Original Article

Braz J Oral Sci.
January | March 2015 - Volume 14, Number 1

A finite element study on the mechanical behavior of reciprocating endodontic files

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Abstract

Aim: To evaluate the mechanical behavior of reciprocating endodontic files, comparing nickel-titanium (NiTi) and stainless steel 316L (St.St. 316L) as manufacturing material for such instruments. **Methods:** A three-dimensional finite element model was designed for this study. The simplified instrument model geometry was created on commercial CAD/CAM software. Real strain stress curves of St.St. 316L and NiTi were used in the analysis. Non-linear static analysis was performed to simulate the instrument inside root canal at an angle of 45° in the apical portion, and subjected to torsion of 0.3 N.cm. **Results:** Non-linear NiTi material showed super elasticity and high functionality in such applications. Very high levels of stress appeared in the file at 3 mm from the tip close to yield point. **Conclusions:** St. St. 316L is not suitable for manufacturing reciprocating instruments. Modeling of the instrument with equivalent circular cross-sectional area did not affect results quality. Reciprocating instruments have short lifespan, thus manufacturers recommend using one file per tooth. Reciprocating instruments are recommended for less experienced dentist.

Keywords: endodontics; stainless steel; nickel; titanium.

Introduction

The goals of endodontic instrumentation are to shape without deviating from the original canal position, to enlarge until the walls are smooth and free of soft tissues, to completely remove microorganisms and debris, and to create a canal form that converges toward the foramen[1]. Stainless steel endodontic instruments, whose characteristics include stiffness that increases with size, may set limitations to successful shaping. During enlargement of the apical third, this characteristic may be responsible for curvature defects such as apical transportation, ledging or zipping, which might compromise the outcome of treatment[2].

In the early 1960s, a nickel-titanium (NiTi) alloy was developed by Buehler, during the investigation of nonmagnetic, salt resisting, and waterproof alloys for the space program at the Naval Ordnance Laboratory in Silver Springs, Maryland, USA[3]. Nitinol is the name given to a family of inter-metallic alloys of nickel and titanium, which has unique properties of shape memory and super-elasticity. Nickel titanium instruments are more flexible than stainless steel instruments and have the ability to revert to their original shape after flexure. It has been reported that NiTi instruments are 2 to 3 times more flexible than stainless steel instruments

Received for publication: November 11, 2014
Accepted: March 17, 2015

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and more resistant to fracture[4].

However, despite these advantages, the main problem with rotary NiTi instruments is a probable failure of the instruments. Instrument fracture is a serious problem and can jeopardize the outcome of the root canal treatment. Separation of rotary NiTi instruments can occur due to two reasons: torsional fracture or cyclic fatigue[5]. Torsional failure occurs when the tip of the instrument is locked in the canal while the shaft continues to rotate. If the elastic limit of the metal is exceeded, the instrument undergoes plastic deformation, which can be followed by fracture if the load is high enough. Failure by torsional overload was reported as the most common cause of separation of rotary NiTi instruments[6].

Endodontic files are subjected to stress when they are bent around a curve. Every bent segment of the file experiences a cycle of both compressive and tensile stresses; this may lead to cyclic fatigue. Due to initiation, propagation, coalescence of micro-fractures it may ultimately cause an overt fracture of the file. Because the micro-fractures cannot be seen even with the aid of a surgical operating microscope, there is no warning preceding fracture[7].

Possible strategies to increase efficiency and safety of NiTi rotary instrument include improving the manufacturing process or using new alloys that provide superior mechanical properties. The stiffness and flexibility of endodontic files are greatly dependent on their geometric design, including taper, helix angle, cross section shape, tip size and length[8].

In an attempt to increase the resistance to cyclic fatigue of the rotary instruments, M-Wire was introduced by applying a series of heat treatments to NiTi wire blanks[9]. Before the grinding process, the alloy was thermally treated to improve its properties. The final goal was to produce instruments with superelastic behavior (reduced generation and accumulation of lattice defects during each load-unload cycle) and increased resistance to cyclic fatigue, compared to those constructed from traditional NiTi alloy[10]. The first commercially available endodontic rotary system using the new M-Wire NiTi material was GTX (Dentsply Tulsa Dental Specialties, Tulsa, OK, USA).

Recently, costly experimental studies[11-13] were implemented on different brands and types of instruments like Reciproc, WaveOne, HyFlex, Mtwo, ProTaper, EndoWave, etc., according to ISO 3630-1. Tens of instruments were tested in order to statistically prove that heat treated instruments have better cutting efficiency and higher fatigue resistance than conventional NiTi files.

In 2008 Yared[14] proposed a new preparation motion (reciprocating), using only F2 ProTaper rotary file to prepare the root canal. It has been claimed that rotary NiTi endodontic files show more resistance to cyclic fatigue, when used in reciprocating motion. Various cyclic fatigue tests have been conducted to compare file systems which allow the files to rotate till fracture. Flexural-fatigue failure occurs when the instrument rotates inside a curved canal while subjected to an excessive number of tensile-compressive strain cycles in the region of maximum canal curvature.

The stresses generated during flexural loading are directly associated to the fatigue life of the material[15]. The stress conditions within instruments cannot be revealed by inspection of broken segments but require a mathematical/ numerical simulation. Finite element analysis (FEA) has been applied as alternative to study the mechanical behavior of endodontic instruments for detailed assessment of stress distributions in instruments[15-16].

Arruda Santos et al.[17] confirmed the potential of FEA as a numerical method to assess the mechanical behavior of endodontic instruments comparing the behavior of three different types of instruments: Mtwo (VDW, Munich, Germany), RaCe (FKG Dentaire, La-Chaux-de-Fonds, Switzerland) size 25, .06 taper (0.25 mm tip diameter, 0.06% conicity) and PTU F1 (Dentsply Maillefer, Ballaigues, Switzerland) experimentally and numerically by FEA[17].

The aim of this study was to evaluate the mechanical behavior of reciprocating endodontic files, comparing nickel-titanium (NiTi) and stainless steel 316L (St.St. 316L) as manufacturing material for such instruments.

Material and methods

In this study the WaveOne (Dentsply Maillefer, Ballaigues, Switzerland) primary file (equivalent to ProTaper F2 file) was modeled in 3D (Figure 1). The file tip size was ISO-25 with an apical taper of 8% that reduces towards the coronal end. The 3D geometric model was prepared on a commercial general purpose CAD/CAM software (AutoDesk Inventor version 8.0; Autodesk Inc., San Rafael, CA, USA). Although the cross section of the Wave One primary file is a convex triangle, it was simplified in this study to be circular with equivalent cross-sectional area, while the change in cross section in the apical part was neglected. The NiTi instruments and wires with different cross sections showed similar behavior in previous studies[17-18] which inspired the simplification of the modeled file cross section.

The geometric model was transferred as IGES file to the meshing and finite element analysis package (ANSYS version 14.5; ANSYS Inc., Canonsburg, PA, USA). The meshing element was 20 nodes “Solid 186” which has three degrees of freedom (translations in the global directions). Mesh density is a parameter that improves the result accuracy and reduces artificial peak stresses by improving the representation of the actual geometry. The mesh density effect was evaluated before extracting results with 20,935 nodes and 13,057 elements.

Multi-linear material was defined as presented in Figure 2. NiTi alloy and AISI 316L stainless steel, widely used in biomedical applications and described by an elasto-plastic constitutive model with kinematic hardening[19]. In both material models, the values of the characteristic parameters were derived from the literature. Considering the NiTi alloy, the transformation starting stress σ_s and the transformation finishing stress σ_f, are the stress values when, at the working temperature, the transformation between austenite and single-variant martensite starts and finishes, respectively. The limit

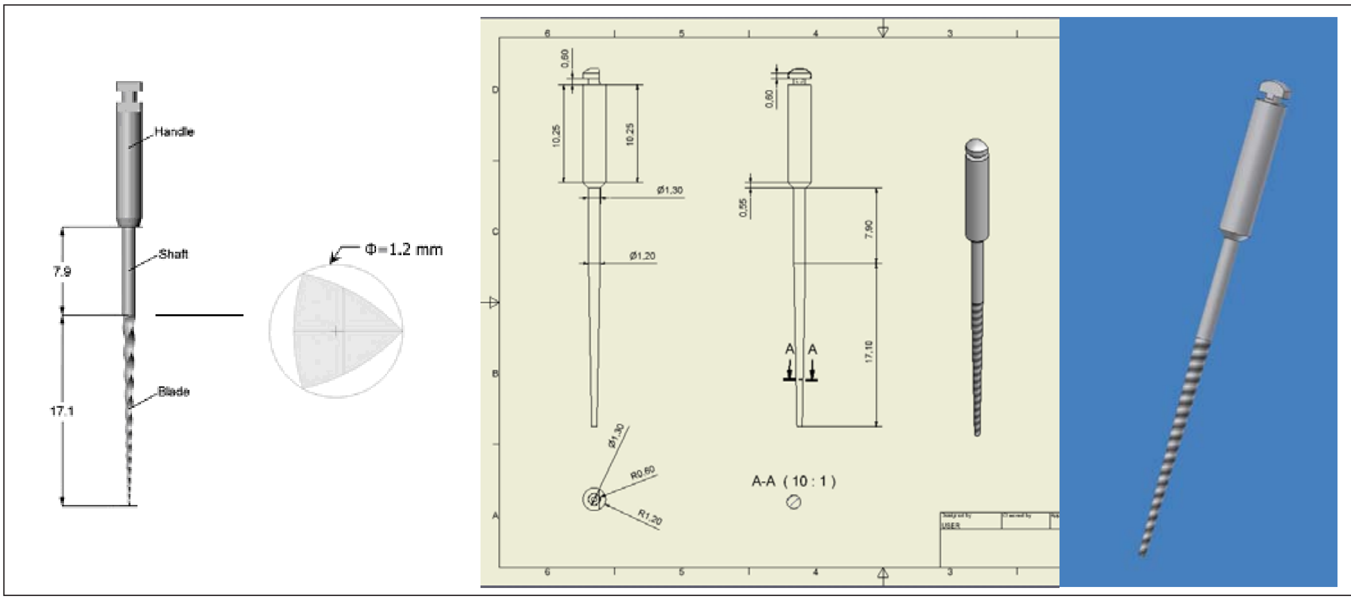

Fig. 1: Modeled File geometry on Inventor screen

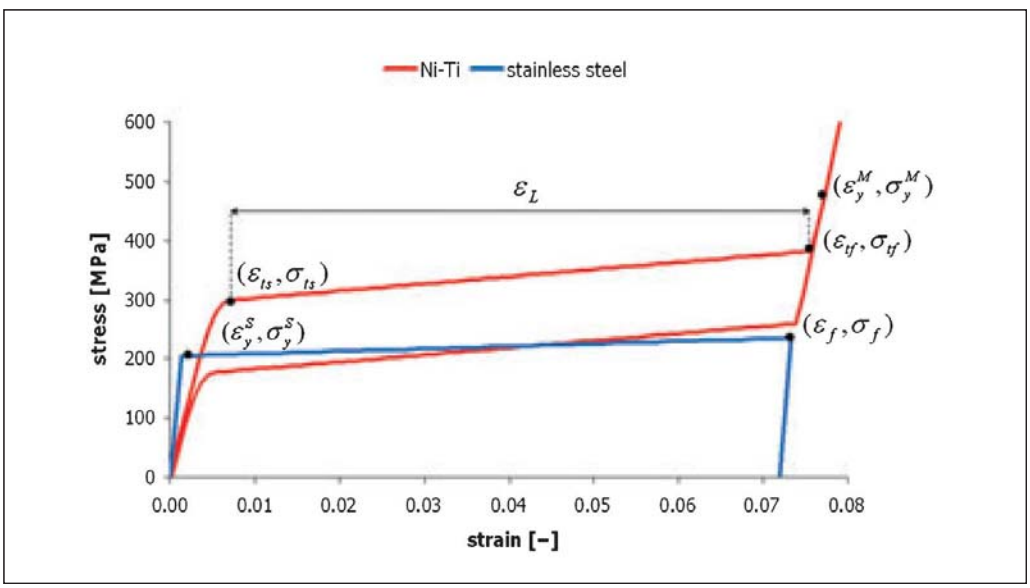

Fig. 2: NiTi and St.St. 316L material properties (uniaxial stress-strain curves)[19]

transformation strain ε_L is the amplitude of the transformation strain interval. The capacity to recover all the deformation (i.e. pseudo-elastic behavior) ends when the martensitic yielding stress 'σ_y' and the martensitic yielding strain 'ε_y' (indicated as pseudo-elastic limits) are assessed[19].

The boundary conditions were imposed to simulate the behavior of the files under bending and torsional conditions in compliance with the ISO 3630-1 specification[20]. To test the bending resistance, the bending moment was calculated while the file was clamped 3 mm from the tip and the shaft was deflected until 45° inclination[21]. To evaluate the torsional resistance, the file was held at 3 mm from the tip, and a clockwise torsional moment of 0.3 N.cm was applied. The boundary conditions used in the bending and torsional simulations are presented in Figure 3.

The model used in this study was confronted with previously published researches[18-19], and showed close and comparable results.

In this study was planned to perform non-linear static analysis under the worst loading conditions. This analysis was followed by fatigue failure check on St.St. 316L and NiTi, stress vs number-of-cycles curves of both materials to estimate the instrument lifespan, as evaluation procedure steps in previous study by Cheung et al.[18]. As presented in Figure 4(a) Cheung et al.[18] used Bannantine et al.[22] equations and tabulated parameter values (Table 1) to estimate the instrument lifespan. In Figure 4(b) Norwich et al.[23] showed the endurance strain amplitude % limit of 0.6 for 0.23 mm diameter NiTi wire.

$$\sigma_a = K'(\varepsilon_{ap})^{n'} \quad \text{.... (1)}$$ [18]

$$\varepsilon_a = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \quad \text{.... (2)}$$ [18]

Table 1. Parameters used in evaluating fatigue behavior of St.St. and NiTi wires[18]

	Symbol	Stainless Steel (304 annealed)	Nickel-Titanium (NiTi) alloy (super elastic)
Cyclic strain hardening exponent	n′	0.334	0.1
Cyclic strength coefficient	K′	2275 MPa	733 MPa
Fatigue strength exponent	b	-0.139	-0.06
Fatigue strength coefficient	σ'_f	1267 MPa	705 MPa
Fatigue ductility exponent	c	-0.415	-0.6
Fatigue ductility coefficient	ε'_f	0.174	0.68

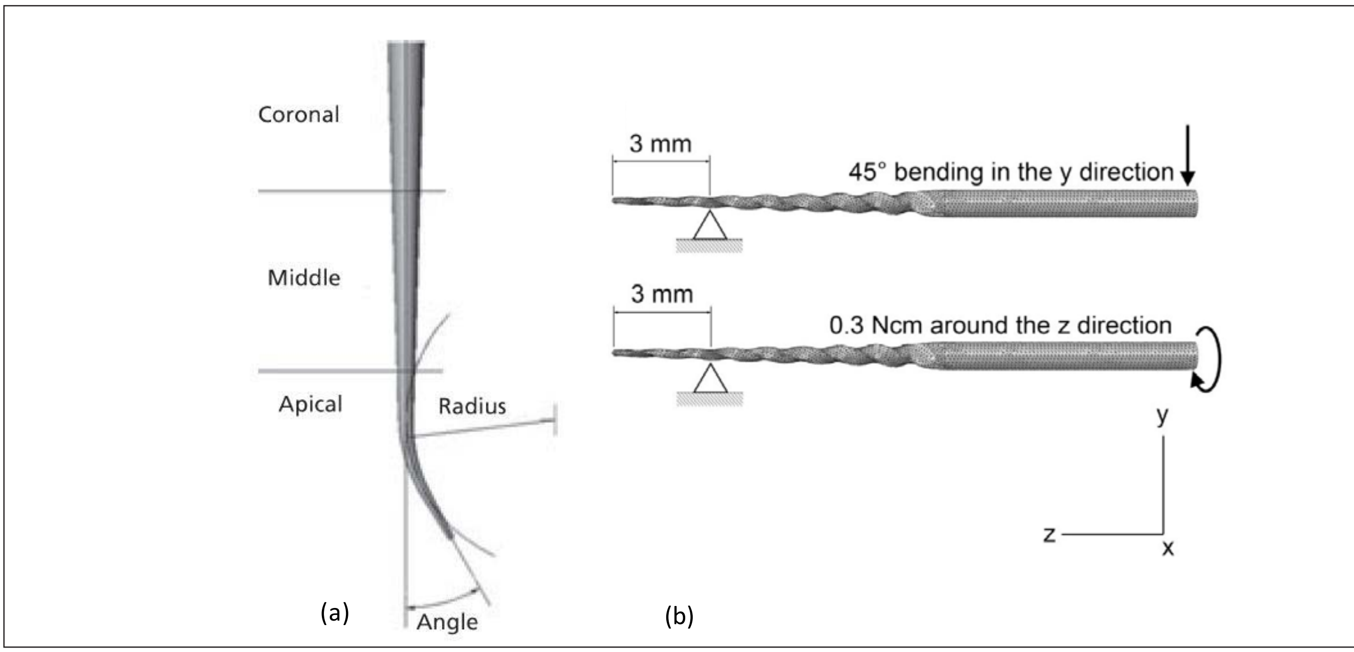

Fig. 3: (a) file outlines and regions, (b) boundary conditions for the bending and torsion simulations[21]

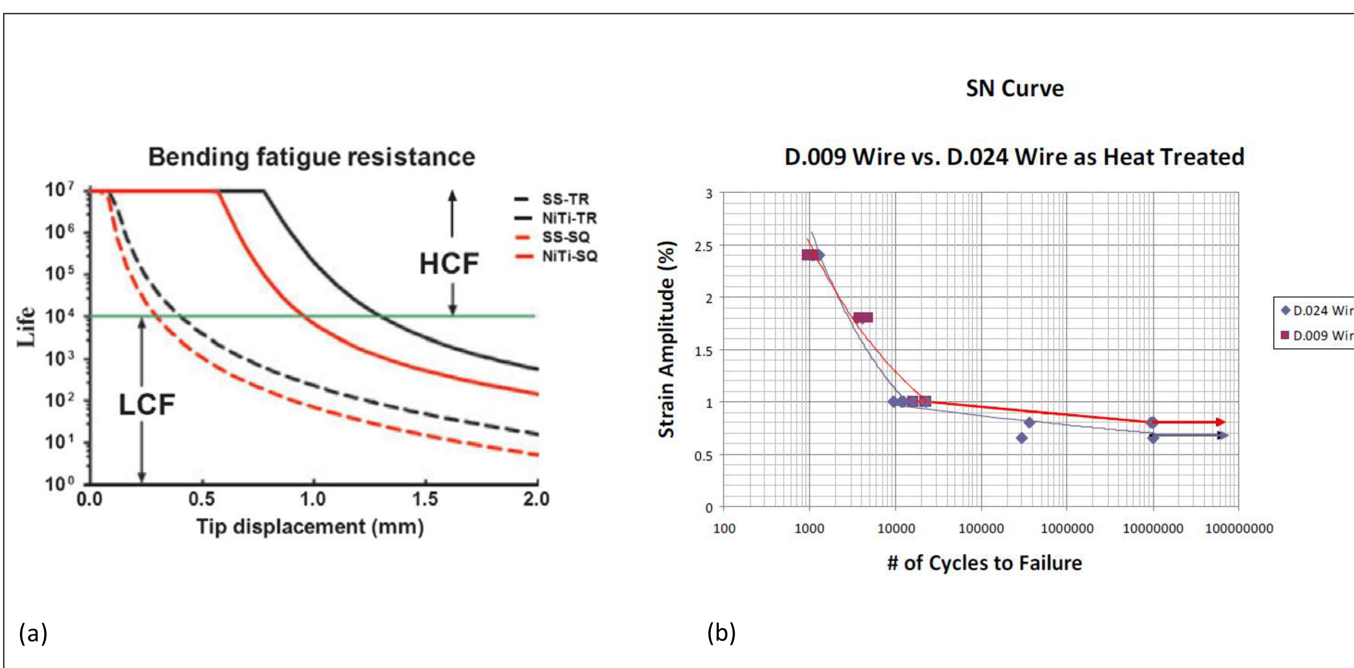

Fig. 4: (a) Comparison between triangle and square cross sections of StSt and NiTi wires Life-time vs. tip displacement[18] and (b) NiTi (Ti-55.8/55.9 wt%Ni) 0.23 & 0.61 mm heat treated wire diameters; strain % vs. Life-time curves[23].
LCF is Low Cycle Fatigue, HCF is Low Cycle Fatigue, SQ is square cross section, TR is triangular cross section.

Where E is Young's modulus, ε_{ap} is plastic strain amplitude, ε_a and σ_a are total strain and total stress amplitudes respectively.

The solid modeling and finite element non-Linear static analysis were performed on a Server HP ProLaint ML150, with Intel Xeon 3.2 GHz processors (with 12 MB L2 cache), 10 GB RAM.

Results

The linear static analysis showed unrealistic stress level, thus a multi-linear stress strain curve is essential in non-linear analysis. Therefore, two runs on the constructed model were performed, simulating the use of the files under bending and torsional conditions in compliance with the ISO 3630-1 specification[20].

First simulation was performed for St.St. 316L as the file material and its stress strain curve was imported to ANSYS as multi-linear material. As presented in Figures 2, 4, and 5, the generated stress and strain levels on the instrument exceeded the fracture point of St.St. 316L, which indicated instrument failure. Thus St.St. 316L as a material is not suitable for manufacturing rotary/reciprocating files.

Second simulation was performed for NiTi as the file material, and its stress strain curve was imported to ANSYS as Multi-linear material, as illustrated in Figure 2. The meshed model, deformed shape and total deformation of the studied model are presented in Figure 6.

Figures 7(a) and 8(a) illustrated the distributions of Von Mises strain (*ca* 0.61) and stress (*ca* 480 MPa) respectively, showing the critical points at file tip and outer layer in the bending region. The total plastic strain in Figure 7(b) represents the majority of total strain that indicated fatigue failure expectation. Maximum tensile stress in Figure 8(b) dominated the total stress and showed the critical point (maximum total stress) at the outer layer at the bending region (3 mm from tip).

Discussion

Using basics of mechanics from literature[5-6] to compare between the two systems (rotary and reciprocating) with the

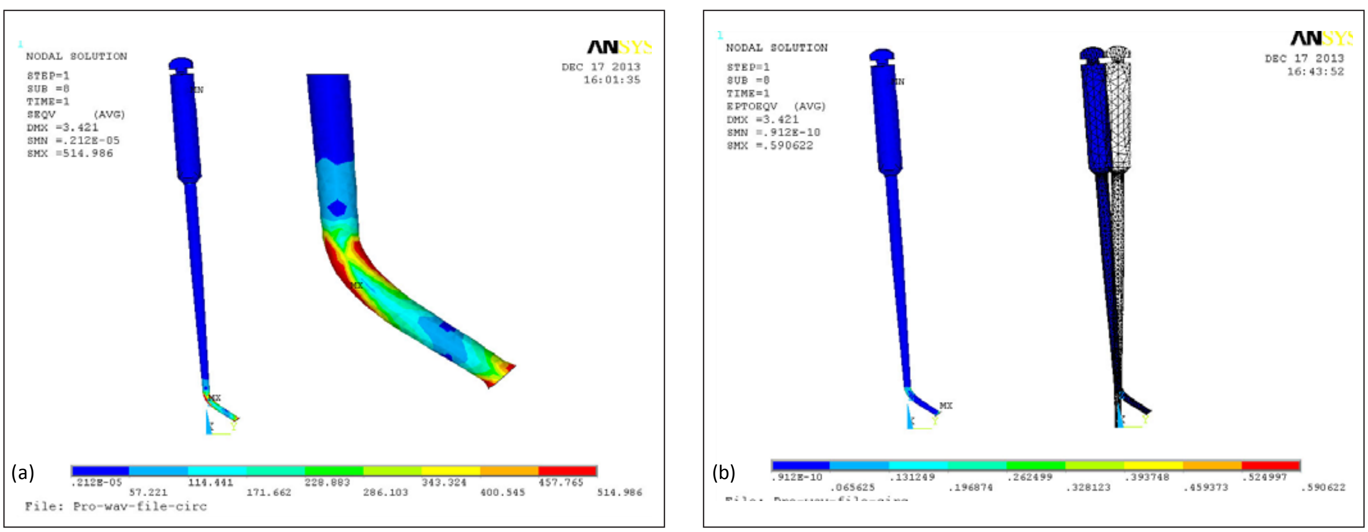

Fig. 5: St.St. 316L file behavior (a) Von Mises stress distribution and (b) Plastic Von Mises strain distribution, with deformed/un-deformed shape

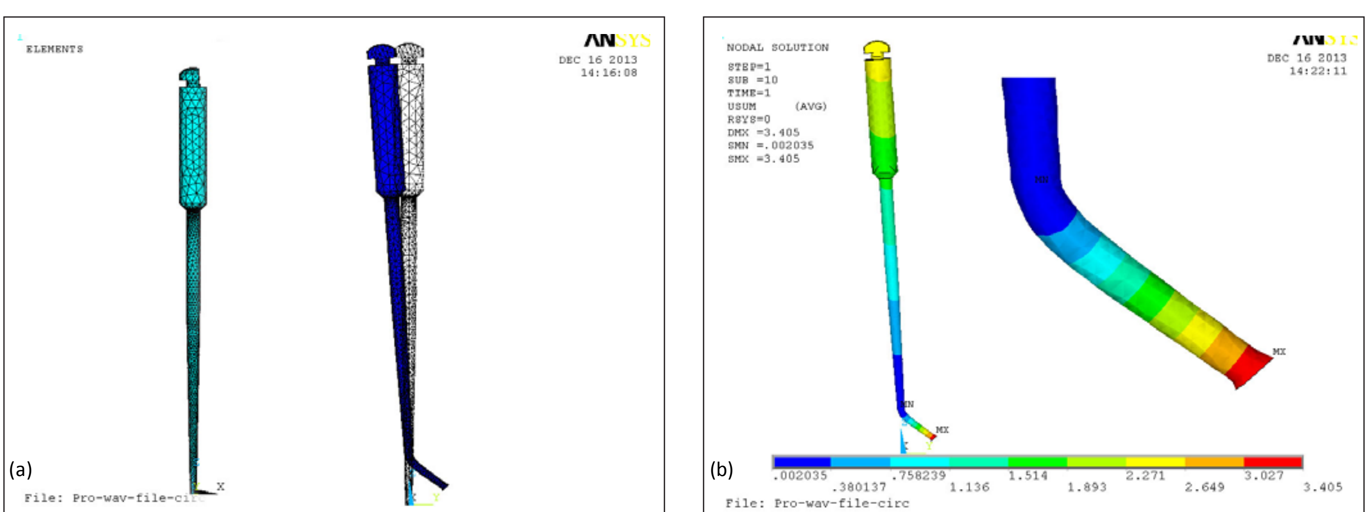

Fig. 6: NiTi file (a) Mesh & deformed shape and (b) total deformation distribution

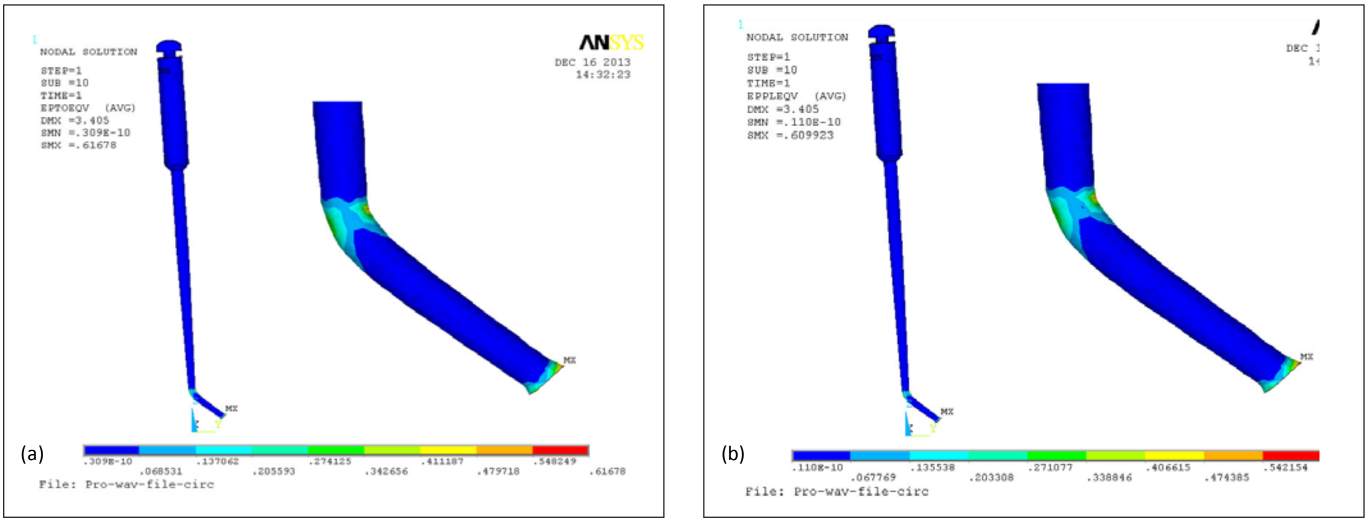

Fig. 7: NiTi file (a) Von Mises strain and (b) Total plastic strain distributions

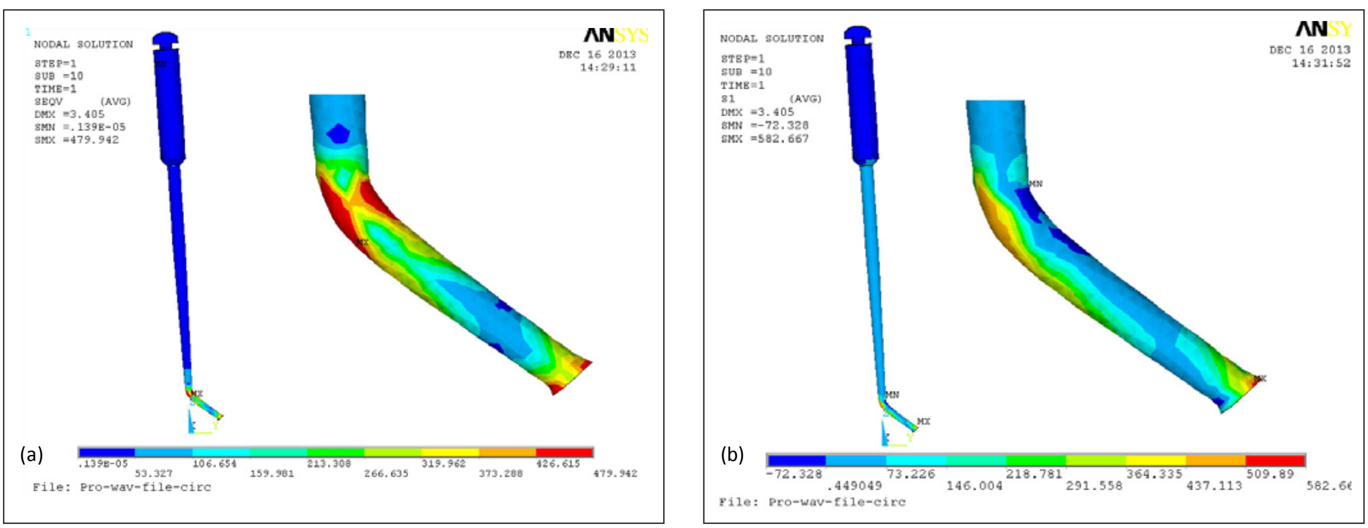

Fig. 8: NiTi file (a) Von Mises Stress and (b) Maximum tensile stress distributions

same file will give good indications. The reciprocating system will have three advantages and one drawback. The first advantage is reducing the torsional stress, since during reciprocation movement the instrument engages dentin at its tip during the counterclockwise movement, whereas the clockwise movement disengages the instrument immediately afterwards[24].

Second, extended fatigue life of the NiTi file when used in reciprocation movement compared to continuous rotation, which may be explained by smaller angular movement that induces less stress on the file in case of locking[25]. Finally, reciprocating action working as hammer at the file's cutting edge, increased the applied load on the root canal to double its value. The drawback is an expected shorter lifespan in comparison to rotating one, due to increased load applied at the blade tip.

Finite element analysis has been applied for detailed assessment of stress distributions in instruments. Few researches have studied the influence of reciprocating motion on cyclic fatigue resistance of rotary NiTi files using finite element analysis[16].

In this research, St.St. 316L file analysis showed that the generated stress levels on the instrument exceed the fracture stress (*ca* 568 MPa)[26], which indicated instrument failure. This may be attributed to the rigidity of stainless steel alloy, which is not suitable for instrumentation of curved canals under high torsional load.

On the other hand, the NiTi file analysis showed maximum values of total Von Mises stress (*ca* 480 MPa) and strain (*ca* 0.61) as indicated in Figures 7 and 8 which are matching similar studies[22,27], although with less instruments' cross sectional details in current study. Plastic stress and strain components are dominating the total Von Mises stress and strain that indicates fatigue failure expectation after certain number of such type of load(45° bend without locking). The expected number of cycles under such level of stress may be obtained from Figure 4, is approximately 500 cycles (file lifespan before failure).

Pessoa et al.[28] reported a comparable average number of 310 cycles to failure for RaCe rotary NiTi files (FKG Dentaire, La-Chaux-de-Fonds, Switzerland), size #5, taper 0.04 inside buccal canals with an angle of curvature of 40°, curvature of 5 mm radius and 21 mm long, and the beginning of the curve was positioned 14 mm from the canal orifice.

Three roots per tooth require about 2 min to be treated by reciprocating instrument, if the average rotating speed of the instruments is 250 rpm. That was experimentally proven by You et al.[29] who estimated the time for one root preparation by reciprocating instrument at 21.15 ± 6.70 second[29] i.e. less than 2 min. In addition, applying equations 1 and 2 on the obtained results with NiTi instrument with locking at 3 mm from tip and 45° bend with 3 N.cm torque (as the worst possible loading condition), it will resist up to three locking cases during its life, which is too difficult to occur during root preparation of one tooth.

In addition, the improvement in cyclic fatigue resistance shown by the reciprocating movement is related to two main factors. First, the rotation cycles are slightly reduced and consequently the overall number of rotations is reduced. Second, during reciprocation there is a different distribution of the same tensile stress values in time and this may reduce the overall accumulation of fatigue[29]. Reciprocating preparation with only one file was much faster than root canal instrumentation with continuous rotation. However, one file can be safely used a limited number of times in reciprocating motion[29]. Inexperienced operators achieved better canal preparations with reciprocating and/or rotary Ni-Ti instruments than with manual stainless steel files. However, rotary preparation was associated with significantly more fractures[30].

Within the limitations of this study, the following conclusions can be drawn:

- Finite element analysis indicated that modeling the instrument with fewer details (using equivalent circular cross sectional area) did not affect results quality.
- St.St. 316L, the traditional material used in manufacturing manual files, is not suitable for rotary or reciprocating instruments.
- Reciprocating instruments have short lifespan, and it is usually recommended to use one file per tooth.
- Reciprocating system has great advantages over other root therapy instruments. Therefore, it is recommended to be used by less experienced dentist.

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