1997), the effect of varying composite surface area on the failure of fixed retainers has not been evaluated. Given that different composition and treatment of wires during production may affect their mechanical properties (Kapila & Sachdeva, 1989), an evaluation of the characteristics of forces in a fixed retainer when subjected to loading would facilitate further understanding of the factors contributing to post-treatment changes.

CHAPTER 2. REVIEW OF THE LITERATURE

2.1 Background

Throughout the history of modern orthodontics, there have been four main schools of thought that were proposed regarding the factors governing retention protocols (Riedel, 1960). Norman Kingsley (1880) opined that "the occlusion of the teeth is the most potent factor in determining the stability in a new position". Meanwhile, Rogers (1922) proposed that functional balance of the musculature was the key to stability of occlusion. Lundström (1925) regarded the state of the apical base as a major determinant in the maintenance of normal occlusion. Conversely, Grieve (1944) suggested that mandibular incisors should be positioned upright and over the basal bone to ensure success of treatment. Such is the uncertainty and complexity surrounding the longevity of treatment outcome that Hawley (1919) quoted his colleague, saying, "If anyone would take my cases when they are finished, retain them and be responsible for them afterward, I would gladly give them half the fee."

Moyers (1973) defined orthodontic retention as 'the holding of teeth following orthodontic treatment in the treated position for the period of time necessary for the maintenance of the result.' Relapse is defined as the 'return, following correction, of features of the original malocclusion' (British Standards Institution, 1983). Orthodontic relapse should not be confused with any late changes that take place during the post-retention phase which immediately follows a period of retention. Unlike relapse that occurs due to failure to retain a tooth in its corrected position until complete remodelling of periodontal structures has taken place, late changes during post-retention tend to be multifactorial and may be linked to normal developmental processes (Thilander, 2000).

Different approaches have been proposed in an effort to maintain the teeth in their end of treatment positions. Aside from the mechanical approach of prescribing retainers after completion of orthodontic treatment, other biological and surgical means using pharmacological agents, circumferential supracrestal fibrotomy, laser therapy or mechanical vibration have also been explored. Unfortunately, the invasive nature and potential risk of systematic effects of such methods meant that they have yet to be widely accepted by patients and clinicians alike. The quality of evidence on their efficacy have also been deemed at best low by two recent systematic reviews carried out on the relevant animal studies (Veginadu, *et al*., 2020; Kaklamanos, *et al*., 2021). Consequently, until more robust evidence becomes available to support the administration of these adjunctive procedures, traditional retainers will most likely remain as the primary mode of retention in mainstream orthodontic practice.

2.2 Rationale for retention

Three overarching reasons for use of orthodontic retention have been suggested (Fleming & Seehra, 2019). These include unstable tooth positioning, physiological recovery, and growth and maturational changes.

2.2.1 Unstable tooth positioning

Not dissimilar to Newton's first law of motion, Weinstein *et al.*(1963) first hypothesized that for an element of the dentition to be at rest, it is said to be in a state of equilibrium, whereby the resultant from all moments and forces acting upon it by the surrounding structures is zero. This is known as the equilibrium theory of tooth position. Utilising different protheses fitted with miniature transducers and a series of exercises, Weinstein (1963) studied the influence of the action of the oral musculature on the position of dentition. Their results led to the conclusion that "forces exerted upon the crown of the tooth by the surrounding soft tissue may be sufficient to cause tooth movement in the same manner as that produced by orthodontic appliances". Other conclusions that were also drawn from the work of the same team is the possibility for teeth to have more than one position of stability and the importance of force duration as even small differential forces when applied over a considerable period can cause tooth movement.

Consequently, a state of equilibrium should exist between the intrinsic forces of tongue, lips and cheeks, as well as extrinsic forces from habits or appliances, occlusal forces and forces from periodontal membrane in order for teeth to remain stable (Proffit, 1978). If teeth are moved out of this neutral zone, relapse is more likely to occur due to exertion of uneven, soft tissue pressures on teeth. Given that unstable tooth movement like advancement of mandibular incisors or mandibular canine width expansion may occasionally be done for aesthetic reasons (Fleming & Seehra, 2019), long term retention becomes vital for improving the stability of treatment outcome.

Following a review of evidence from Nance (1947) and other authors, Riedel (1960) suggested that one of the rules to promote stability is that arch form, particularly in the mandibular arch, cannot be altered permanently by appliance therapy. On that account, treatment should be aimed at maintaining the arch form presented by the original malocclusion. McCauley (1944) explained that orthodontic treatment has very minimal lasting effect on the lateral dimensions of the mandible as the musculature surrounding it limits the chance of maintaining any treatment expansion. Since the maxillary teeth are housed in bone that is much less dense than the mandible, they are essentially supported by the lower teeth and treatment should thus be planned around the mandibular arch form for the best chance of stability. Strang(1949) concurred with the opinion that the mandibular inter-canine width is an accurate representation of an individual's muscular balance. Hence, the limits of arch expansion will be determined by the pre-existing dimensions.

2.2.2 Physiological recovery

Following tooth movement during orthodontic treatment, fibrous structures incorporated in the newly formed surrounding bone are usually under tension and rearrangement of these stretched fibres will occur, resulting in increased relapse tendencies. Given the variability in the types of fibrous tissue and influence of age on the reaction of fibrous supporting structures in different individuals, variations can be observed during the retention period even in cases managed according to the same treatment principles (Reitan, 1954; Reitan, 1967).

Tipping, bodily and rotational movements are examples of tooth movements that require retention to mitigate against the remodeling of stretched principal fibres prior to calcification of the newly deposited bone layer. The rapidity of such relapse following tipping was described by Reitan (1967) using the crown of an experimental tooth which was tipped 2mm over a 40-day period in dogs. Relapse was observed within the first 2 hours upon release of active force without any retention.

While reorganisation of bone and principal fibres in the middle and apical thirds of roots may occur after a short period of 8 to 9 weeks, the supracrestal fibres remain displaced after 232 days of retention. This can in part be explained by their slower turnover rate, as demonstrated by the lack of new cells in the supraalveolar group of fibres. If left unretained after treatment, the teeth may relapse, causing compression or even hyalinisation of the previous tension side (Reitan, 1967). Retainers are therefore important in limiting the undesirable changes from periodontium remodeling.

2.2.3 Growth and maturational changes

Following a series of studies with different co-workers, Little (1990) concluded several characteristic features that may affect the dentition over time in both samples of treated cases with varying initial malocclusion and those of untreated normals. Decrease in arch length and arch width typically occurs well into the fourth decade and beyond, albeit with a reduced rate after age 30. While this is normally accompanied by concomitant increase in irregularity, it may explain the rather satisfactory post-retention stability of treated individuals who originally presented with generalised spacing (Little & Riedel, 1989).

Sinclair and Little (1983) postulated that analogous biological processes underpin the changes in arch length as a similar annual rate in reduction of arch length was observed in both the ten years post-retention and untreated samples of their study. However, unlike the former study, the authors found that arch width was very stable in males and only minimal decrease was identified in females between 13 and 20 years. Such observations clearly highlight the need for indefinite retention to reduce long term relapse.

2.3 Types of retainers

One of the earliest recorded forms of retainer was a removable rubber plate covering the mucosa with perforations to accommodate the teeth (Kingsley, 1880). Two decades later, Edward Angle (1900) acknowledged the importance of retention by describing the use of a retaining device that was based on the same principles of banded fixed appliance, except with a looser fit of bands. In 1908, Cavin Case proposed an alternative consisting of a platinum-gold removable retainer with nickel-silver joints to maintain the maxillary anterior teeth. This was next followed by the introduction of the widely accepted Hawley retainer by Charles Hawley in 1919. Easier oral hygiene maintenance, potential for occlusal settling and minor tooth adjustments in the event of any inevitable minor post-retention relapse were ascribed as related benefits. However, compliance with the regime of wear was highlighted as a cause of concern even within Hawley's initial article itself (Hawley, 1919).

Meanwhile, removable vacuum-formed retainers which were initially described by Ponitz (1971) were reportedly preferred by patients over Hawley retainers due to the improved appearance, comfort and articulation during speech. Unfortunately, this preference amongst patients did not necessarily translate into better compliance in retainer wear away from home (Hitchens, *et al*., 2007). In fact, Pratt *et al.* (2011) in a questionnaire-based study reported that, although patients who were prescribed vacuum-formed retainers demonstrated better compliance than those who were given Hawley retainers in the initial two years post-debond, the decline in compliance was more significant amongst patients with vacuum formed retainers thereafter. It was suggested by the authors that this could potentially be attributed to the difference in occlusal coverage which in turn affects their respective durability.

With the unpredictable and less than ideal compliance rate associated with removable retainers in mind, an alternative means of retention to be considered would be the use of fixed retainers. Traditionally, fixed retention was done by cementing a banded lower soldered lingual retainer from cuspids to cuspid or bicuspid to bicuspid. However, the unaesthetic presence of metal bands around lower cuspids and risks of decalcification underneath the bands led to the development of lingual bonded retainer which was first reported by Knierim in 1973. Described as an invisible lower cuspid to cuspid retainer, a 0.028 round stainless-steel wire was adapted to intimately contact the lingual surfaces of lower incisors with both ends bent at 90 degrees to the occlusal and bonded lingually to the cuspids (Knierim, 1973). Since then, different authors have suggested various fixed retention protocols involving different wire diameters and materials, bonding and wire placement techniques, adhesive systems, and number of teeth bonded.

Amongst the many recommendations made, one notable suggestion was by Zachrisson, who proposed the use of multi-stranded wires as the spirals in such wires were expected to provide good mechanical retention and still be sufficiently flexible to permit physiologic tooth movement, thus reducing stress concentration in the composite (Zachrisson, 1977; Dahl & Zachrisson, 1991). The importance of elasticity and flexibility of bonded retainers was highlighted in his previous trial whereby direct tooth contact splinting using sealants and composite resins broke, most likely due to the increased rigidity which prevented teeth from exerting their normal physiologic mobility. Following further experiments with different types of flexible wires of varying diameters and number of strands, Zachrisson advocated the 5-stranded wire as the wire of choice to be used in fixed retention (Zachrisson, 2015).

Another material that was later proposed as a possible choice for fixed retention is the fiber reinforced composite retainer (Diamond, 1987). Despite possessing the advantage of being user friendly for patients with nickel allergy, reduced bulk and superior aesthetics as a tooth-coloured material, the increased stiffness associated with this technique have resulted in it showing a significantly higher failure rate at 51% compared to the 12% failure of multi-stranded lingual retainer at the end of a two-year period. Amongst the failures observed in the glass fibre reinforced group, 77% were fractures of upper retainers while detachment of retainer was more common in the mandibular arch (Tacken, *et al*., 2010).

Recently, alternative techniques like solid gold chain or CAD-CAM produced retainer have also been introduced. The solid gold chain has been said to reduce chairside time and eliminate laboratory cost due to its easier adaptation to lingual surfaces of teeth, greater flexibility, increased surface area for bonding and improved comfort for patients (Aldrees, *et al*., 2010). Meanwhile, CAD-CAM technology has enabled digital visualization and planning of retainer position in relation to the surrounding hard and soft tissues prior to its custom fabrication. With the access to such minute details, it is now possible to achieve precise adaptation of bonded retainer to the lingual morphology of each tooth with elimination of any premature contacts, thereby hopefully reducing the frequency and need for future repairs (Wolf,*et al.*, 2015). Unfortunately, the high cost of such technology meant that it is yet to be widely accepted by both patients and clinicians.

2.4 Global trends in retainer prescription

Various retention protocols are currently practiced by clinicians internationally with a lack of consensus on the appropriate retention regime for different clinical presentations. In a Cochrane review, Littlewood *et al.*(2016) concluded that “there is insufficient high-quality evidence to make recommendations on retention procedures for stabilizing tooth position after treatment with orthodontic braces”.

In the Netherlands, mean use of bonded retainers increased from 63% to 88.3% in the maxillary arch and from 91% to 97% in the mandibular arch between 2005 and 2015 (Renkema, *et al*., 2009; Padmos, *et al*., 2018). Although not as overwhelmingly popular as in the Netherlands, fixed lingual retainer remained the preferred choice of retention in the mandibular arch amongst clinicians in the United States (Pratt, *et al*., 2011), Norway (Vandevska-Radunovic, *et al*., 2013), Switzerland (Lai, *et al*., 2014), Saudi Arabia (Al-Jewair, *et al*., 2016), New Zealand (Padmos, *et al*., 2019) and India (Sandhya, *et al.*, 2019). In the United Kingdom and Republic of Ireland, they were mostly prescribed either as a standalone or in combination with removable retainers in the mandible by private practitioners (Singh, *et al.*, 2009; Meade & Millett, 2013).

With regards to duration of retention, a majority of clinicians in Australia, the United States, United Kingdom and Netherlands advocated indefinite retention (Singh, *et al*., 2009; Pratt, *et al*., 2011; Padmos, *et al*., 2018; Meade & Dreyer, 2019). Meanwhile, similar protocol was preferred by about half of the orthodontists in Saudi Arabia and less than 20% in Norway (Vandevska-Radunovic, *et al*., 2013; Al-Jewair, *et al*., 2016)

2.5 Fixed or removable retainers

2.5.1 Effectiveness in orthodontic stability

There is currently no clear evidence supporting the use of either form of retention (Littlewood, *et al*., 2016). Nevertheless, a previous RCT has concluded that fixed retainers are more effective in maintaining lower arch alignment after four years post-treatment. No significant difference was found in the inter-canine and intermolar width, arch length, and reopening of extraction space of both treatment groups (Al-Moghrabi, *et al*., 2018). The findings should be interpreted with caution due to the high dropout rate at follow up, resulting in a much smaller sample size than originally intended.

Similarly, Forde *et al*. (2018) evaluated the stability of results for both modality of retention and reported that bonded retainers offer superior preservation of mandibular labial segment alignment at one-year follow up, albeit with a higher failure rate than the VFR group. There is however no significant difference in the effectiveness and survival of both retainers when used for the maxillary teeth.

In another RCT conducted by O'Rourke *et al.*(2016), 82 subjects were evaluated for comparison of the clinical effectiveness of bonded and vacuum-formed retainers. Although bonded retainers were better at maintaining alignment of mandibular incisors during the first six months after debond, this superiority was not observed at the 12- and 18-months assessments. Artun *et al.*(1997), Xu *et al.*(2011) and Krämer *et al.*(2020) all noted that fixed and removable retainers were equally effective at maintaining stability of treatment outcomes at least for a short term.

2.5.2 Patient acceptance and quality of life

As long term retainer wear is now widely accepted (Littlewood, *et al*., 2017; Littlewood, S; on behalf of the British Orthodontic Society, 2018), the impact of retainer type on quality of life becomes an important consideration as it may influence the eventual compliance and acceptance of the retainer. While comfort level has been reported to have a strong correlation with compliance of retainer wear, fixed retainers have been perceived to be more acceptable than removable retainers by patients (Wong & Freer, 2005). Moreover, Pratt *et al.*(2011) showed that compliance with removable retainer wear reduces over time regardless of type, albeit with a faster rate of decrease in the VFR group.

Qualitative research has revealed an almost universal dislike for retainers. Some problems shared include difficulties with speech, eating, increased salivation, smell, embarrassment of appearance and ease of losing the retainer. In fact, some participants had also expressed that retainer wear posed more of a challenge than the actual fixed appliance itself (Bennett & Tulloch, 1999; Travess, *et al*., 2004).

On the contrary, participants from both groups of a RCT comparing bonded and vacuum-formed retainers had a better or comparable experience with retainers than their fixed appliances. Although VFRs were still associated with more discomfort and speech problems than BRs, the clinical relevance may not be as significant as initially feared given that VFRs are mostly prescribed for nighttime wear. Additionally, subjects prescribed with VFRs found it easier to maintain the hygiene of their retainers compared to those given BRs (Sawhney, 2013; Forde, *et al*., 2018). Meanwhile, fixed retention has been linked with increased complexity in oral hygiene maintenance, altered speech and tongue irritation. Subjective tongue problems may however reduce over time (Störmann & Ehmer, 2002).

Another RCT conducted in Sweden found that patients in retention generally experienced low levels of pain and discomfort with no differences in the maxillary arch between the experimental groups. This may be due to the prescription of upper VFRs to all participants despite half of them originally allocated to the canine-to-canine retainer group. Similar to findings by Forde *et al.*(2018), the authors reported a higher score for pain, discomfort and soreness in the mandible for the VFR group (Krämer, *et al.*, 2021).

2.6 Limitations of fixed retainers

2.6.1 Bond failures and wire fractures

Despite its many benefits documented within the literature, fabrication of a fixed retainer is a technique sensitive procedure and a common problem seen clinically is the failure of the retainer post-treatment. This may occur either through bond failure at the tooth-adhesive junction, detachment at the adhesive-wire interface or as wire fracture at inter-proximal regions. Prevalence of the different patterns of failure however vary widely due to the wide array of materials and bonding techniques used. According to a systematic review by Iliadi *et al.*(2015), the reported failure rate for metal retainers ranged from 3.5% (Zachrisson, 2007) to 50% (Pandis, *et al*., 2013), while those of glass-fibre reinforced retainers and polyethylene ribbon were 11.8-71% (Bolla, *et al*., 2012; Ardeshna, 2011)and 50% (Salehi, *et al.*, 2013) respectively. Al-Moghrabi *et al.,*(2016) summarized that mandibular stainless-steel fixed retainers bonded to six anterior teeth had 0.29 mean failure risk over follow-up period of 6 to 36 months.

Of the different modes of failure described, the enamel-adhesive junction had been reported to be the most common site of failure. It should however be noted that the mode of failure was only possible to be ascertained in 65% of failures in this study (Pandis, *et al.*, 2013). In contrast, Dahl and Zachrisson's (1991) study saw similar rates of wire loosening and fractures, with most loosening occurring at the wire-composite interface.

While failure at the enamel-composite junction may be attributed to moisture contamination of enamel surface during the bonding process (Pandis, *et al.*, 2013), insufficient composite or abrasion of adhesive by the opposing dentition have been suggested as possible reasons for failure at the wire-composite interface and metal fatigue being the cause for wire breakage (Bearn, *et al.*, 1997; Årtun & Urbye, 1988). Following an in-vitro study, Bearn *et al.*(1997) concluded that increased thickness of overlying composite increases the force required to detach wire from composite. Nevertheless, any increase beyond 1mm thickness is unlikely to give any significant clinical benefit. Additionally, retentive loops are not necessary when using multistranded wire for retention as the irregular surface of wire will provide sufficient mechanical retention (Bearn, *et al*., 1997).

2.6.2 Effects of fixed retainers on periodontal health and caries susceptibility

Given that fixed retainers are bonded to the lingual or palatal surfaces of anterior teeth and cannot be easily removed, they offer the advantage of reduced dependence on patient's compliance. Unfortunately, this same property of fixed retainers has also become a cause of concern among clinicians as it complicates accessibility of interdental regions for routine oral hygiene maintenance. The rough surface design of retainer wires and resin margins also provide increased retentive sites for plaque accumulation and microbial colonization intraorally. This problem is further complicated during the positioning of maxillary bonded retainers as avoidance of occlusal interference with the opposing mandibular incisors has to be balanced against a more gingival placement of the wire which may promote gingival inflammation (Pandis, *et al*., 2007).

Artun (1984) noted that despite an increased tendency for plaque and calculus accumulation along retainer wire with time, presence of fixed retainers did not contribute to any damaging effects on the adjacent soft and hard tissues even after eight years post-treatment. Similarly, a 20-year follow-up study reported that although calculus was noted in patients bonded with mandibular canine-to-canine retainers, there was no significant difference in the gingival index of these patients with those that were without retainers at follow-up. In fact, patients with fixed retainers may have better overall oral hygiene and more regular recalls for prophylaxis as indicated by their improved gingival health of the opposing arch when compared to those without a retainer (Booth, *et al.*, 2008). Hence, it has been postulated that the patient's personal attitude and motivation as the more likely determining factor in dental health status (Årtun, 1984).

In another four-year follow up RCT, comparable degree of gingival inflammation was associated with both fixed and removable retainers (Al-Moghrabi, *et al*., 2018). A recent systematic review concluded that fixed retainers are generally compatible with periodontal health and no severe deleterious implications on the periodontium have thus far been reported. However, it should be noted that all the included studies were assessed to have unclear or high risk of bias (Arn,*et al.*, 2020). This lack of high-quality evidence corroborates the findings from a Cochrane review by Littlewood *et al.* (2016).

2.6.3 Unwanted tooth movements post-treatment

Additionally, a range of unwanted tooth movement not attributed to relapse have been described in relation to fixed retainers during the post-retention phase. Although the underlying mechanisms contributing to such changes have yet to be identified, some of the speculated reasons include mechanical properties of wire acquired during production, mechanical distortion of wire from masticatory forces or lack of wire passivity as elastic deflection may have inadvertently been introduced by the operator during bonding (Katsaros, *et al.*, 2007; Arnold,*et al.*, 2016).

Katsaros *et al.* (2007) described two distinct post-treatment changes observed in patients during routine follow up appointments : torque difference between two adjacent mandibular incisors and increased buccal inclination and movement of a single mandibular canine. Of the 21 patients identified for exhibiting such patterns, almost half of them required retreatment despite having earlier received flexible spiral wire retainers bonded to their six mandibular anterior teeth. A retrospective study by Renkema *et al.* (2011) reported such post-treatment complications to be 2.7% in their sample of 221 patients who were provided with similar fixed retainers bonded to all mandibular anterior teeth. In contrast, these changes were not observed in 235 patients reviewed after five years who received thick stainless-steel retainers bonded only on the mandibular canines. However, 40% of these patients exhibited an increase in lower incisor irregularity as the retainers provided were not bonded to the mandibular incisors (Renkema, *et al*., 2008).

In Wolf *et al.'s* (2016) cohort of 30 patients bonded with Twistflex retainers on all six mandibular anterior teeth, 30% exhibited moderate degree of changes that required monitoring while 13.32% of the cases had severe changes that necessitate another course of orthodontic treatment. Following 3D superimposition of virtual models, mandibular canines were found to have undergone the most pronounced rotational and translational movements. Additionally, their results also concluded that excessive inter-canine expansion and overjet reduction may pose higher risks for post-treatment changes. It should however be noted that the sample size included in this study was relatively small and may not represent the general population.

Meanwhile, another retrospective study which assessed a total of 3500 consecutive patients identified 38 (1.1%) cases with unexpected complication at post-treatment review. 21 of the patients had developed an opposite inclination of the contralateral canines (twist effect), 12 had a torque difference on two adjacent incisors (X-effect) and 5 showed nonspecific complications. A majority of these complications were detected within the first five years of retention and reduced thereafter. Unfortunately, the significant number of subjects lost to drop out meant that some may have developed similar changes but failed to attend the review appointments or have seek intervention elsewhere (Kučera & Marek, 2016).

Whilst previous case reports and retrospective studies have documented the unwanted post-treatment changes observed in the mandibular anterior region, few have reported such changes in the maxillary arch since Brenchley (1997) who observed unexpected distolabial movement of one maxillary central incisor following bonding of fixed retainer to the two maxillary central incisors. Consequently, a 3D-analysis pilot study conducted at the Department of Orthodontics of the Justus-Liebig-University Giessen, Germany, serves as a useful insight to the prevalence of unwanted tooth movements in the maxillary arch. The maxillary retainers (20.9%) were found to be more susceptible to these complications than the mandibular retainers (14.1%). Contrary to the studies by Wolf *et al.*(2016) and Kučera and Marek(2016), the authors did not find a statistically significant correlation between inter-canine expansion, overjet reduction, mandibular plane angle or the incisor proclination with unexpected tooth movements. Instead, they concluded that oral dysfunction and lack of interincisal contact as potential risk factors (Klaus, *et al*., 2020).

The significance of these unexpected changes lies in their ability to cause deleterious effects to the periodontium when left undetected for prolonged periods. Even in the presence of intact fixed retainer and no wire breakage, teeth that have been bonded to retainer wire may be torqued so severely that the root apices are moved out of the cortical bone. In such cases, the affected patients will need to undergo another course of orthodontic treatment to move the teeth back to their normal positions and periodontal surgery to stimulate new bone formation (Pazera, *et al.*, 2012; Shaughnessy, *et al*., 2016), thus increasing the financial and time burden on patients.

A task force from the Netherlands recently developed clinical guidelines recommending the use of square or rectangular stainless-steel wire material for fixed retainer fabrication (Wouters, *et al*., 2019). The basis for their recommendation was the higher torque resistance demonstrated by these wires in comparison to round co-axial or twisted stainless-steel wires (Arnold, *et al.*, 2016). Similarly, Engeler and co-workers (2020) found that round multistranded wires had lower torsional load transfer and were thus more likely to demonstrate unexpected complications than rectangular wire due to the higher stored energy in the inter-composite regions.

CHAPTER 3. AIMS AND OBJECTIVES

- To evaluate the effect of adhesive coverage on the force required to promote failure of fixed orthodontic retainers,
- To assess the effect of wire type on the load required to produce deformation or fracture, and
- To assess the presence and extent of force propagation along two different fixed orthodontic retainer wires.

Null Hypotheses

1. Different adhesive (composite) coverage have no effect on fixed retainer failures

2. There are no differences in either the load required to produce deformation or fracture of two forms of retainer wire

3. There is no difference in force propagation between two different retainer wires.

CHAPTER 4. MATERIALS AND METHODS

Two types of wires were used in this study: (1) Ortho-Care Perform^{TM} coaxial wire 0.0175" and (2) Ortho-FlexTech^{TM} (stainless steel). These wires were bonded using Transbond^{TM} LR (3M), a light-cured composite material.

4.1 Effect of varying adhesive (composite) coverage on retainer failure

Four resin templates with varying diameters (2mm, 3mm, 4mm, and 5mm) of the raised central circular area were 3D-printed (Figure 1 and 2) with an Anycubic Photon 3D printing machine (Shenzhen Anycubic Technology Co., Ltd).

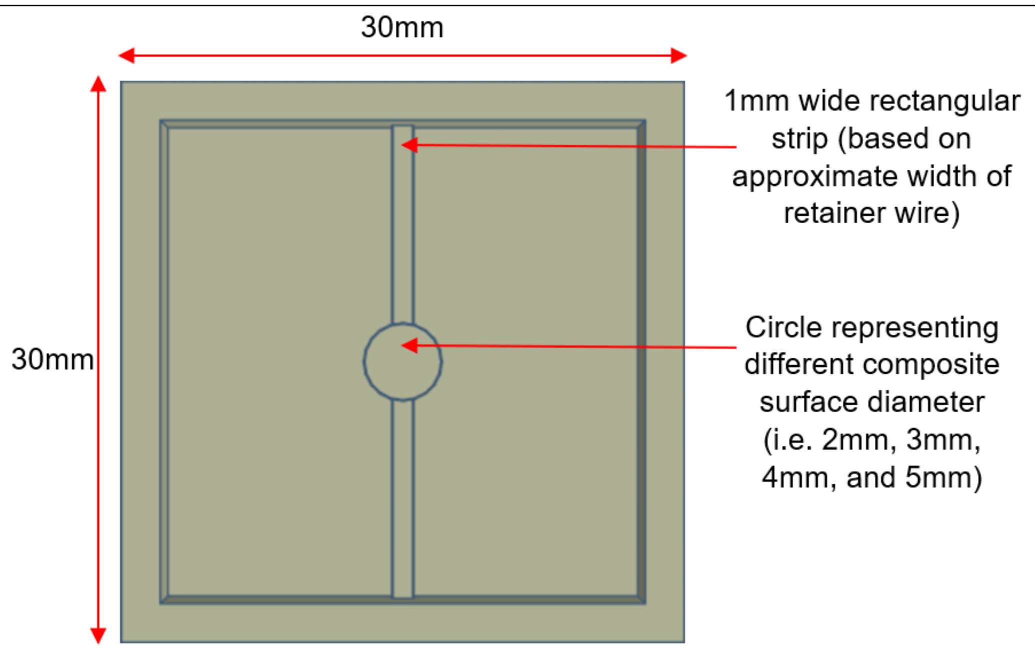


Figure 1. Superior view of 3D-template

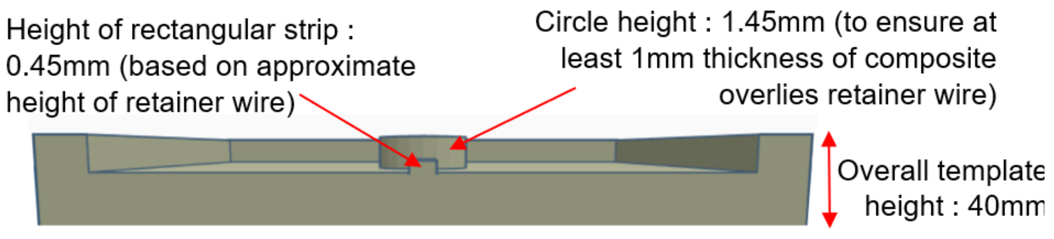


Figure 2. Cross-section of 3D-template

An impression of each template was made with medium-body silicone impression material to create a guide for consistent wire positioning during the experiments (Figure 3).

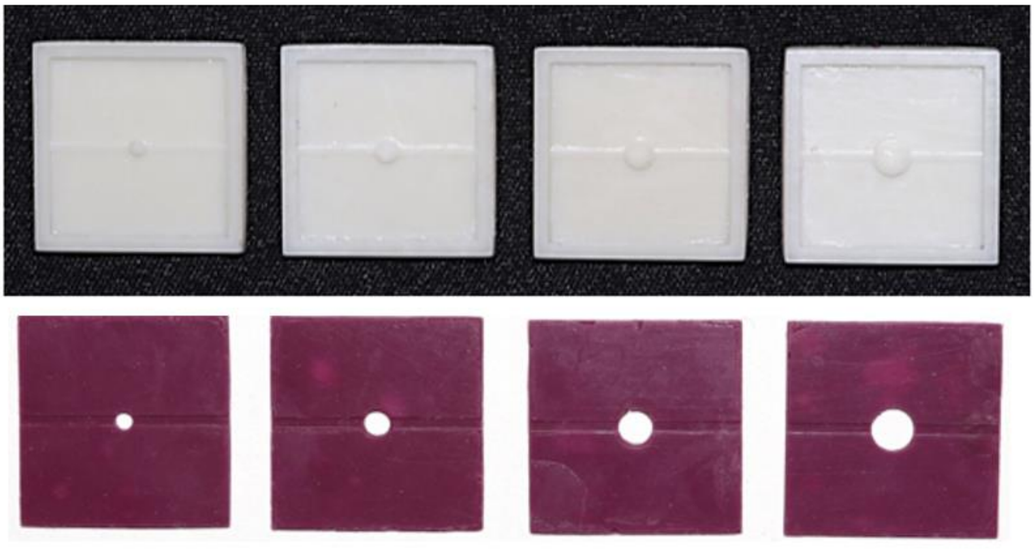


Figure 3. 3D-printed templates and the corresponding silicone guides with central cut-out of varying diameters

Each retainer wire of 15cm length was bonded individually on an acrylic block using the previously fabricated silicone guide. In the case of Ortho-FlexTech™, the wire was always bonded with the surface possessing a wider area facing the acrylic base. The diameter and consequently the surface area of composite placed could therefore be controlled by using the silicone guides.

A celluloid strip and flat load were placed on top of the composite before curing to ensure a smooth surface and the elimination of excess material. The composite was first cured for 20 seconds before removal of the silicone guide. It was then cured for an additional 10 seconds with the light source placed as close as possible to the composite. This ensured complete curing of surfaces which may have been hindered by the opaque silicone material (Figure 4).

At least 1mm of acrylic surface was trimmed before bonding of the retainer wire to ensure a fresh surface was used for each new sample. The samples were tested to failure on an Instron testing machine in a tensile mode with crosshead speed of 10mm/min according to previous allied research (Bearn, *et al*., 1997). The force required to debond the wire was recorded (Figure 5).

The study was done based on a 2x4 model, whereby two main groups involving different retainer wires were further subdivided based on four composite surface diameters (2mm, 3mm, 4mm, and 5mm). Following a pilot study involving four samples for each subgroup, the resulting effect size (0.297) and sample size were calculated with the G*Power 3.1.9.6 for Windows statistical programme using a two-way analysis of variance (ANOVA) (Faul, *et al*., 2007). It was estimated that at least 150 samples were required to achieve 95% power and significance level of $P \leq 0.05$. Consequently, 160 samples were prepared for the main study and divided equally into each subgroup (n=20).

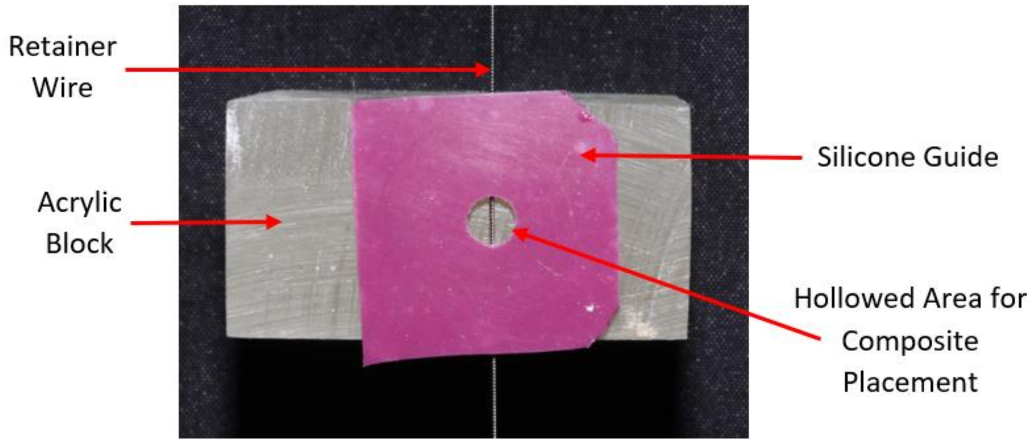


Figure 4. Preparation of sample to assess effect of different composite surface diameter on retainer failure

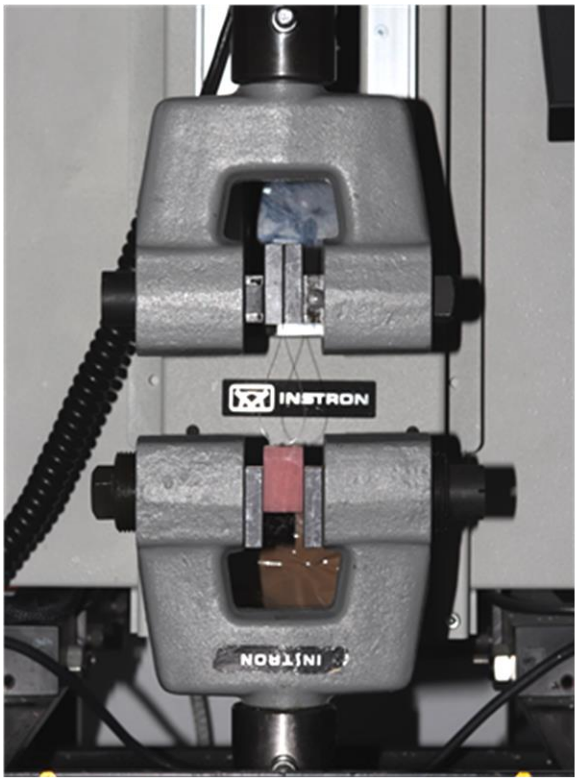


Figure 5. Experimental set-up for tensile testing using the Instron machine

4.2 Force propagation in fixed retainers

The composite surface area exhibiting highest resistance to failure from the previous part of this study was used. Similarly, an acrylic model replicating the final experimental set-up was first 3D-printed and an impression made from it with medium body silicone impression material (Figure 6). Notches were incorporated in the design of the 3D model to facilitate creation of projections on the resulting impressions. These projections were designed to aid seating of silicone guides onto the corresponding notches created on dental arch models used for fabrication of fixed retainer wire. This would hopefully help minimise positioning errors of the retainer wire and composite during bonding. The set-up also enabled the distance between composite bonding sites to be pre-determined according to the average mesiodistal width of natural teeth during creation of the 3D stereolithographic (STL) file.

Additionally, a separate STL file mimicking the shape of a maxillary arch upon which the bonded retainer was to be fabricated was created and 3D-printed (Figure 7). The decision to incorporate the dimensions of a maxillary arch and the corresponding maxillary teeth in this experiment was guided by the need for sufficient inter-composite distance to allow for consistent and unhindered movement of the Instron™ attachment during load application. For the same reason, notches were created in the dental arch model to prevent friction between acrylic base and load attachment. Impressions of the 3D model were next made with silicone putty and 72 copies of the dental arch model were fabricated by pouring cold-cure acrylic resin into the resulting impressions.

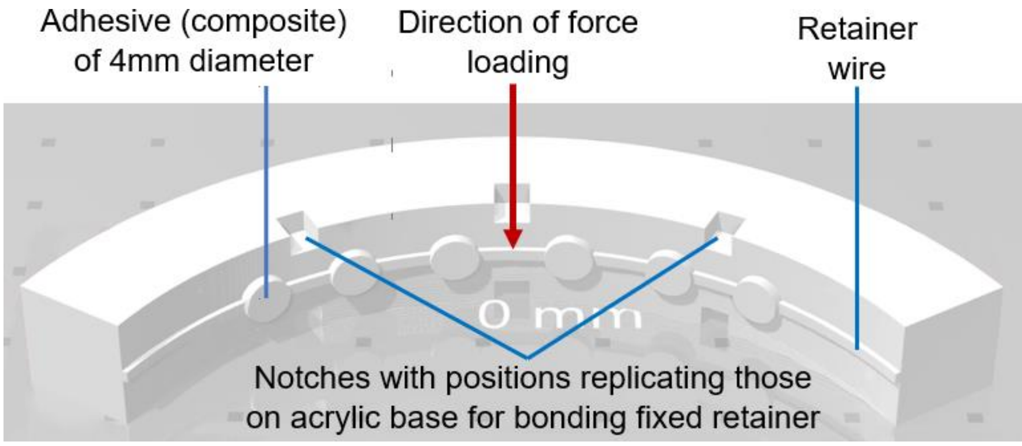


Figure 6. 3D model of experimental set-up for assessment of force propagation

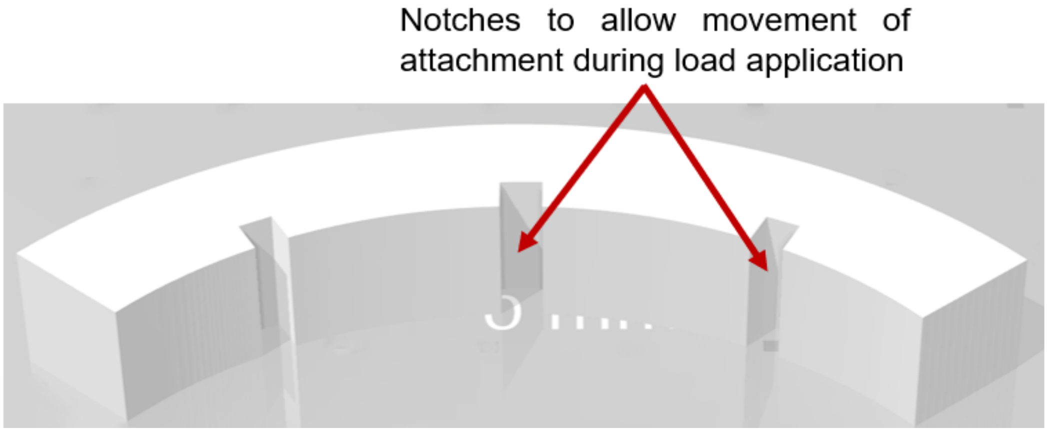


Figure 7. 3D model of dental arch base for bonding of fixed retainer

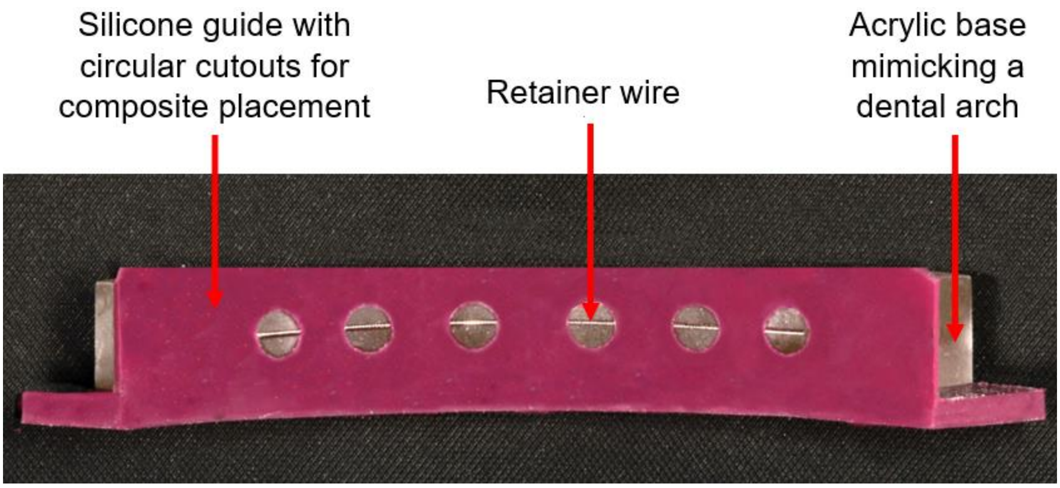


Figure 8. Preparation of sample for study of force propagation along a retainer wire

A fixed retainer wire was subsequently bonded to the inner surface of each acrylic model with the aid of a previously fabricated silicone guide (Figure 8). Each lumen of the silicone guide was filled with adhesive and light-cured for 20 seconds with a LED curing device. The composite was light-cured for a further 10 seconds after removal of the silicone guide to ensure all surfaces covered by the opaque silicone material were completely cured. Of the 72 acrylic models created, 36 each were used for placement of Ortho-Care Perform™ coaxial wires 0.0175" and Ortho-FlexTech™ (stainless steel).

Each of the groups was further divided and subjected to mechanical testing until first sign of failure (Table 1).

Table 1. Experimental sample distribution

Group	Retainer wire	Number of Samples (n)	Location of force loading
A	Ortho-FlexTech™	18	Between two central incisors
B	Ortho-FlexTech™	18	Between the lateral incisor and canine
C	Ortho-Care Perform™	18	Between two central incisors
D	Ortho-Care Perform™	18	Between the lateral incisor and canine

A fixed retainer was deemed to have failed when either bond failure or wire fracture had occurred. Bond failure was possible either at the acrylic-composite or wire-composite interface.

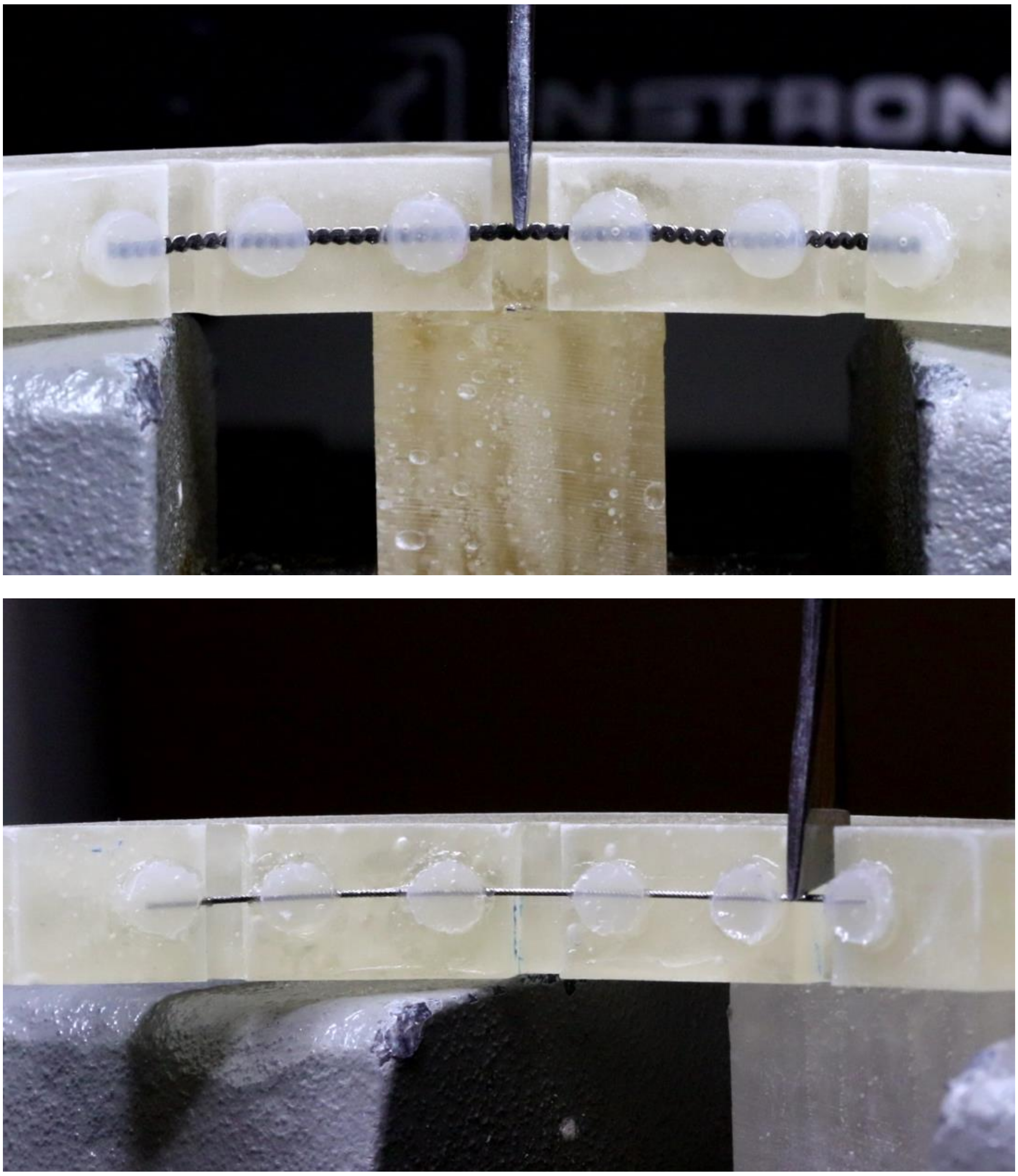


Figure 9. Experimental set-ups to assess force propagation along a fixed retainer.

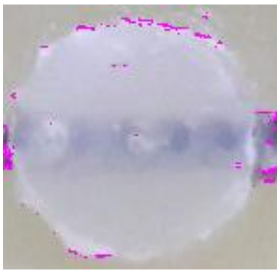
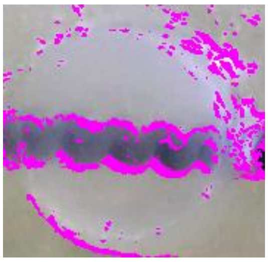
Force was applied on the fixed retainers in an occluso-apical direction (Figure 9). Data on the wire extension at the first sign of retainer failure was recorded and subsequently presented as deformation in the analysis of results as permanent deformation of the wires were observed. A fixed retainer was considered to have failed if the retainer wire fractured, or if cracks or complete debond of any of the composite were observed. Of the 18 samples in each subgroup, 10 were concurrently video-recorded throughout force loading until the first indication of retainer failure. The videos were recorded at 25 frames per second with full high definition (FHD) quality.

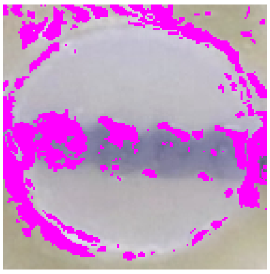
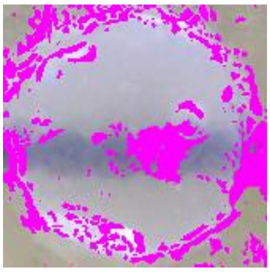
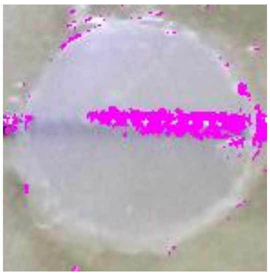
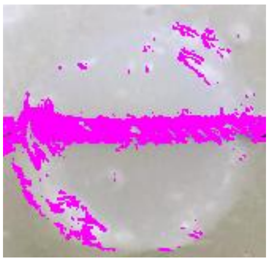
The video recordings were processed through VLC media player 3.0.8 (Free Software Foundation, Inc., Boston, MA, USA) to allow extraction of individual frames extracted at 0.2-second intervals. The video frames at the start of force application and just before the first indication of retainer failure were compared and their differences highlighted using Diffchecker (Checker Software Inc., 2022).

A scoring system was developed to quantify the force propagation observed along a retainer wire (Table 2). Each composite pad and the corresponding wire segment covered by it were scored individually based on the extent of differences highlighted. Unsupported sections of wire which were not covered with composite were not scored even if they were highlighted to eliminate differences which may have been influenced by the surrounding environment.

Given that the wire is a continuous object, force propagation should occur in a continuous manner. Hence, the score for a composite pad further away from the point of force application should always be lower or equal to that which is closer to the force origin. The maximum score for each sample was 24, reflecting evidence of distortion at all six possible locations.

Table 2. Novel force propagation index to quantify the difference observed at the start of force application and just before retainer failure

Score	Description	Examples
0	Highlighted areas only :- a) Margins of the composite And / or b) Minimal dots on composite body with none outlining segment of wire bonded with composite	
1	Discontinuous speckled patterns along margins of wire with its central region remaining relatively empty	 

2	Dense continuous expanse of highlighted region covering less than half of the wire segment bonded with composite with/without additional discontinuous speckled patterns on the composite body	 
3	Continuous expanse of highlighted region covering half / more than half of the wire segment bonded with composite with/without additional dense speckled patterns on the composite body	 
4	Dense continuous expanse of highlighted region covering entire length of wire segment bonded with composite	

4.3 Statistical analysis

Descriptive statistics including means and standard deviations were calculated. IBM SPSS Statistics for Windows, version 28 (IBM Corporation, Armonk, NY, USA) was used for inferential statistical analysis. From the pull-out test data, Levene's test confirmed the homogeneity of variances amongst groups, $F(7,152) = 1.725$, $=0.107$, while the Shapiro-Wilk test showed that the data was distributed normally. Hence, a two-way analysis of variance (ANOVA) was used to analyse the effect of each independent variable, as well as interaction between both factors (composite surface area and type of retainer wire) on the outcome of interest.

Assessment of video recordings for 3 random samples of each group from the study of force propagation were subjected to intra-rater reliability testing by assessing agreement between repeated measurements. The samples were selected through a randomisation software and their respective video recordings were scored twice by the same assessor at two-week interval. Excellent agreement was observed with an intraclass correlation coefficient of 0.993. Since Levene's ($F(3, 36) = 2.154$; $p=0.110$) and Shapiro-Wilk tests confirmed the homogeneity of variance and normality of the data from the video recording scores, a two-way analysis of variance (ANOVA) was also carried out for the analysis of force propagation.

Additionally, quantitative data generated by the Instron machine during mechanical testing for force propagation were assessed for wire extension at first sign of retainer failure. As the data obtained did not fulfil the normality and homogeneity requirements for parametric testing, it was subsequently analysed using a Mann-Whitney U test. The significant threshold for all the analyses was set at $P=0.05$.

CHAPTER 5. RESULTS

5.1 Effect of varying adhesive (composite) coverage on retainer failure

The adhesive surface area (A) in contact with the acrylic base can be calculated by subtracting the area of acrylic-facing surface of the retainer wire from the circular area ($A = \pi r^2$, r being the radius of the circle) of hollowed region in the silicone guide. Although Ortho-Care Perform™ has a circular cross-section, its area of acrylic-facing surface was estimated based on a rectangular dimension with the assumption that its width is equal to the wire diameter. This was done as the amount of composite underlying the wire was deemed to be too minimal to provide a significant effect on the overall bond strength. Hence, the estimated composite surface areas used differed for all groups due to the non-identical cross-section of both wires (Table 3).

Table 3. Estimated composite surface area used

Composite Surface Diameter(mm)	**Estimated Composite Surface Area (mm^2)**	
	Ortho-FlexTech™ 0.974mm(w) x 0.402mm(h)	**Ortho-Care Perform™ coaxial wire 0.0175” (0.4445mm)**
2	1.19	2.25
3	4.15	5.74
4	8.67	10.79
5	14.76	17.41

Ortho-FlexTech™ and Ortho-Care Perform™ recorded the highest mean debonding force when composite pads of 4mm diameter were used. Figure 10 shows a rising trend in mean debonding force and correspondingly increasing resistance to debond for both wires as the composite surface diameter increases up until 4mm. A slight decline in pull-out force was then recorded when the diameter was increased to 5mm. With regards to the effect of different types of wire on retainer failure, the coaxial wire demonstrated better resistance to debond than Ortho-FlexTech™ when composite pads of smaller diameters (2mm and 3mm) were used. The converse was true for composite pads of larger diameters (4mm and 5mm).

Table 4. Summary of mean debonding force

Groups		**n**	**Mean Debonding Force (N)**	**Standard Deviation (N)**	**Standard Error**
Retainer Wire	**Composite Surface Diameter(mm)**				
Ortho-FlexTech™ (Stainless Steel)	2	20	14.13	6.49	1.45
	3	20	22.68	9.76	2.18
	4	20	33.02	13.95	3.12
	5	20	30.78	13.86	3.10
Ortho-Care Perform™ coaxial wire 0.0175”	2	20	18.94	9.16	2.05
	3	20	26.57	12.29	2.75
	4	20	30.42	12.65	2.83
	5	20	29.95	9.10	2.03

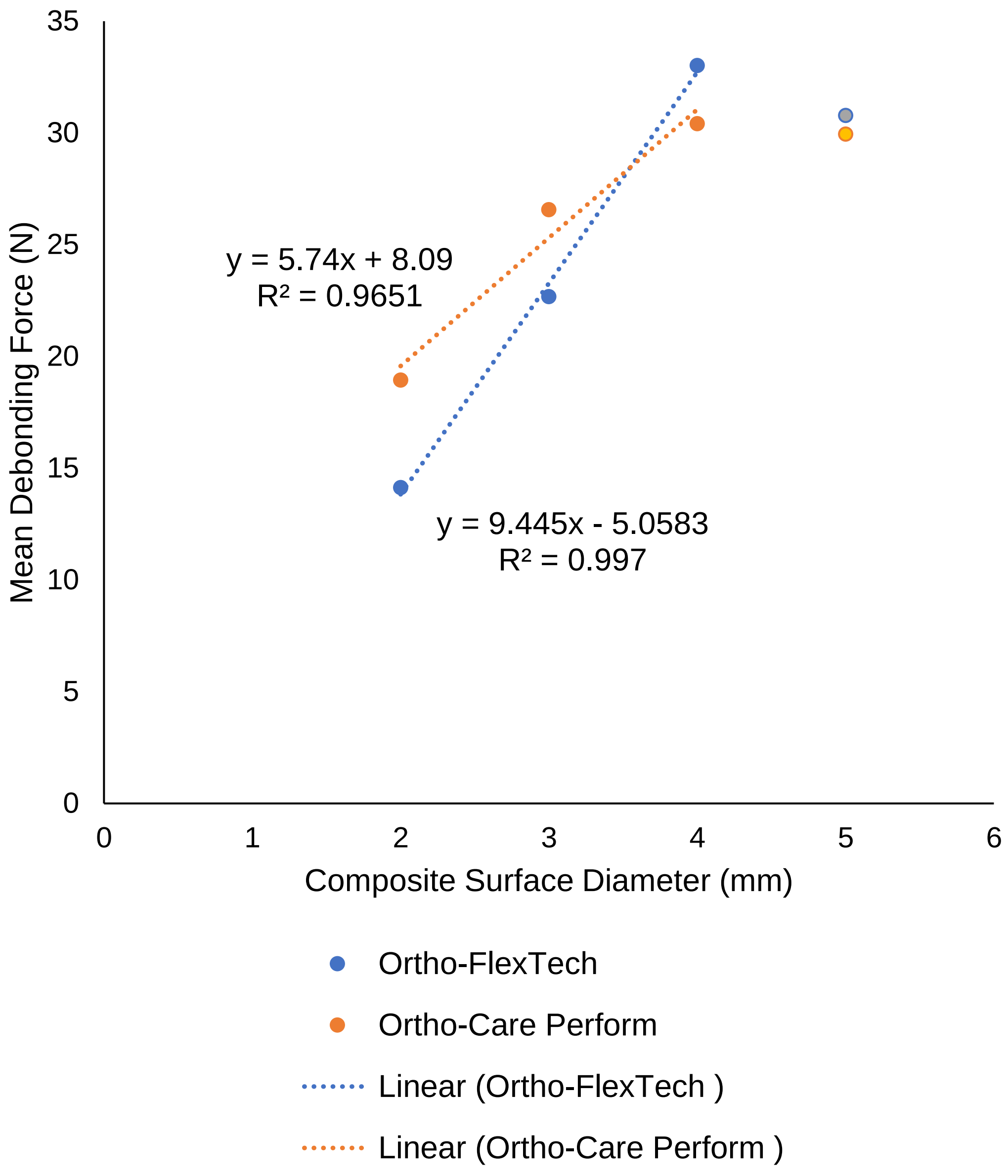


Figure 10. Scatter plot and trendline of mean debonding force (N) for different retainer wire at varying composite surface diameter (mm)

Statistical difference was observed for varying composite surface diameter (*P*=<0.001), with the mean debonding force for a composite pad of 2mm diameter being significantly lower than that of the other three dimensions (3mm, 4mm, and 5mm). A retainer wire bonded with composite pad of 3mm diameter required a significantly lower pull-out force for detachment compared to a retainer bonded with 4mm composite diameter (*P*=0.026; 95% CI: -13.59, -0.60). The average debonding force for retainer wires at 3mm composite diameter was also lower than their 5mm counterparts with a mean difference of 5.74N (*P*=0.104; 95% CI: -12.24, -0.76). Similarly, there was a marginal reduction in force required to trigger retainer failure when composite diameter was increased from 4mm to 5mm diameter (*P*= 0.949; 95% CI: -5.14, 7.86). Post-hoc comparisons of the four surface diameters are shown in Table 5. Hence, the null hypothesis for the effect of adhesive coverage on fixed retainer failures is rejected. On the contrary, there was no statistically significant difference in the debonding force for both types of wire (*P*=0.457).

Table 5. Tukey HSD post-hoc comparison of debonding force for different composite surface diameter

Dependent variable: debonding force

Composite Surface Diameter(mm) (I)	(J)	Mean Difference(N) (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
2	3	-8.09*	2.50	0.008	-14.59	-1.59
	4	-15.19*	2.50	<0.001	-21.69	-8.69
	5	-13.83*	2.50	<0.001	-20.33	-7.33
3	2	8.09*	2.50	0.008	1.59	14.59
	4	-7.10*	2.50	0.026	-13.59	-0.60
	5	-5.74	2.50	0.104	-12.24	0.76
4	2	15.19*	2.50	<0.001	8.69	21.69
	3	7.10*	2.50	0.026	0.60	13.59
	5	1.36	2.50	0.949	-5.14	7.86
5	2	13.83*	2.50	<0.001	7.33	20.33
	3	5.74	2.50	0.104	-0.76	12.24
	4	-1.36	2.50	0.949	-7.86	5.14

* The mean difference is significant at 0.05 level

5.2 Force propagation in fixed retainers

The average force propagation scores for Ortho-Care Perform™ when force was loaded between two central incisors and between a lateral incisor and canine were 18.2 and 13.8 respectively. In contrast, testing with Ortho-FlexTech™ produced average scores of 6.8 and 6.5 for the same locations of load application (Figure 11). We can thus infer that force was consistently propagated further in the coaxial wire than that of a flexible chain. A two-way ANOVA analysis showed that the mean difference of 9.35 recorded for both types of wires was of statistical significance (*P*=<0.001; 95% CI: 7.94, 10.77). Force propagation was also significantly more extensive when loading was done between two central incisors than when a wire was loaded between the lateral incisor and canine (*P*= 0.002; 95% CI: 0.94, 3.77).

Further analysis revealed that the Ortho-FlexTech™ exhibited more deformation when loaded at the centre of the retainer prior to failure. Nevertheless, the variation in deformation under loading between the different wires and their point of force loading were not statistically significant (Table 6). Similarly, one-way ANOVA testing on the mean load recorded at first sign of failure for all groups revealed an insignificant difference ($F(3, 68)=2.630$; *P*=0.057). Notwithstanding this, the mean load for Ortho-Care Perform™ is the highest of the four groups when force is loaded between a lateral incisor and canine (Table 7).

In terms of mode of failure, there was an almost equal number of wire fractures for both types of wire (Ortho-FlexTech™ = 6; Ortho-Care Perform™ = 5). Only three out of all the samples had a complete debond of one of the composite pads. Cracks and partial bond failure were observed in the remaining samples (Ortho-FlexTech™ = 28; Ortho-Care Perform™ = 30)

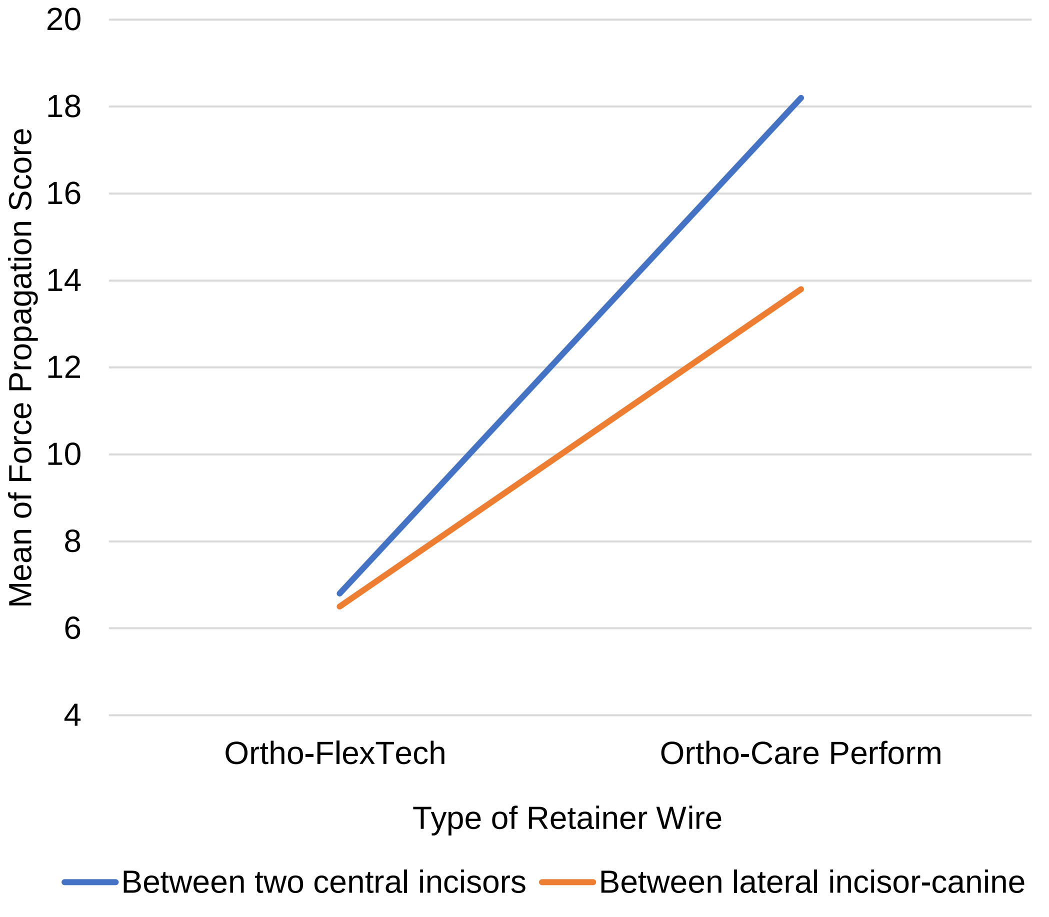


Figure 11. Line graph of force propagation score for different retainer wire and force loading position

Table 6. Median values of wire extension just before failure and the corresponding Mann-Whitney U comparisons.

	Ortho-FlexTech™		Ortho-Care Perform™	
Position of force loading	**Between the central incisors**	**Between the lateral incisor and canine**	**Between the central incisors**	**Between the lateral incisor and canine**
Median (mm)	2.37	1.66	1.78	1.68
Wire extension at failure (*P*-values pairwise comparison)				
Ortho-FlexTech™ (force between the central incisors)	-	-	-	-
Ortho-FlexTech™ (force between the lateral incisor and canine)	0.068	-	-	-
Ortho-Care Perform™ (force between the central incisors)	0.091	0.563	-	-
Ortho-Care Perform™ (force between the lateral incisor and canine)	0.051	0.791	0.791	-

* The mean difference is significant at 0.05 level

Table 7. Mean load at first sign of retainer failure

	n	Mean (N)	SD	Std. Error	95% CI	
					Lower Bound	Upper Bound
Ortho-FlexTech™ (force between the central incisors)	18	67.26	18.86	4.44	57.89	76.64
Ortho-FlexTech™ (force between the lateral incisor and canine)	18	66.62	24.91	5.87	54.23	79.01
Ortho-Care Perform™ (force between the central incisors)	18	69.45	17.01	4.01	60.98	77.91
Ortho-Care Perform™ (force between the lateral incisor and canine)	18	81.99	12.51	2.949	75.768	88.21

* *P*-value = 0.057

CHAPTER 6. DISCUSSION

6.1 Effect of varying adhesive (composite) coverage on retainer failure

As the R^2 value for trendlines relating to 2mm, 3mm, and 4mm coverage exceeded 0.9, it was possible to use the corresponding equations to estimate the force necessary to promote retainer failure based on coverage ranging from 2 to 4mm (Figure 10). Within the limitations of this experimental set-up, the data collected appears to suggest that a minimum of 4-mm composite diameter should be used during fabrication of bonded retainers. Any value less than 4mm may render the retainer of insufficient strength to resist debonding force while a larger dimension does not seem to offer additional benefits. Notwithstanding, this trend should be balanced against the increased rigidity associated with larger composite pads with the importance of retainer flexibility to allow for physiologic mobility of teeth well-recognised (Zachrisson, 2015).

Although the chain-like design of Ortho-FlexTech™ offers superior flexibility and increased surface area for bonding, its resistance to debond was inferior to the Ortho-Care Perform™ coaxial wire at 2mm and 3mm diameter. On the contrary, the performance of both wires was reversed at 4mm and 5mm diameter, albeit with a lower mean difference. This was most likely due to the larger cross-section of Ortho-FlexTech™ which enabled transfer of forces over a wider surface area, resulting in lower stress concentration at any single point of the composite-wire interface. This effect was not observed in the smaller diameter groups as the actual amount of adhesive supporting the wire may have been too thin to resist the propagated forces, particularly at margins near the composite-wire interface.

Overall, the debonding force in this study appeared to be lower than those reported by Bearn and co-workers (1997). This can be attributed to the different methods in which the samples were prepared. Bearn *et al*. used a circular notch in an acrylic block and filled this with composite after seating of the retainer wire. As such, the curved surface area and base of the composite were both bonded to the surrounding acrylic notch. Conversely, only the composite base was bonded to an acrylic surface in the present study to replicate the clinical set-up. The ensuing decrease in composite surface area which was bonded most likely led to reduced resistance to pull-out and consequently failure of the retainer wire at lower force levels.

The debonding force observed in the present study was lower than the 59N bond strength reported by Schulz *et al.*(1985) during *in vitro* tensile testing of wires embedded in composite. However, their experiment was conducted by bonding wires to extracted natural teeth; therefore, an increase in bond strength would have been expected. In contrast, Papazoglou and Vasilas (1999) reported a shear strength of composite bonded to untreated acrylic resin denture teeth of 3.99MPa. The polymerisation process used in the latter study involved the use of reactive methacrylate groups of methyl methacrylate (MMA) and bisphenol A-glycidyl methacrylate (bis-GMA), which reflects the experimental set-up used in the present investigation. The present finding of mean debonding force per square millimetre for Ortho-FlexTech™ with a 4-mm composite diameter of 3.8MPa (following conversion to bond strength in megapascal; MPa) is therefore compatible with these findings (Papazoglou & Vasilas, 1999).

6.2 Force propagation in fixed retainers

6.2.1 Experimental set-up

In this part of the study, we attempted to quantify the differences observed at the start of force loading and just before first sign of failure to enable analysis of the extent of force propagation in different retainer wires. By extracting the individual video frames and processing them through an image comparison website, we were able to compare two almost identical pictures pixel-by-pixel. The colour of pixels that have the same coordinates within an image were identified by the comparison algorithm and compared. Pixels that do not match were highlighted by the software and quantified by the operator using a force propagation scoring index (Table 2). Specimens with higher scores meant that more differences were identified and thus were deemed to have the loading force propagated through the retainer wire more extensively.

In order to maintain the mandibular inter-canine width following treatment, lower bonded retainers are routinely placed from canine to canine. Meanwhile, a range of bonding sites exists for maxillary bonded retainers depending on a patient's original malocclusion, occlusion at the end of treatment, tooth morphology, ability to maintain good oral hygiene and clinician's preference.

An upper retainer wire can either extend from canine-to-canine, lateral incisor-to-lateral incisor, central incisor-to-central incisor, or occasionally include the first premolars as well. Although maxillary retainers involving canines exhibited a higher propensity for failure (Schneider & Ruf, 2011), their ability to maintain alignment of the labial segment was superior to those bonded solely to incisors (Dietrich, *et al*., 2015). Hence, we decided to conduct our study based on the canine-to-canine set up.

Taking into account the results from the initial study concerning the effect of different adhesive surface area on retainer failure, a 4-mm composite pad was used on all the bonding site in our set-up as it offers superior resistance to debonding force. Unfortunately, due to limitations in the available choices of force loading attachment dimensions, only the mesiodistal widths of maxillary anterior teeth were incorporated in our experiment design. This allowed unhindered movement of attachments between adjacent composite pads upon delivery of the vertical force. With regards to the location of force loading, the central incisor-to-central incisor and lateral incisor-to-canine positions were chosen as they represent two different but important clinical presentations: 1) having only one bonding site adjacent to force origin and 2) having more than one bonding site adjacent to force origin. As mentioned by Schneider and Ruf (2011), a reduced number of bonding sites is associated with higher proportion of retainer failures. The central incisor-to-lateral incisor position was, however, not tested here as we felt that it offers an almost similar representation to the central incisor-to-central incisor set-up.

6.2.2 Outcome

The force propagation scores assessed for Ortho-Care Perform™ was observed to be significantly greater than that of Ortho-FlexTech™. We can thus infer that the load applied had propagated more extensively through the multistranded coaxial wire. This contrasts with Engeler *et al*. (2020) which analysed the torsional load transfer in different wires using a robotic device. They found that multistranded wires in general demonstrated less torsional load transfer than Ortho-FlexTech™. However, their set up differed from the current study as the load transfer was generated by torsional bend whereas force loading in the present study was done in an inciso-apical direction at the unsupported inter-composite segment of the wire. Additionally, the aforementioned study was done on a two-teeth set up, while a total of six bonding sites mimicking a canine-to-canine retainer were used here (Engeler, *et al*., 2020).

Conversely, the findings of the present study appeared to be comparable with those reported in the work by Sifikakis and co-workers (2015). In the latter study an acrylic resin model of the mandibular arch was fitted with a fixed retainer, split into two unequal segments at one of the lateral incisor-canine region and an adaptor attached to each of the segments prior to mounting on the Orthodontic Measurement and Simulation System (OMSS). This system was based on the principle of two-tooth model despite being bonded to all six anterior teeth (canine-to-canine). Nevertheless, in keeping with our observation of a multistranded wire propagating forces more extensively than a chain-like wire, they reported higher reactionary maximum force and moment on the smaller segment when a gradual intruding force was applied on the larger segment when multistranded wire was used (Sifakakis, *et al*., 2015).

Arnold *et al.* (2016) studied the torque resistance of various commercial stainless-steel wire used for fixed retention by retracting the lateral incisor at its apex, producing a rotation of the tooth around the retainer wire, and twisting of the wire on a 2-teeth and 3-teeth set-up. Although the resulting moment on the neighbouring teeth were consistently higher for Triple Flex than for Ortho-FlexTech™, the stiffness of both wires were not statistically different to each other but were statistically different from the findings for plain, rectangular and 8-stranded braided rectangular wires (Arnold, *et al*., 2016). This corresponds to our results whereby the wire deformation just before failure was greatest for Ortho-FlexTech™ when force was loaded between the central incisors, indicating lower stiffness compared to the rest of the set-ups. The difference was however not statistically significant.

6.3 Clinical significance

Our results appear to have reinforced the opinion of previous authors on the need to account for a degree of flexibility in fixed retainer fabrication (Zachrisson, 2015). A retainer that is excessively rigid may prevent physiologic mobility of teeth and in turn exert damaging forces on the periodontium to cause unwanted tooth movement post-retention. The rigidity of a retainer can be influenced by both the amount of composite used during fabrication and selection of wire type. The composite covering each bonding site should be at least 1mm in thickness (Bearn, *et al*., 1997) and 4mm in width. Having said that, a marginally larger width of coverage may be tolerated by the teeth bonded as unlike our study which used spherical shaped adhesives with uniform thickness, the composite pad used clinically resembles more of a dome shaped structure with a thick central region tapering to a thinner layer peripherally to enhance patient comfort, and to limit undercuts and plaque accumulation on the tooth surface bonded.

The manufacturer of Ortho-FlexTech™ has advised that a secondary retainer wire should be used in cases with pre-treatment diastemas as the wire tends to stretch and allow reopening of spaces. As per our results showing greater deformation and stretching of Ortho-FlexTech™ when loaded until the first sign of failure, there seems to be sufficient grounds to take the manufacturer's suggestion into consideration when bonding such retainers clinically.

In terms of wire selection, the resistance to detachment when sufficient composite was used was also slightly better for Ortho-FlexTech™ although the difference between both wires was not significant. Notwithstanding this, it should be noted that failure of fixed retention intraorally is not confined solely to detachment or fracture of wire. Activation of the retainer wire precipitating unwanted tooth movement post-treatment is a further form of failure. In this regard, Ortho-Care Perform™, the more rigid of the two wires may be susceptible to developing more stress in response to external forces. This would then propagate further down towards the terminal ends of the retainer as documented by the significantly greater difference scored using our force propagation index. Given that the coaxial wire is manufactured by wrapping five strands of wire around a single core wire, the higher load accumulated at the ends of the wire is thus more likely to be converted into other forms of energy, one of which may be expressed as untwisting of wire and transfer of undesirable forces to the bonded teeth. This would explain the opposite inclination of contralateral canines (twist effect) and buccal inclination or movement of a single mandibular canine reported in previous literature (Katsaros, *et al*., 2007; Kučera & Marek, 2016).

Unlike the coaxial design of Ortho-Care Perform^{TM}, Ortho-FlexTech^{TM} has a rectangular interlocking chain design which is more resistant to twisting. Irrespective of the site of load application, video recordings for Ortho-FlexTech^{TM} showed that none of the specimens underwent a large amount of force propagation (scores 2, 3, and 4) beyond the composite pads immediately adjacent to the point of force application. On the basis of our experiment, force applied is therefore not completely transmitted along the length of the Ortho-FlexTech^{TM} wire during plastic deformation as the energy within the system may likely be dissipated in the form of kinetic and thermal energy due to friction when the constituent atoms slide over each other. Ortho-FlexTech^{TM} which has a larger surface area than Ortho-Care Perform^{TM} in contact with the overlying adhesive may also loose a higher proportion of energy through friction at the wire composite interface. Intuitively, therefore, a retainer wire with greater inherent flexibility and wider surface area may lose more energy on deformation and consequently have less residual energy capable of causing unwanted tooth movement following release of force.

Additionally, lower force propagation scores and reduced wire deformation at failure were recorded for both wires when force is loaded between a lateral incisor and canine. This may be attributed to the single bonding site (canine) present on one side of the force origin, predisposing to a faster rate of retainer failure before the load applied can propagate further or cause more wire deformation. Most of the samples loaded at the lateral incisor-canine region were detached from its terminal bonding site instead of the lateral incisor, thus agreeing with the article by Schneider and Ruf (2011) that reduced number of bonding sites is linked with a higher proportion of retainer failures.

6.4 Limitations

The present study is ultimately an *in-vitro* set up that tries to replicate a clinical situation. Whilst external forces during function are exerted both on the teeth being bonded as well as the wire segments exposed intraorally, the force applied in the present experiment is only at a single inter-composite region for each specimen. Moreover, intraoral forces most often occur in a cyclic pattern, whereas the experimental force was loaded in a continuous manner. As an acrylic model was used instead of natural teeth, the collective bond strength with composite, mechanical properties of the periodontium and biological influence from the intraoral environment have also not been accounted for.

Only two commercially available wires were tested in our experiment. Consequently, the findings may not necessarily represent the general properties of retainer wires available in the market. Specifically, for a multistranded coaxial wire, the number of strands wrapped around the central core and its overall dimensions can also influence the properties exhibited by the individual wires (Arnold, *et al*., 2016).

Similarly, the inter-composite span is likely to have an effect on the mechanical properties of fixed retainer. Although a 4-mm composite pad was assessed to have the best resistance to failure, this may not be true in the case of a mandibular arch as the reduced inter-composite distance will increase the rigidity of retainer wires and their associated failure rate. Moreover, the composite pads applied clinically resemble a dome with thinner peripheries instead of the circular pad with uniform thickness used here. Consequently, even if a similar width and thickness of composite is used, the actual amount of overlying composite supporting a retainer wire intraorally will be less than the composite applied in our study.

Although intra-rater reliability for force propagation assessment had been shown to be excellent, it would have been beneficial to have a second rater evaluate the recorded video independently. It would however be impossible to blind the assessor as the translucency of the composite coverage would have revealed the wire used based on its dimension.

6.5 Further research

Inclusion of fixed retainers made with a wider range of wire dimensions, designs and materials in future studies could be helpful to clinicians in retaining treatment results without causing irreversible harm to the supporting structures. With the increasing digitalisation of dentistry as a whole, studies involving newer retainer wires like CAD-CAM produced Memotain^{TM} would be beneficial in discerning the actual benefits of such technology from those marketed by manufacturers.

More in-depth comparison of clinical findings should also be done to further our understanding of fixed retainer behaviour clinically. Measuring methods with improved sensitivity such as the 3D-digital image correlation (DIC) technique can be used to detect changes in retainer material at the grain scale.

CHAPTER 7. CONCLUSION

Based on the limitations of the experimental set-up used, the following conclusions can be drawn:

1. A minimum of 4mm diameter or width of composite coverage per tooth should be used when bonding a fixed retainer. A broader area of coverage does not appear to offer appreciable benefit and may promote failure of retainers due to the increased stiffness which resists physiologic mobility of teeth bonded.
2. It appears that force may be propagated further in Ortho-Care Perform™ than Ortho-FlexTech™. Hence, these wires may be more prone to stress accumulation at the terminal ends of a retainer wire exerting unwanted forces on the adjacent teeth bonded to these terminal ends.
3. Ortho-FlexTech™ being a more flexible wire may be susceptible to stretching prior to failure.

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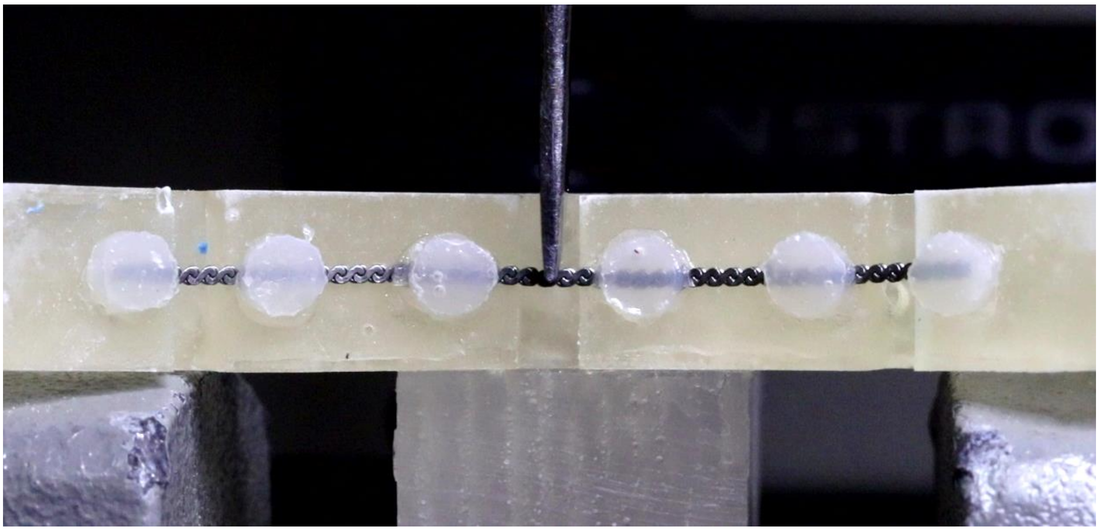
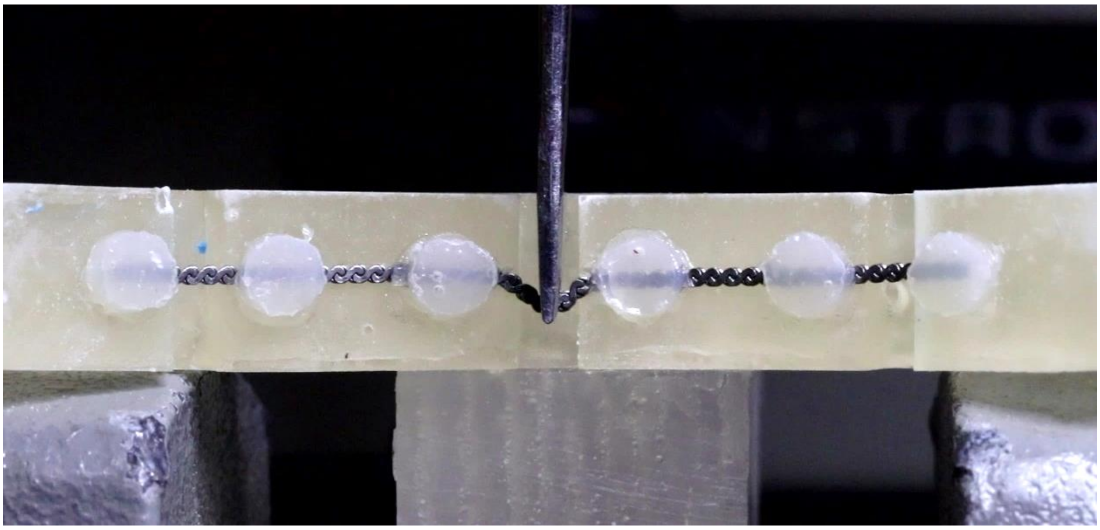
APPENDICES

Appendix 1. Sample scoring of force propagation observed along an Ortho-FlexTech™ wire when loaded between the central incisors.

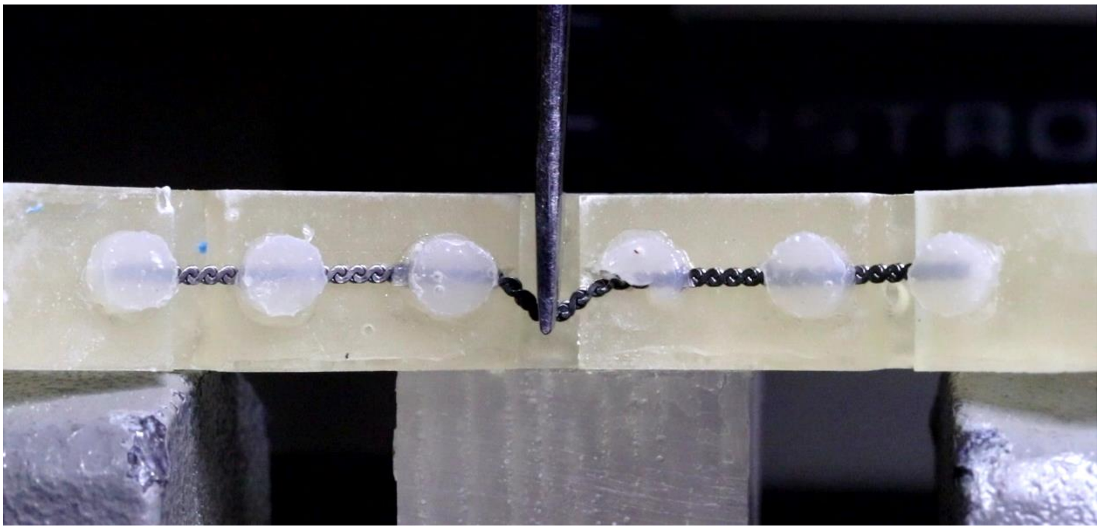
a) Video frame extracted at the start of force loading



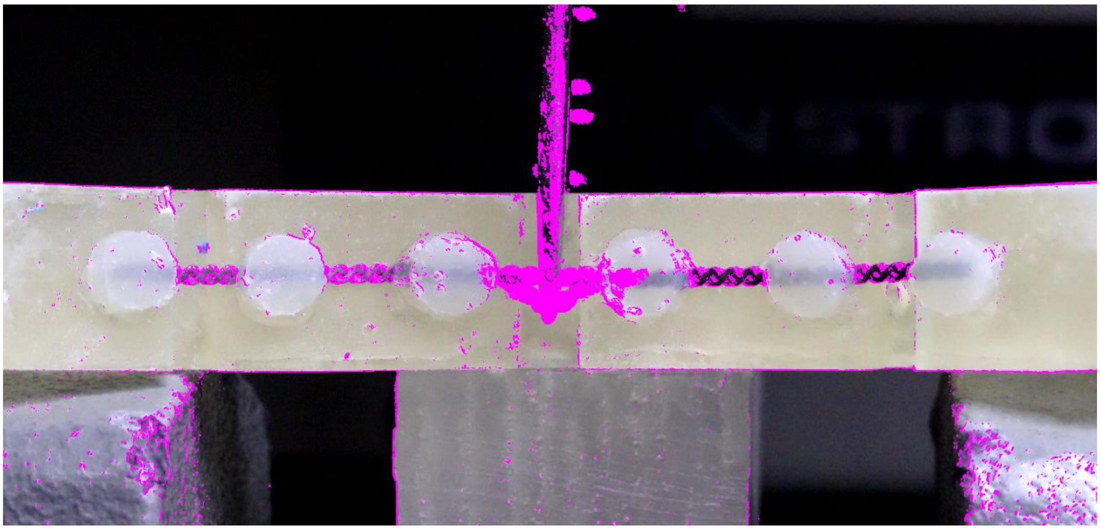
b) Video frame extracted just before first sign of retainer failure



c) Video frame extracted after failure of the fixed retainer.



d) Highlighted differences between image (a) and (b) after processing through an image comparison website

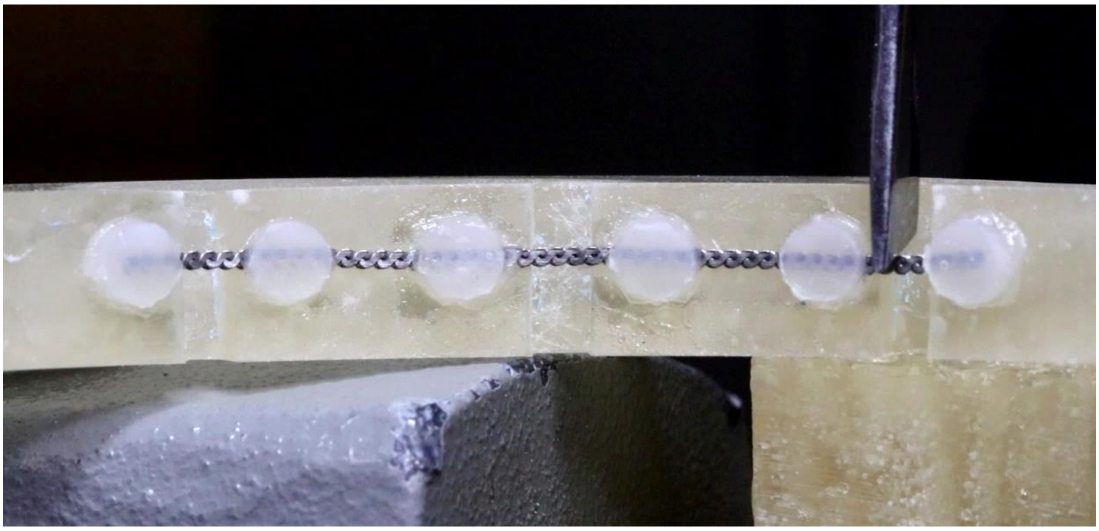


Composite Pad	3	2	1	1	2	3
Force propagation score	0	0	2	3	0	0

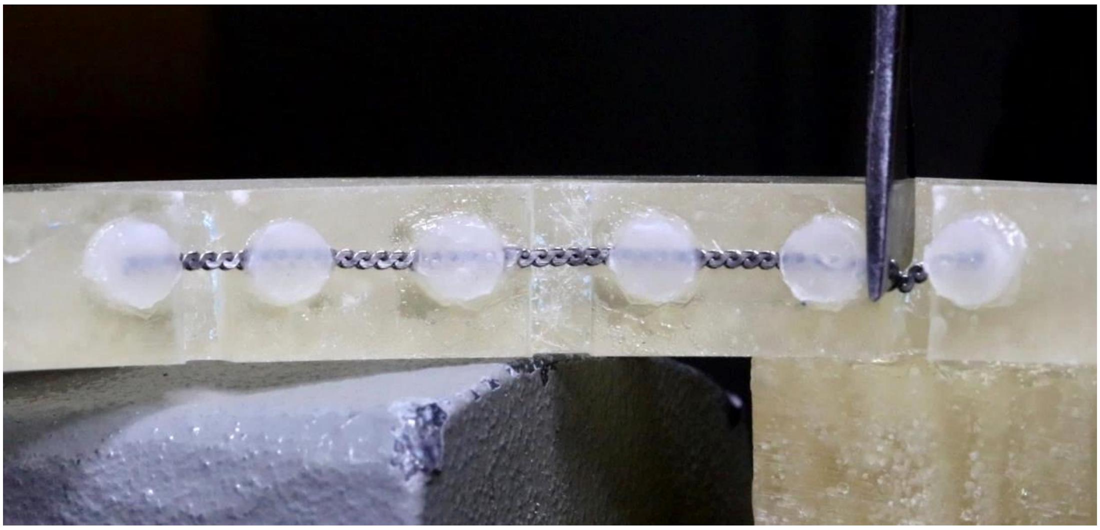
Total Score = 5

Appendix 2. Sample scoring of force propagation observed along an Ortho-FlexTech™ wire when loaded between the lateral incisor and canine.

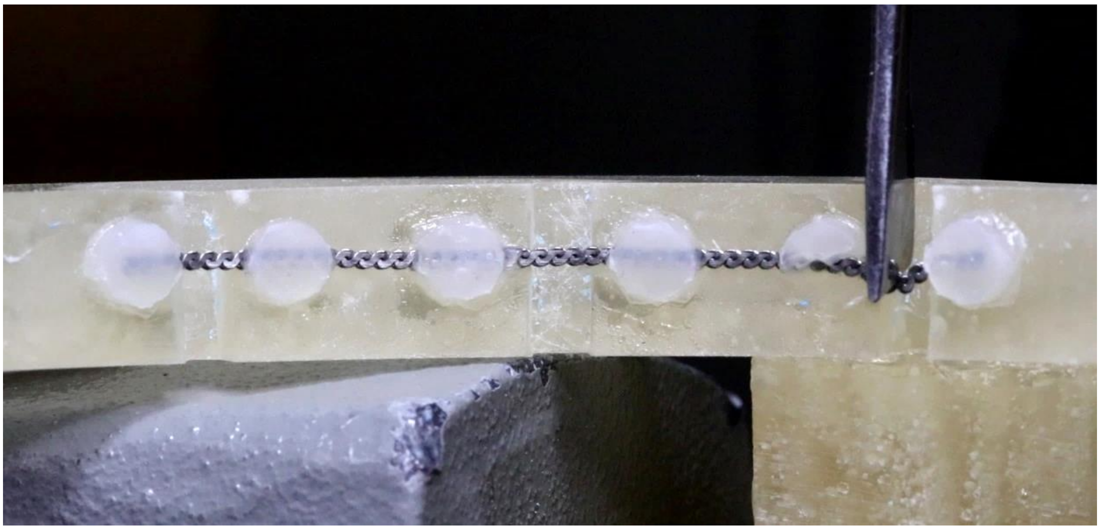
a) Video frame extracted at the start of force loading



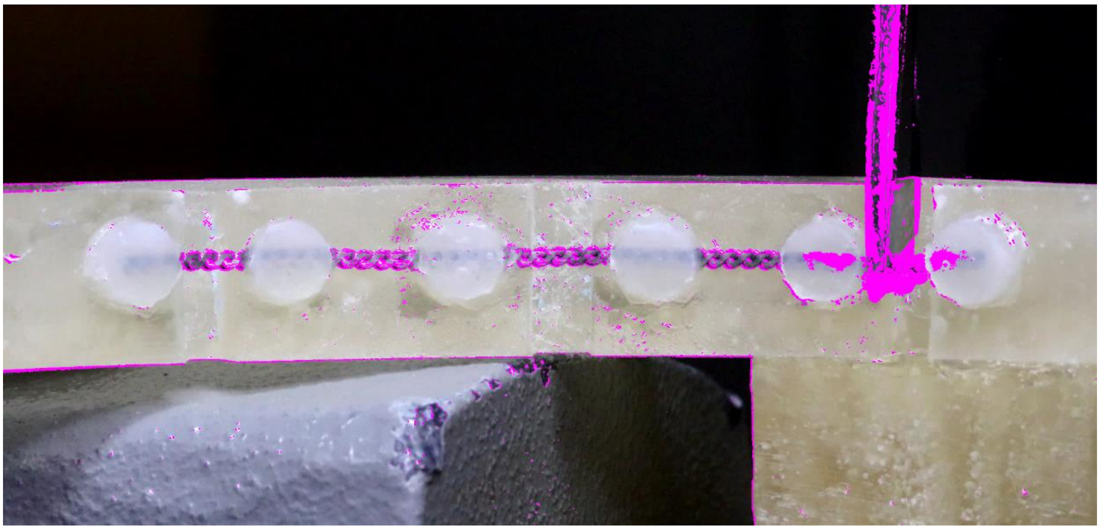
b) Video frame extracted just before first sign of retainer failure



c) Video frame extracted after failure of the fixed retainer.



d) Highlighted differences between image (a) and (b) after processing through an image comparison website

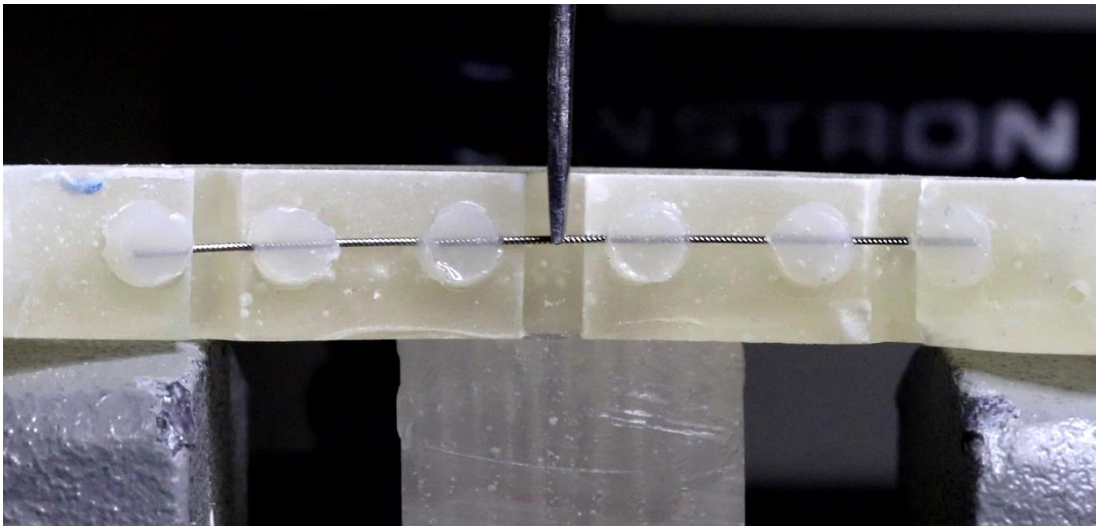


Composite Pad	3	2	1	1	2	3
Force propagation score	0	0	0	0	3	2

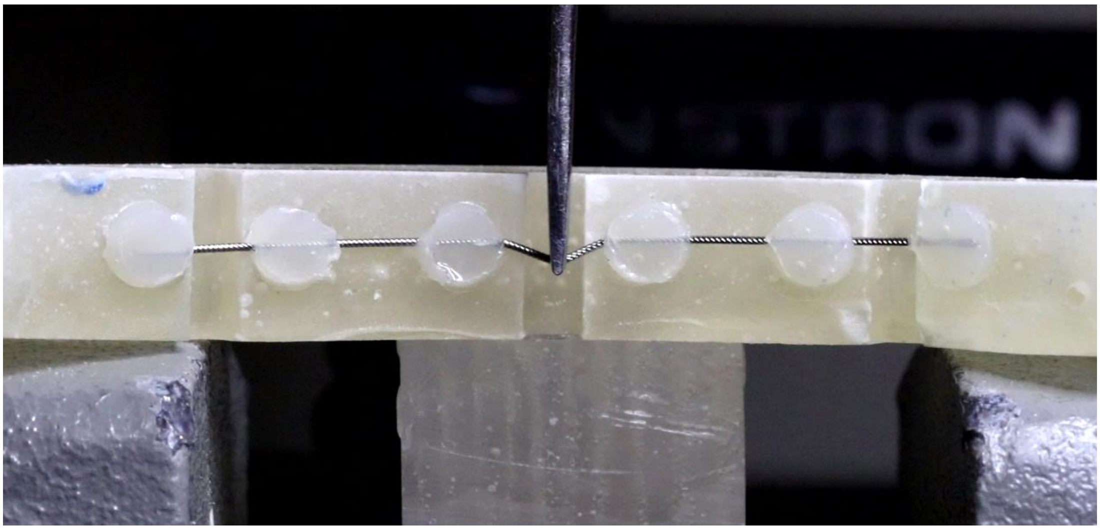
Total Score = 5

Appendix 3. Sample scoring of force propagation observed along an Ortho-Care Perform^{TM} wire when loaded between the central incisors.

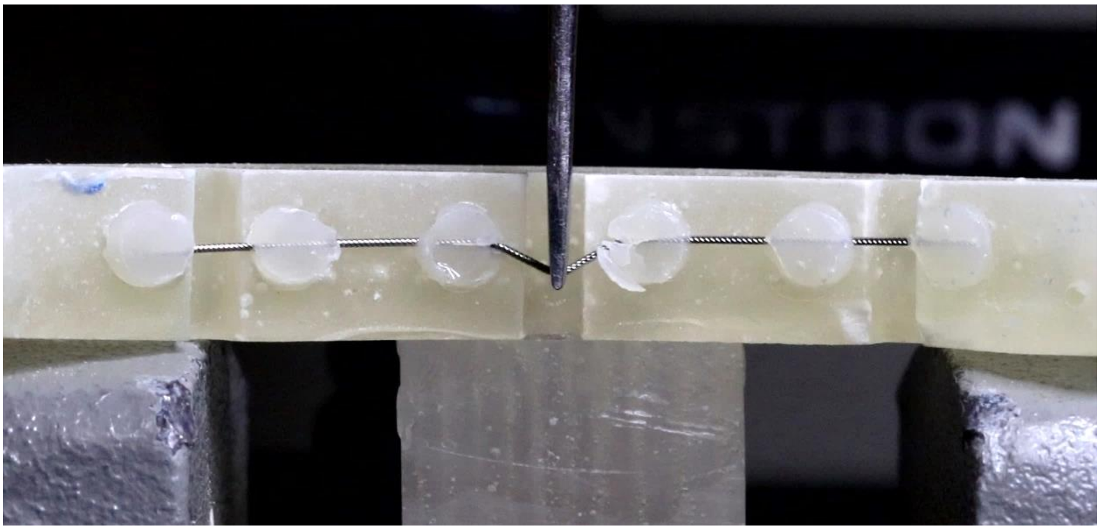
a) Video frame extracted at the start of force loading



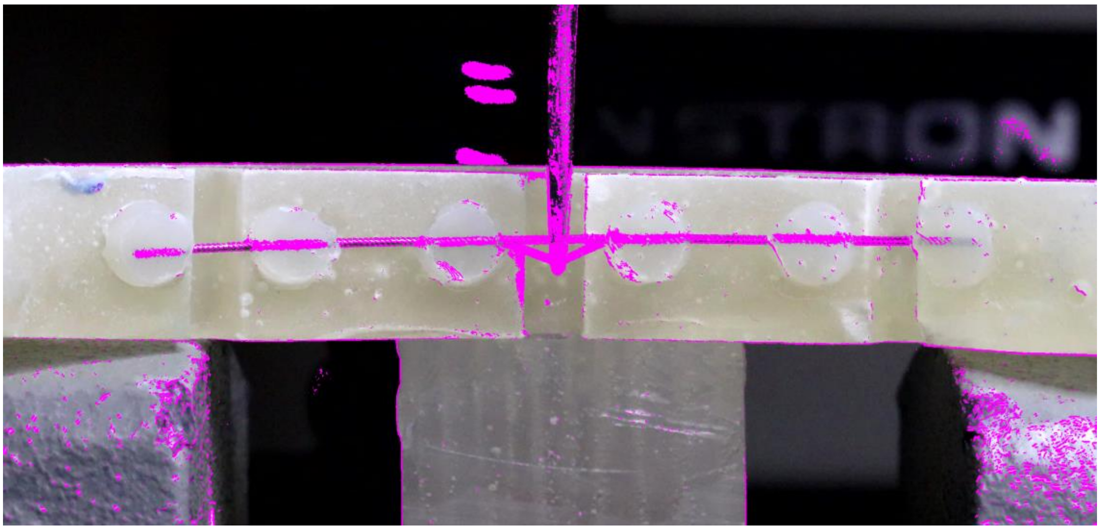
b) Video frame extracted just before first sign of retainer failure



c) Video frame extracted after failure of the fixed retainer.



d) Highlighted differences between image (a) and (b) after processing through an image comparison website

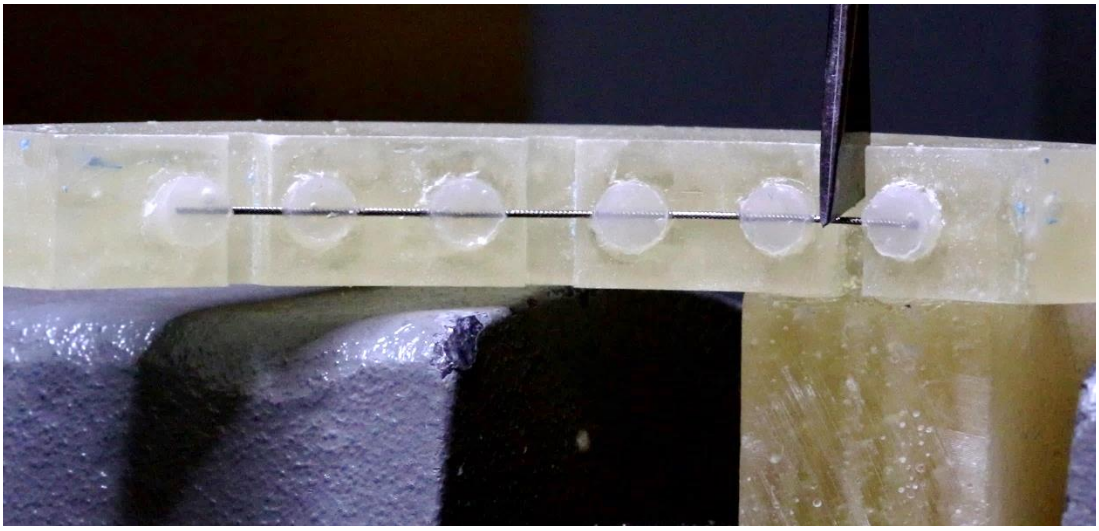


Composite Pad	3	2	1	1	2	3
Force propagation score	4	4	4	4	4	1

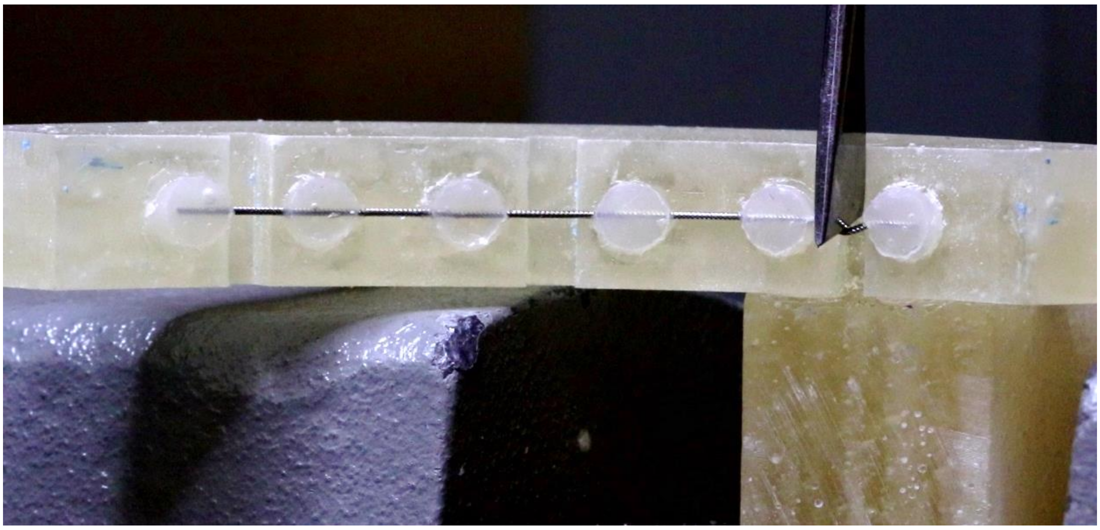
Total Score = 21

Appendix 4. Sample scoring of force propagation observed along an Ortho-Care Perform^{TM} wire when loaded between the lateral incisor and canine.

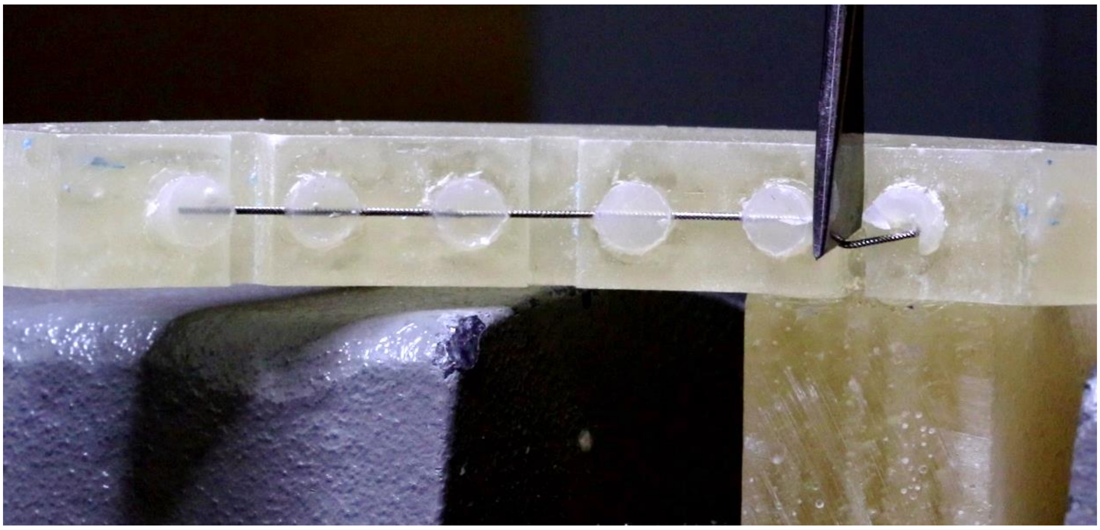
a) Video frame extracted at the start of force loading



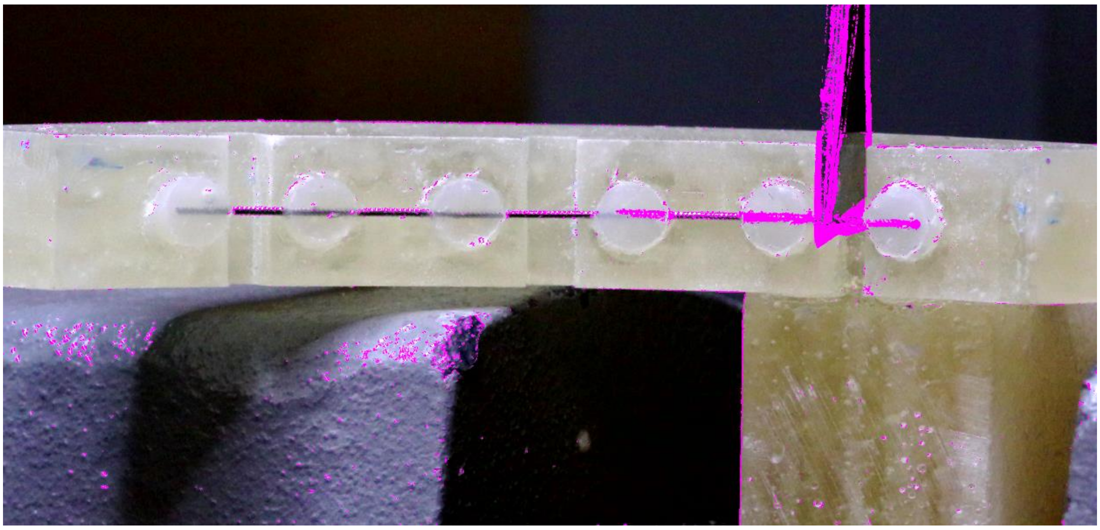
b) Video frame extracted just before first sign of retainer failure



c) Video frame extracted after failure of the fixed retainer.



d) Highlighted differences between image (a) and (b) after processing through an image comparison website



Composite Pad	3	2	1	1	2	3
Force propagation score	0	0	0	3	4	4

Total Score = 11