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Effect of axial wall height and total occlusal convergence of VITA Enamic implant abutments on the retention of adhesively bonded VITA Enamic crowns

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Effect of axial wall height and total occlusal convergence of VITA Enamic implant abutments on the retention of adhesively bonded VITA Enamic crowns

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ABSTRACT

Statement of Problem: Currently, no published data exists to provide clinical guidance on decisions relative to axial wall height and degree of occlusal convergence regarding a hybrid ceramic crown bonded to a hybrid ceramic implant-supported custom abutment.

Purpose: The purpose of this study was to evaluate and quantify the effect that axial wall height and degree of total occlusal convergence have on the resistance to dislodgement of milled VITA Enamic crowns bonded to milled VITA Enamic custom implant abutments.

Material and Methods: Eight groups of ten hybrid ceramic (VITA ENAMIC® EM-14) crown and abutment pairs (n=10) were fabricated. Each group varied in axial wall height (4mm, 3mm, 2mm, 1mm) and total occlusal convergence (7°, 15°) of the abutment and corresponding crown. Enamic crowns and abutments were adhesively bonded to each other using the Panavia V5 resin cement system. Samples were artificially aged then mounted into the Instron Universal Testing Machine where force directed at 45° to the long axis of each sample was applied until failure (debonding or fracture). The mode of failure and the load at which failure occurred was recorded.

Results: No crowns debonded from their respective abutments. The mode of failure for 100% (80/80) of samples across all groups was fracture of ceramic.

Conclusions: Results of this *in vitro* study indicate that, when bonded with resin cement, milled hybrid ceramic crowns will not dislodge from milled hybrid ceramic abutments despite lack of traditional resistance form and regardless of axial wall height or total occlusal convergence. Even abutments with only a single millimeter of axial wall height and 15 degrees of total occlusal convergence retained their respective crowns. These crowns remained bonded until a force much greater than the average human bite-force was reached, at which point cohesive failure occurred by means of fractured ceramic rather than failure of the resin bond.

CLINICAL IMPLICATIONS

When using a split file technique to fabricate hybrid ceramic single-unit implant-supported restorations, an axial wall height of 1mm with a total occlusal convergence of 15 degrees will resist dislodging forces when the crown and abutment are bonded together. This allows for an edentulous space with minimal vertical restorative space to be restored using the split file technique.

INTRODUCTION

Dental implant crowns continue to increase in popularity as the restoration of choice for missing or failed teeth. Bonded implant restorations are favorable due to the availability of more esthetic restorative materials and the ease and efficiency of computer-aided design and computer-aided manufacturing (CAD/CAM) technologies (Christensen, 2008). Compared to implant-supported restorations, abutment-supported implant restorations provide distinct advantages in esthetics and clinical placement. However, their usefulness can be limited by factors such a deficient vertical restorative space which may not allow enough room for the restorative material and the traditionally defined resistance form of the abutment. With the continued development of restorative materials, clinical advances in bonding, and the improvement of CAD/CAM technologies, one may question the need to maintain the traditional standards of resistance form when designing and preparing implant abutments for bonded restorations.

The four basic treatment options for the restoration of a failed or missing tooth are: no treatment, removable partial denture, fixed partial denture, or implant crown. Employment of any of these options depends on a variety of clinical and patient-based factors. Endosseous dental implants can be used to support and/or retain single unit crowns, fixed partial dentures, removable partial dentures, complete dentures, or hybrid prostheses. It has been shown that tooth-supported fixed partial dentures and implant-supported single unit restorations have similar survival rates of about 95% after five years and 89% after ten years (Pjetursson *et al.*, 2007). Single unit crowns that are screwed directly into the dental implant are considered implant-supported crowns, also known as screw-retained crowns. Alternatively, abutment-supported crowns are single unit crowns that are cemented or bonded to implant abutments that are screwed to the corresponding dental implants.

There are advantages and disadvantages to both implant-supported and abutment-supported crowns. A significant reason to restore a dental implant with an implant-supported crown is to avoid use of cement, the excess of which is the leading cause of peri-implant mucositis, peri-implantitis, and dental implant failure (Linkevicius *et al.*, 2013; Wadhwani *et al.*, 2012; Wilson, 2009). On the other hand, abutment-supported crowns aid in a more efficient crown delivery procedure. Rather than having to repeatedly screw and unscrew crowns to place while checking proximal and occlusal contacts (as with implanted-supported crowns), individual abutments are screwed to place and the crowns are seated and unseated just as with traditional tooth-supported crowns (Gapski *et al.*, 2008; Kotsakis *et al.*, 2016; Linkevicius *et al.*, 2013; Wilson, 2009). Furthermore, by leaving the abutments screwed to place, the surrounding soft tissues are maintained throughout the crown fitting procedures. Decreasing the trauma to the surrounding tissue minimizes patient discomfort, produces more esthetic immediate results, and yields improved gingival outcomes (Linkevicius *et al.*, 2013; Wadhwani *et al.*, 2012). However, abutment-supported crowns may require more restorative space due to their multiple components.

Every implant restoration requires enough vertical space for the restorative materials and components. If sufficient space is not available, then it must either be created (*e.g.* increase occlusal vertical dimension) or another restorative treatment rendered (*e.g.* a removable partial denture). The Crown Height Space (CHS) is the measure of space needed for the occlusal materials, abutment, and emergence of the abutment/crown (Misch *et al.*, 2005, 2006). Together, these components require a minimum of 8mm of space to restore an implant with a crown. While at least 2mm is typically necessary for the emergence profile, this can vary with the depth of implant placement, gingival architecture, and size of implant platform relative to horizontal restorative space. Studies have shown that crown abutments traditionally need at least 4mm of height (Goodacre *et al.*, 2001). The occlusal material accounts for the last 2mm of required space, but that may vary depending on the specific type of material used, which may include metal, ceramic, or both (Shillingburg *et al.*, 2012).

Implant abutments also can be fabricated from different materials, to include: gold, titanium, zirconia, lithium disilicate, and hybrid ceramics (Shillingburg *et al.*, 2012). Gold and titanium are strong abutments (Bressan *et al.*, 2011), but since they have no predictable bond potential, corresponding crowns should be cemented in place. On the other hand, zirconia, lithium disilicate, and hybrid ceramics, which have varying strengths, can be bonded to restorations with similar compositions. While research has increasingly validated the reliable and predictable use of zirconia and lithium disilicate in restorations (Anusavice, 2013; Elsayed *et al.*, 2017; Sellers *et al.*, 2017;), hybrid ceramics, such as VITA's Enamic, are relatively new and comparatively untested. One of many reasons research should be focused on these materials is because, despite being more technique sensitive, bonding may help compensate for the lack of the retentive features required for traditional cementation (Blatz *et al.*, 2003).

Enamic crowns are made from a polymer-infiltrated ceramic network (PICN), "in which polymers are infiltrated into a porous ceramic network […] developed in order to mimic the physical properties of natural tooth and to overcome the brittleness of ceramics causing wear on antagonistic tooth" (Choi *et al.*, 2017). Enamic has been shown to have an elastic modulus of 30.14 GPa, hardness of 2.59 GPa, and fracture toughness of 1.72 MPa $m^{1/2}$ (He & Swain, 2011), which is slightly higher than that of other novel PICN materials (Coldea *et al.*, 2013). As with other hybrid ceramics, Enamic maintains its mean flexural modulus after thermocycling, but its mean flexural strength and modulus of resilience are significantly decreased (Blackburn *et al.*, 2017). Interestingly, compared to lithium disilicate crowns, Enamic crowns have demonstrated having significantly less mean marginal gap (Azarbal *et al.*, 2017), although they also have less fracture resistance (Al-Akhali *et al.*, 2017). Shear bond strength is increased when the intaglio surface of Enamic crowns are etched with 5% hydrofluoric acid for 30-60 seconds *and* are applied with silane and a universal adhesive, whether bonding with a conventional dual-curing resin or a self-adhesive composite cement (Rohr *et al.*, 2017).

Although cement commonly serves as the primary agent for prevention of dislodgement from an abutment, cement may prove insufficient to resist lateral-occlusal forces. To have any predictive success, the abutment must exhibit resistance features created by, among other things, vertical wall height, total occlusal convergence, surface area, and even grooves or notches (Trier *et al.*, 1998). Tall parallel axial walls are ideal in resisting occlusal torque and axial forces (Smyd, 1944). For traditional crown preparations, it is recommended to have a vertical wall height of at least 4mm for molars and 3mm for other teeth. The total occlusal convergence (*i.e.* the degree of taper of the abutment) should be 10 to 20 degrees. The occlusocervical-to-faciolingual dimension should have a ratio of 0.4:1 or greater. When these features are missing or inadequate, the preparation should be modified with auxiliary resistance features such as axial grooves or boxes, preferably on proximal surfaces (Goodacre *et al.*, 2001). Even though these parameters are specifically for tooth-born crown preparations, the principles are applied to the design and fabrication of implant abutments.

Traditionally, the fabrication of implant custom abutments and crowns involved multiple, sometimes redundant, steps in the dental laboratory. Custom abutments are preferred over stock abutments because they support creation of ideal bulk and contour, and they allow adequate thickness of crown material. Fabrication of custom abutments begins with a full contour wax-up of the restoration, which is then cut-back uniformly. This wax pattern is invested and cast in metal, producing the implant abutment, on which a coronal wax pattern is made. If a full gold crown is desired, this wax pattern is cast as a gold crown. Alternatively, another cut-back may be accomplished and the resulting pattern cast as a metal coping for a crown. Examples include porcelain fused-to-metal (PFM) and porcelain pressed-on-metal (PoM) restorations, the later requiring a third full contour wax-up. This lengthy process, however, is greatly simplified with current computer-aided design and computer-aided manufacturing (CAD/CAM) technologies.

CAD/CAM software derives the location and orientation of an implant from a digital impression (scan) made intraorally by the dental practitioner or made from a cast in the dental laboratory. The software is then used to design a full contour restoration, which may be milled from a single block as an implant-supported (screw-retained) crown. Alternatively, the restoration can be digitally split into an abutment and a crown. The resultant abutment and crown are then milled from two blocks. Following any staining, the abutment and crown are glazed and crystallized. This entire process can be accomplished within an hour or two of the digital impression being made, allowing for same-day delivery of the implant restoration. The efficiency of the CAD/CAM process for implant crowns is not without its shortfalls, though.

While parameters in the CAD/CAM software can be adjusted by a dentist or technician, there are requirements that may limit the ability to create a restoration with traditional resistance form. For example, when a digital implant restoration is split, the resultant abutment may have less than ideal axial wall height. Since the cervical margin of the abutment is determined by the height of gingival tissue, and the minimum occlusal thickness of the crown is defined by the material used, then the abutment axial wall height becomes the adjustable variable. If the restorative space is less than ideal, then the proposed abutment will be too short. The designer must choose which design principle(s) to compromise. Although the default setting for minimum occlusal thickness can be overridden, compromising the manufacturer's recommendations is discouraged. A second option is to "un-split" the design file and produce a monolithic screw-retained restoration, making delivery more cumbersome and possibly having the screw access hole in an esthetically unfavorable position. Finally, the designer can just accept the abutment with its less-than-ideal vertical wall height and rely on bonding to overcome the deficiency in traditional resistance form.

SPECIFIC AIMS

The underlining question proposed by this study sought to determine if bonding can reliably compensate for deficient resistance form. Specifically, the purpose of this study was to evaluate and quantify the effect that axial wall height and degree of total occlusal convergence have on the resistance to dislodgement displayed by crowns bonded to implant abutments. To produce further research on hybrid ceramic restorative materials, VITA Enamic was selected as the material to fabricate both the abutments and the crowns for this project.

HYPOTHESIS

Null hypothesis: There is no statistically significant difference in the amount of force required to dislodge hybrid ceramic crowns bonded to hybrid ceramic abutments when the axial wall height of the abutment and the total occlusal convergence of those axial walls varies.

Alternative hypothesis: The amount of force required to dislodge hybrid ceramic crowns bonded to hybrid ceramic abutments differs significantly when the axial wall height of the abutment and/or the total occlusal convergence of those axial walls varies.

MATERIALS & METHODS

The study had eight test groups, each with ten samples (n=10). Each sample consisted of a milled crown bonded to a milled abutment. Each test group consisted of a different combination of one of four varying axial wall heights (4mm, 3mm, 2mm, and 1mm) and one of two different degrees of total occlusal convergence (7° and 15°) [Figures 1 & 2].

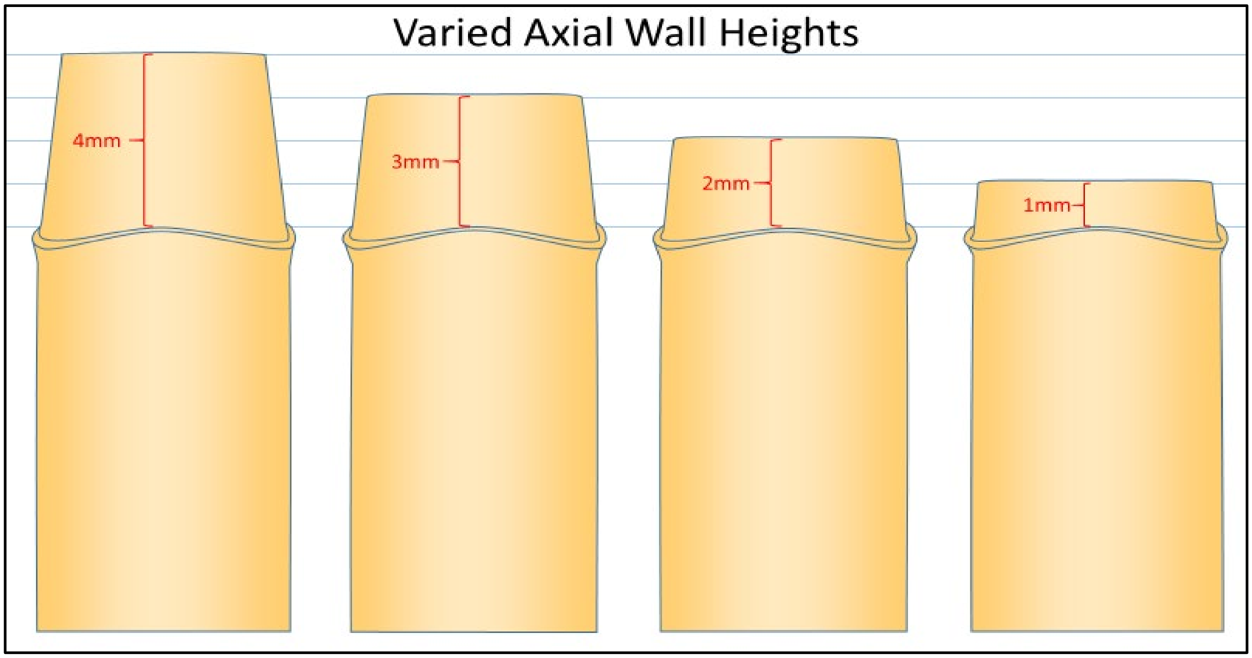

Figure 1. *Varied axial wall heights of 4mm, 3mm, 2mm, and 1mm*

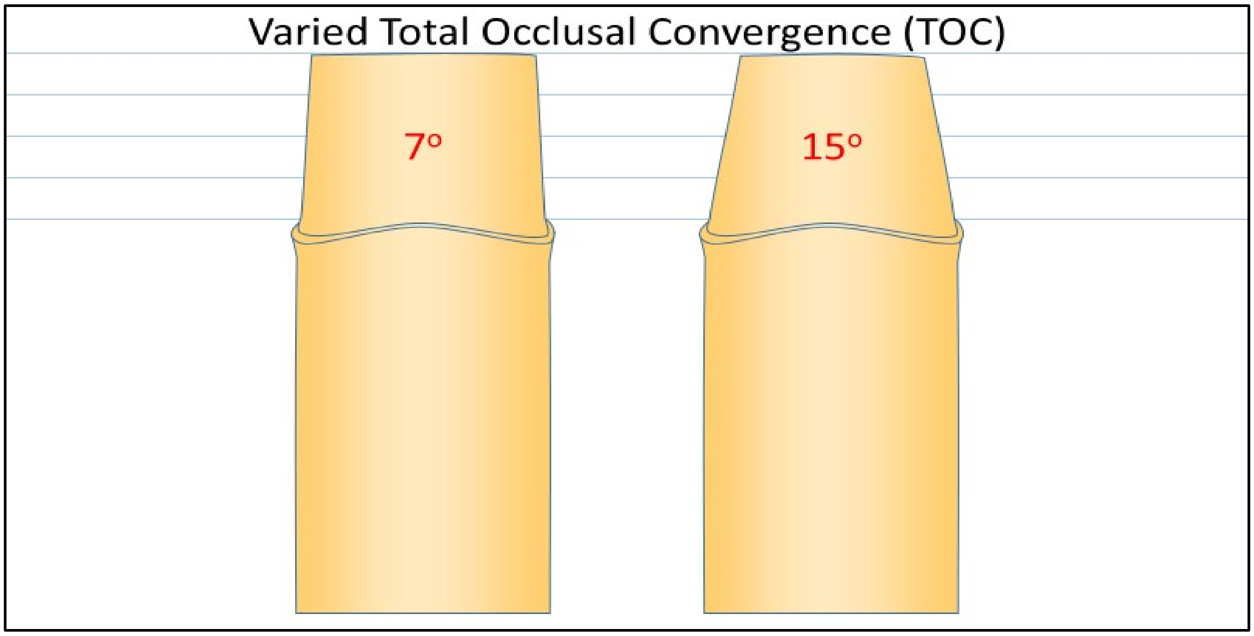

Figure 2. *Varied total occlusal convergence of 7° and 15°*

Eight different abutment designs with varying axial wall heights (1-4mm) and degrees of total occlusal convergence (7° or 15°) were designed using Sirona InLab 16.1 design software. The end product of this design process were STL-design files that were sent to a milling center (Imagine Milling, Chantilly, VA) for production. The abutments had a circumferential shoulder with uniform thickness of 1.5mm. Each sample had a base that extended 20mm apical from the finish line which was used to fixate the abutments in the testing apparatus. Abutments were milled from hybrid ceramic blocks (VITA ENAMIC® EM-14, VITA North America, Yorba Linda, CA).

Eight different crown designs were made to intimately fit the corresponding abutments. Crowns were designed using Freeform Plus (3D Systems, Rock Hill, SC) CAD software. While the axial wall heights and

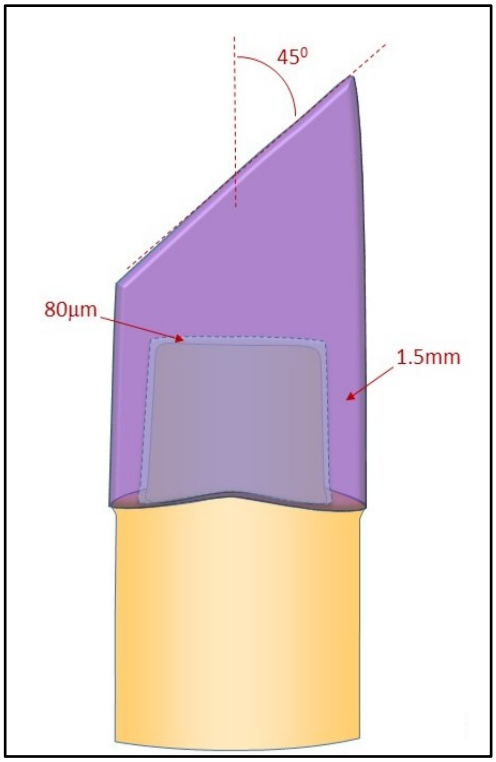

Figure 3. *Crown design*

degree of total occlusal convergence varied, all the crowns had a uniform cement space of 80 micrometers, an axial wall thickness of 1.5mm, a crown height of 16.5mm, and an occlusal surface angled at 45 degrees to the long axis of the abutment/crown [Figure 3]. Crowns were milled from hybrid ceramic blocks (VITA ENAMIC® block EM-14, VITA North America, Yorba Linda, CA).

To prepare the samples for adhesive bonding, the intaglio surface of each crown and the cameo surface of each abutment was etched with 5% hydrofluoric acid gel (VITA CERAMICS ETCH, VITA North America, Yorba Linda, CA) for 60 seconds, then rinsed with water and dried for 20 seconds with compressed, oil-free air at 30 PSI. Clearfil Ceramic Primer Plus (Kuraray America Inc., New York, NY) was applied to the same surfaces per manufacturer instructions, allowed to react for 60 seconds, then dispersed with a stream of compressed, filtered, oil-free air at 30 PSI for 2 seconds. Resin cement (Panavia V5, Kuraray America Inc., New York, NY) was then applied to the intaglio surface of each crown. Subsequently, each crown was placed on its corresponding abutment using a 3D-printed resin seating index with 10 pounds of pressure for 5 minutes [Figures 4, 5, & 6].

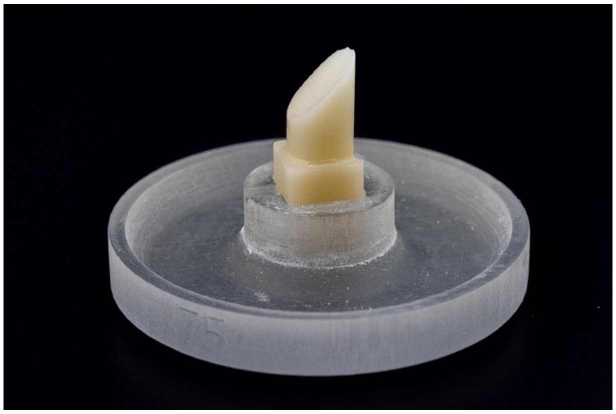

Figure 4. *Crown seating index base*

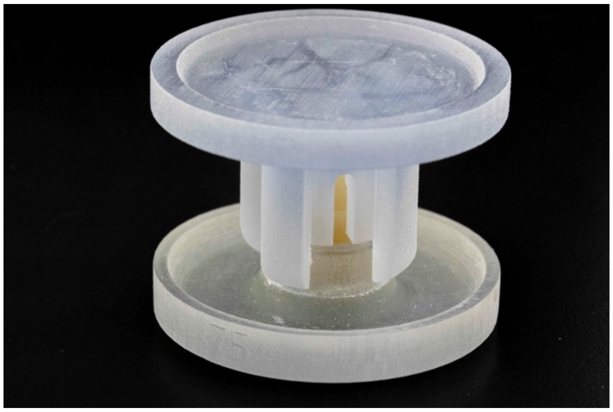

Figure 5. *Crown seating index top*

Following cementation, samples were stored at 37ºC in 100% humidity for 24 hours, then thermocycled for 500 cycles in accordance with ISO/TS 11405 (Technical specification, 2003) standard for intermediate aging protocol prior to failure testing. Each Enamic abutment/crown sample was inserted into the testing apparatus: a custom-milled CoCr abutment holder bolted to the plate of an Industrial Series Instron Universal Testing System (Instron, Norwood, MA). Compressive force, advanced at one millimeter per minute, was applied to the flat surface of the crown, 45 degrees to the long axis of the sample [Figure 7], until failure was achieved, including debonding or fracture of the crown, abutment, or both [see Appendix 1]. The mode and load at which failure occurred was recorded [see Appendix 2].

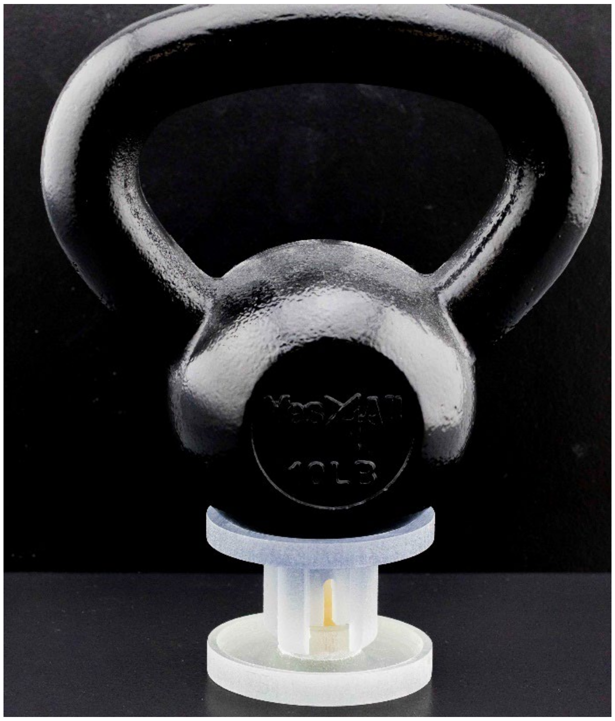

Figure 6. *Crown seating index with 10-pound weight*

The sample size of 10 per group provided 80% power to detect the following moderate effect sizes: 0.32 or approximately 0.64 standard deviations difference between means for the main factor of total occlusal convergence (2 levels) and 0.38 or approximately 0.76 standard deviations difference among means for the main factor of axial wall height (4 levels) as well as the interaction term, tested with a two-way ANOVA at the alpha level of 0.05 (NCSS PASS 2012). Post hoc testing was accomplished by using one-way ANOVA tests on each main factor since the interaction term was not significant.

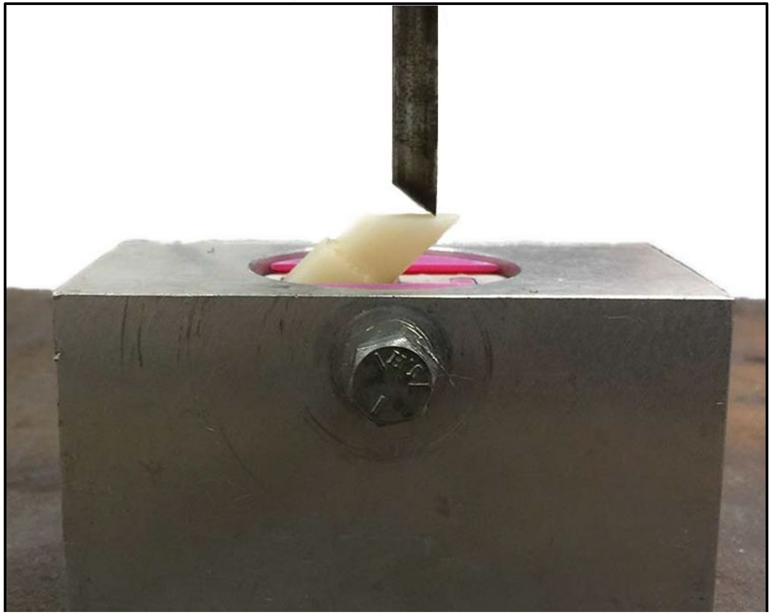

Figure 7. *Instron testing assembly*

RESULTS

The mode of failure was evaluated and recorded for each sample, the two primary categories being 1) the crown debonded or 2) the ceramic fractured. None of the crowns (0/80) debonded from their respective abutments. The mode of failure for 100% of the samples (80/80) was fracture of ceramic [Table 1]. These results confirm, within the parameters of this *in vitro* study, that an Enamic crown bonded to an Enamic abutment will resist dislodgement regardless of axial wall height and degree of total occlusal convergence.

Sample Group	Dislodged Crowns	Fractured Samples
1mm x 7°	0	10
1mm x 15°	0	10
2mm x 7°	0	10
2mm x 15°	0	10
3mm x 7°	0	10
3mm x 15°	0	10
4mm x 7°	0	10
4mm x 15°	0	10
Total	**0**	**80**

Table 1. *Mode of failure*

The mode of failure was further evaluated for each sample group, and four subcategories of failure due to fracture were observed [Table 2]. In the majority (61.25%) of samples the fracture occurred at the base of the abutment—meaning that the crown remained bonded to the abutment

Sample Group	Abutment	Abutment & Crown	Crown	Incisal Only
1mm x 7°	5	0	4	1
1mm x 15°	0	5	5	0
2mm x 7°	8	1	1	0
2mm x 15°	6	3	1	0
3mm x 7°	8	1	0	1
3mm x 15°	5	3	0	2
4mm x 7°	7	1	0	2
4mm x 15°	10	0	0	0
Total	**49**	**14**	**11**	**6**

Table 2. *Location of fracture*

and the unit totally fractured off the ceramic block. With 17.5% of the samples, the fracture went through some combination of the crown and abutment. Eleven crowns (13.75%) fractured leaving the corresponding abutments/blocks intact. Finally, with six of the samples (7.5%), an incisal portion of the crown fractured leaving the crown bonded to the abutment on the block.

Since the load at failure data was available, the data was calculated and tabulated [Table 3 & Figure 8]. SPSS computer software was used to calculate the means and standard deviations for each test group. Two-way ANOVA and one-way ANOVA were used to determine whether

Load at Break [N]				
	1mm x 7°	**2mm x 7°**	**3mm x 7°**	**4mm x 7°**
1	685.46680	818.84863	786.44751	916.33649
2	825.22186	595.85425	821.55469	821.78265
3	678.39624	848.20093	753.94360	717.60419
4	795.47314	778.05670	926.54675	710.22211
5	621.12659	746.90881	572.18524	885.86804
6	716.05145	795.52380	771.59253	731.41156
7	640.44891	668.48395	786.30743	989.63977
8	512.20807	777.81677	808.55341	453.67627
9	904.34253	869.32629	797.27771	767.15796
10	699.15649	1019.53595	1075.73865	945.70667
SD	111.51195	114.40752	127.70931	155.91334
	1mm x 15°	**2mm x 15°**	**3mm x 15°**	**4mm x 15°**
1	352.50784	598.44556	736.51971	909.14667
2	552.31604	827.54645	838.29761	764.13751
3	542.09827	801.87170	842.58020	841.29425
4	749.19165	863.75031	839.52991	737.28265
5	795.41058	641.71552	753.71564	798.31781
6	482.42657	787.62177	1064.70581	864.59222
7	515.71576	951.47046	378.19891	716.38080
8	578.00262	777.33246	827.48981	823.25934
9	552.57233	818.47308	770.09052	711.66309
10	476.64642	749.41370	655.33521	809.72015
SD	129.07749	102.02923	174.15239	65.30718

Table 3. *Amount of load [N] at failure point for each sample*

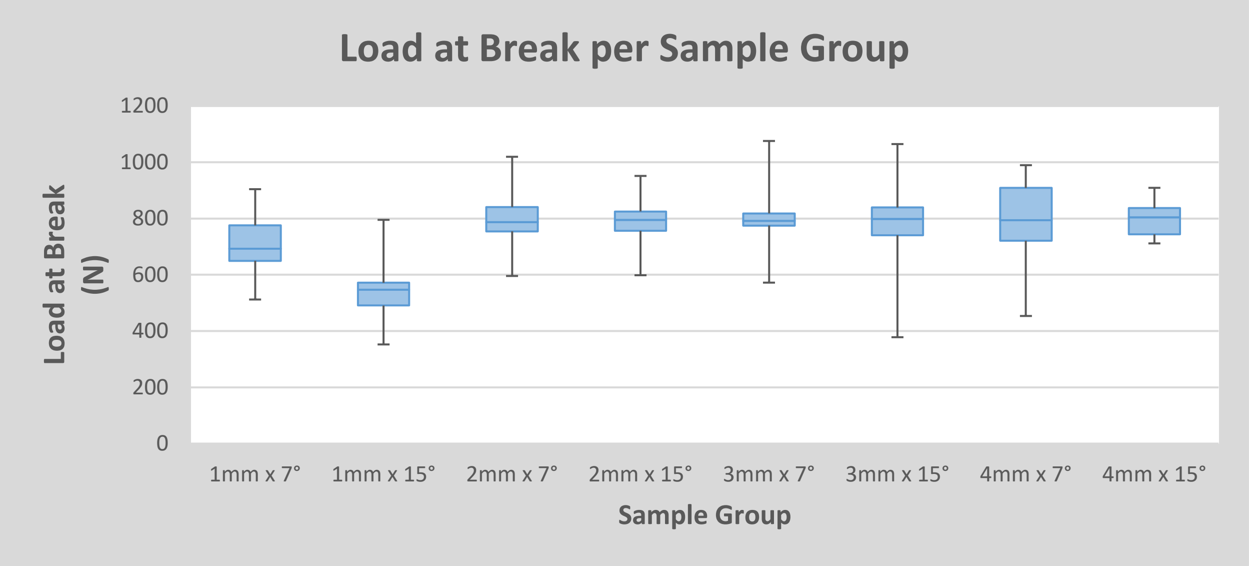

Figure 8. *Boxplots of load [N] at failure for each sample group*

significant differences existed among the study groups (i.e. axial wall height and degree of total occlusal convergence), followed by Tukey pairwise multiple comparisons at 95% confidence interval, which were performed to determine which total axial wall height group at a given occlusal convergence group significantly differed from the other.

Mean and standard deviations of the load at failure are listed in Tables 4 & 5 and depicted in Figure 9. The 3mm x 7° group had the highest mean load at failure at 810 N. The lowest mean load at failure, 560 N, was with the 1mm x 15° group. The sample group with the most consistent

Sample Group	Mean Load at Break (N)	Standard Deviation (N)
1mm x 7°	707.79	111.51
1mm x 15°	559.69	129.08
2mm x 7°	791.86	114.41
2mm x 15°	781.76	102.03
3mm x 7°	810.01	127.71
3mm x 15°	770.65	174.15
4mm x 7°	793.94	155.91
4mm x 15°	797.58	65.31

Table 4. *Mean load [N] at failure by sample group*

Sample Group	Mean Load at Break(N)	Standard Deviation (N)
1mm	633.74	139.84
2mm	786.81	105.63
3mm	790.33	150.00
4mm	795.76	116.36
7°	775.90	130.00
15°	727.42	154.73
TOTAL	751.66	144.08

Table 5. *Mean load [N] at failure by axial wall height and TOC*

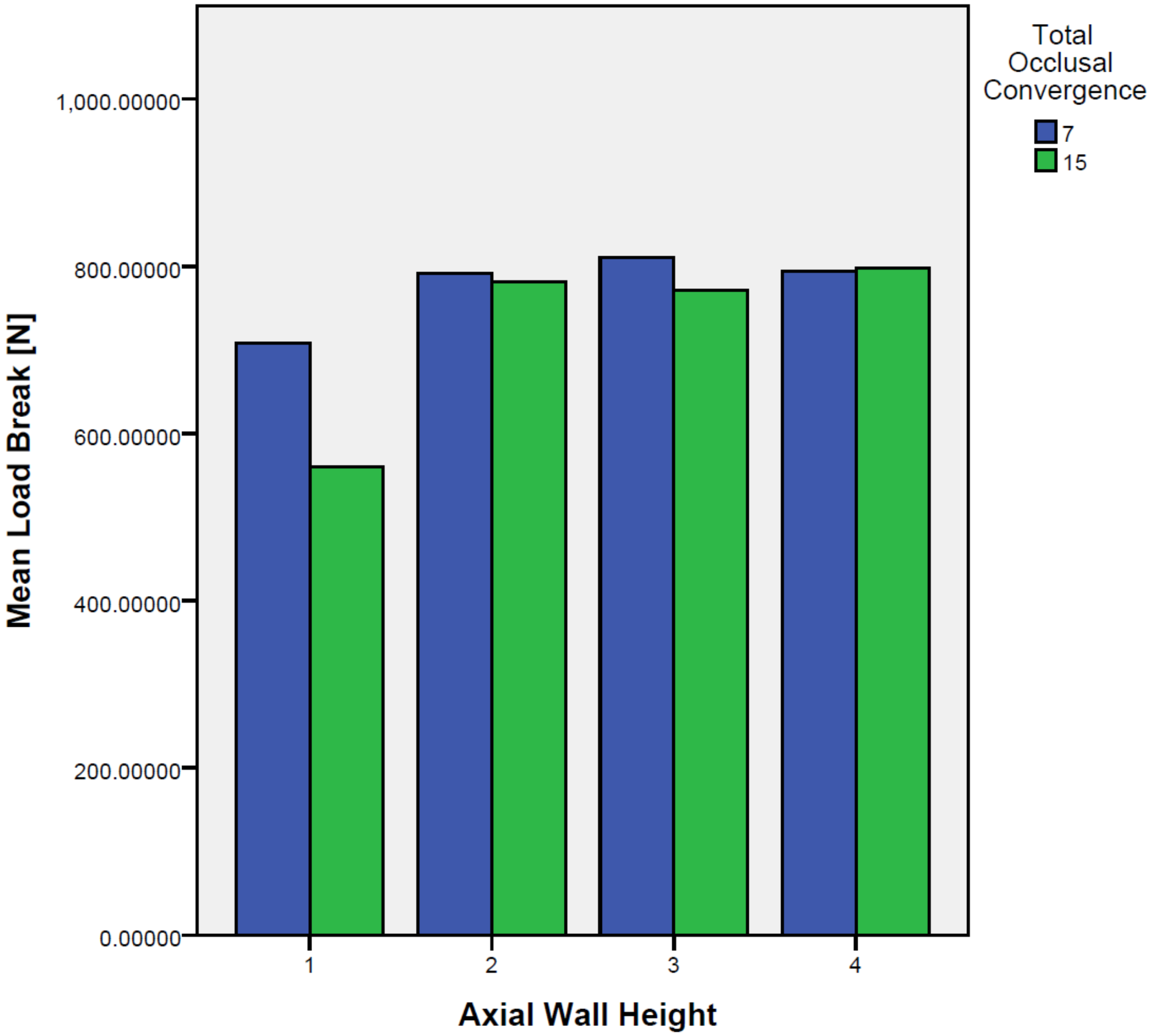

Figure 9. *Mean load [N] at failure for each sample group*

load at failure was the 4mm x 15° group, which yielded a standard deviation of only 65 N. The mean load at failure of all 80 samples was 752 N. With respect to axial wall height, only the 1mm abutments had a lower-than-average mean load at failure at 634 N. Although, the mean load at failure of 7° abutments was higher than the 15° abutments, the mean difference was only 48.5 N.

Two-way ANOVA between axial wall height and total occlusal convergence showed a statistically significant difference in mean values for load at failure based on axial wall height (p=0.000) but not based on total occlusal convergence (p>0.05). The interaction term was found not to be statistically significant, so the interaction between the axial wall height and total occlusal convergence on mean load at failure is not significant [Table 6].

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Axial Wall Height	371621.887	3	123873.962	7.754	0
Total Occlusal Convergence	47006.91	1	47006.91	2.942	0.091
Axial Wall Height * Total Occlusal Convergence	70986.494	3	23662.165	1.481	0.227

Table 6. *Two-way ANOVA of axial wall height and total occlusal convergence*

One-way ANOVA comparing mean load at failure for each different axial wall height at 15° of total occlusal convergence showed a statistically significant difference (p=0.000) between those four groups. However, there was no significant difference between the varying axial wall heights with 7° of total occlusal convergence [Table 7].

Total Occlusal Convergence	Type III Sum of Squares	df	Mean Square	F	Sig.
7°	63829.399	3	21276.466	1.287	0.294
15°	378778.982	3	126259.661	8.19	0

Table 7. *One-way ANOVA of axial wall height at a given total occlusal convergence*

Multiple statistical tests were run as part of a Post hoc analysis. Another one-way ANOVA was completed to compare the mean load at fracture between sample groups of different degrees of total occlusal convergence for each axial wall height. Only the samples with 1mm tall abutments showed a statistically significant difference between the mean load at failure of the 7° and 15° groups, with a significance of p=0.013 [Table 8].

Axial Wall Height	Type III Sum of Squares	df	Mean Square	F	Sig.
1mm	109668.642	1	109668.642	7.538	0.013
2mm	509.193	1	509.193	0.043	0.837
3mm	7749.362	1	7749.362	0.332	0.571
4mm	66.207	1	66.207	0.005	0.946

Table 8. *One-way ANOVA of total occlusal convergence at a given axial wall height*

As part of the Post hoc analysis, Tukey's HSD (honestly significant difference) tests were run to compare the mean load at failure of sample groups of different axial wall heights with the same total occlusal convergence. There was no significant difference between the means of the sample groups with 7° total occlusal convergence [Table 9]. Of the four sample groups with 15° total occlusal convergence, though, the group with 1mm axial wall height did have a statistically significant difference in mean load at failure [Table 10].

Axial Wall Height	**N**	**Subset 1**
1	10	707.789
2	10	791.886
4	10	793.941
3	10	810.015
Sig.		0.300

Table 9. *Tukey HSD for 7° total occlusal convergence*

Axial Wall Height	**N**	**Subset 1**	**Subset 2**
1	10	559.689	
3	10		770.646
2	10		781.764
4	10		797.579
Sig.		1.000	0.962

Table 10. *Tukey HSD for 15° total occlusal convergence*

DISCUSSION

The purpose of this study was to evaluate and quantify the effect that axial wall height and degree of total occlusal convergence have on the resistance to dislodgement of milled VITA Enamic crowns bonded to milled VITA Enamic custom implant abutments. This study clearly shows that no difference existed between the sample groups, as none of sample crowns were dislodged. The null hypothesis was that there would be no statistically significant difference in the amount of force required to dislodge hybrid ceramic crowns bonded to hybrid ceramic abutments when the axial wall height of the abutments and the total occlusal convergence of those axial walls varied. Therefore, the null hypothesis was accepted.

The most important factors to consider in the results of this study are the mode of failure and the mean load required for failure. All of the samples failed due to fracture of the ceramic rather than failure of the resin bond (dislodgement) [Table 1]; and all of the samples failed at loads that far exceeded what the average human can generate. In fact, these *in vitro* forces exceeded the maximum bite force generated in human mastication (Takaki *et al.*, 2014) and during sleep associated bruxism (Nishigawa *et al.*, 2001). This was true even of the 1mm x 15° sample group which had the lowest mean load at failure (560 N). Accordingly, resin bonding of Enamic to Enamic is shown to be more than adequate to resist dislodging forces typically produced in the oral environment.

The design of this study was to replicate *in vitro* a most unfavorable condition that could be encountered *in vivo* of load being applied to a ceramic crown bonded to a ceramic implant-supported abutment. Specifically, that entails 1) a load applied at 45 degrees to the long axis of the restoration, 2) a load potential that exceeds forces that can be produced by human mastication, and 3) a lever arm of approximately 14mm from the point of rotation, which approaches the upper limit of what would exist clinically. In fact, a shorter abutment height would likely be employed in situations where there is limited restorative space, so the crown height would likewise be shorter. In other words, it is extremely doubtful that there would ever be a situation when available restorative space only allowed for a 1mm tall abutment yet required a 14mm tall crown. Consequently, the conditions produced in this study surpass even extreme conditions that may be encountered *in vivo*.

That being stated, the results of this study may not corelate to an *in vivo* study. Many factors can contribute to restoration failure such as load frequency, vector, duration, and distribution. In addition are the factors that affect aging and degradation of the resin bond in the oral environment. It would be impractical to account for all these in an *in vitro* investigation. It is known that the strength of the resin bond does degrade with time in the oral environment, but no published research has been conducted to date on this topic when the substrate is Enamic. Further research is needed to examine the mechanisms of failure of hybrid ceramic crowns cemented to hybrid ceramic implant-supported abutments.

Results of this *in vitro* investigation indicate that there was a statistically significant difference between at least one of the sample groups in the amount of force required to fracture the crown/abutment samples. While the statistical significance of the results may be clinically irrelevant due to how much force was required to break each sample, there may still be something to be gleaned from the findings. For example, the results of failures due to ceramic fracture are not surprising when considering previously established requirements for retention and resistance form (Goodacre *et al.*, 2001). We expect that as axial wall height decreases and total occlusal convergence increases that there will be an increase in risk of crown failure. This study found that abutments with only 1mm of axial wall height are significantly more likely to have crowns fracture at high loads than abutments with 2mm or more of axial wall height. However, it also discovered that a lack of axial wall height can be compensated for with near-parallel axial walls. This finding supports the importance of total occlusal convergence since, even with 1mm tall abutments, the more parallel axial walls had a similar mean load at failure as taller abutments.

Despite providing reinforcement for some of the traditional principles of resistance form, this study shows that the specific guidelines given for minimum axial wall height and total occlusal convergence do not necessarily apply to resin-bonded Enamic implant abutments and crowns. In fact, based on the results, even a 1mm x 15° abutment will be sufficient to retain a bonded crown. What this study lacks, though, is the comparison to crowns bonded to a flat abutment with 0mm of axial wall height. This would help evaluate the effectiveness of the bond itself, controlling for the variable of axial wall height. Furthermore, this study should be replicated with other ceramic materials to determine if the findings, assumptions, and conclusions can be applied broadly to the design parameters of all single-unit implant restorations.

CONCLUSION

Results of this *in vitro* study indicate that, when bonded with resin cement, milled hybrid ceramic crowns will not dislodge from milled hybrid ceramic abutments despite lack of traditional resistance form and regardless of axial wall height or total occlusal convergence. Even abutments with only a single millimeter of axial wall height and 15 degrees of total occlusal convergence retained their respective crowns. These crowns remained bonded until a force much greater than the average human bite-force was reached, at which point cohesive failure occurred by means of fractured ceramic rather than failure of the resin bond.

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DISCLOSURES

The opinions or assertions contained herein are the private ones of the author and are not to be construed as official or reflecting the view of the Uniformed Services University of the Health Sciences, the United States Air Force, the Department of Defense, or the United States Government. The author does not have any financial interest in any commercial products or services that are discussed in this publication.

APPENDIX 1 – Photos of sample groups after load failure testing

1mm x 7°

1mm x 15°

2mm x 7°

2mm x 15°

3mm x 7°

3mm x 15°

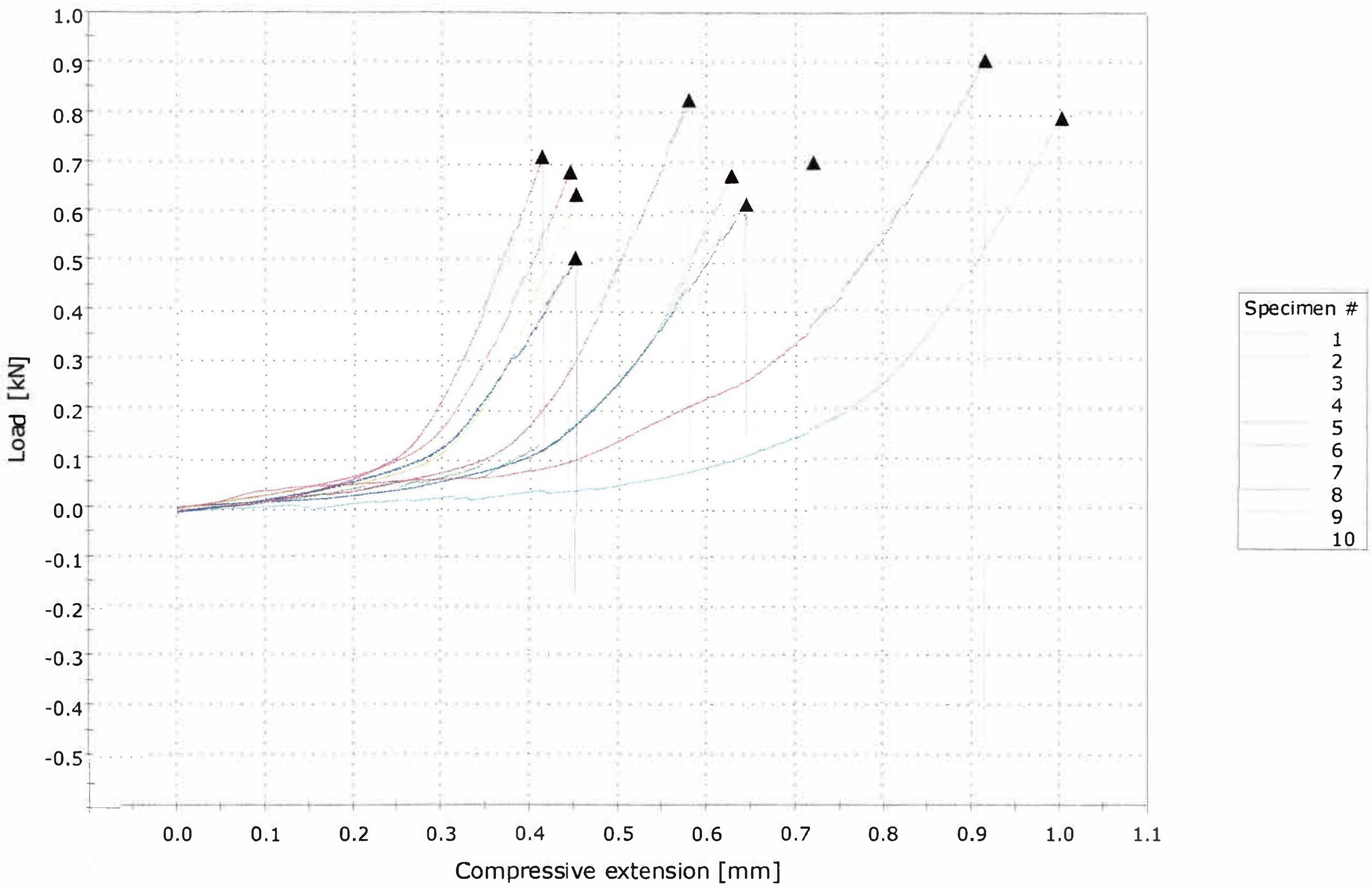
4mm x 7°

4mm x 15°

APPENDIX 2 – Printouts of raw data

Enamic 1x7.is_comp

Specimen 1 to 10



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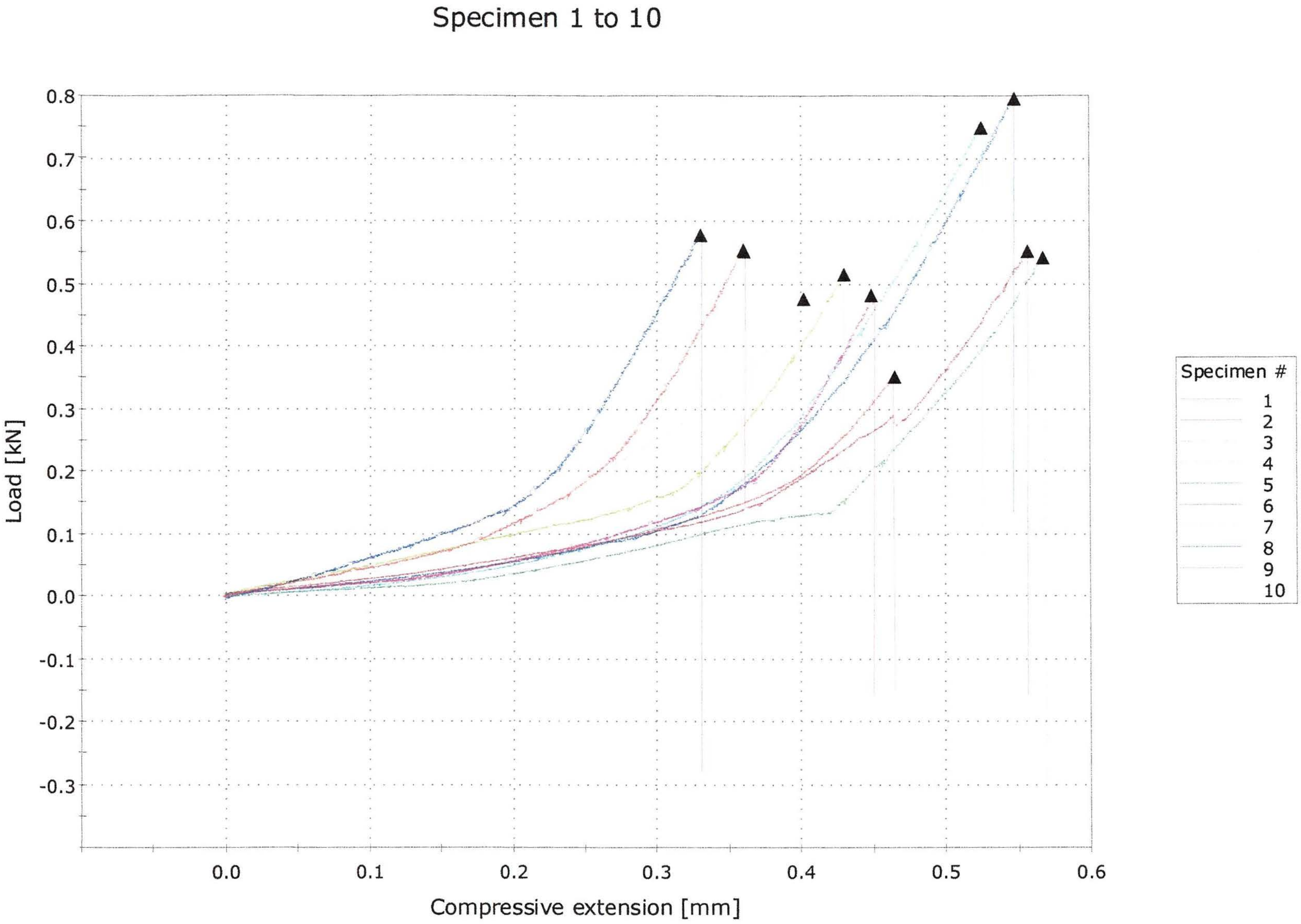
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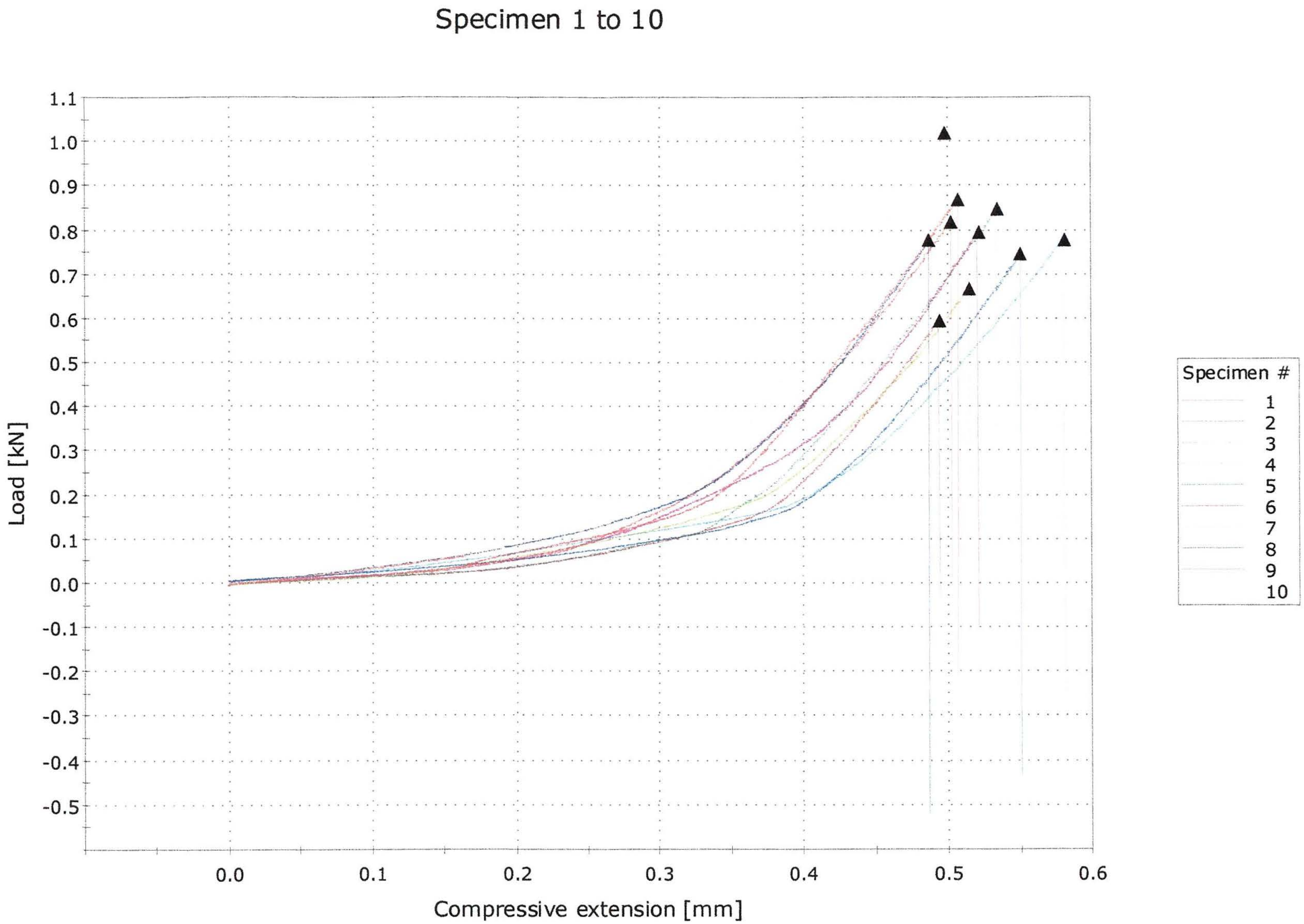
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
Load [kN]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Compressive extension [mm]
Specimen #
1
2
3
4
5
6
7
8
9
10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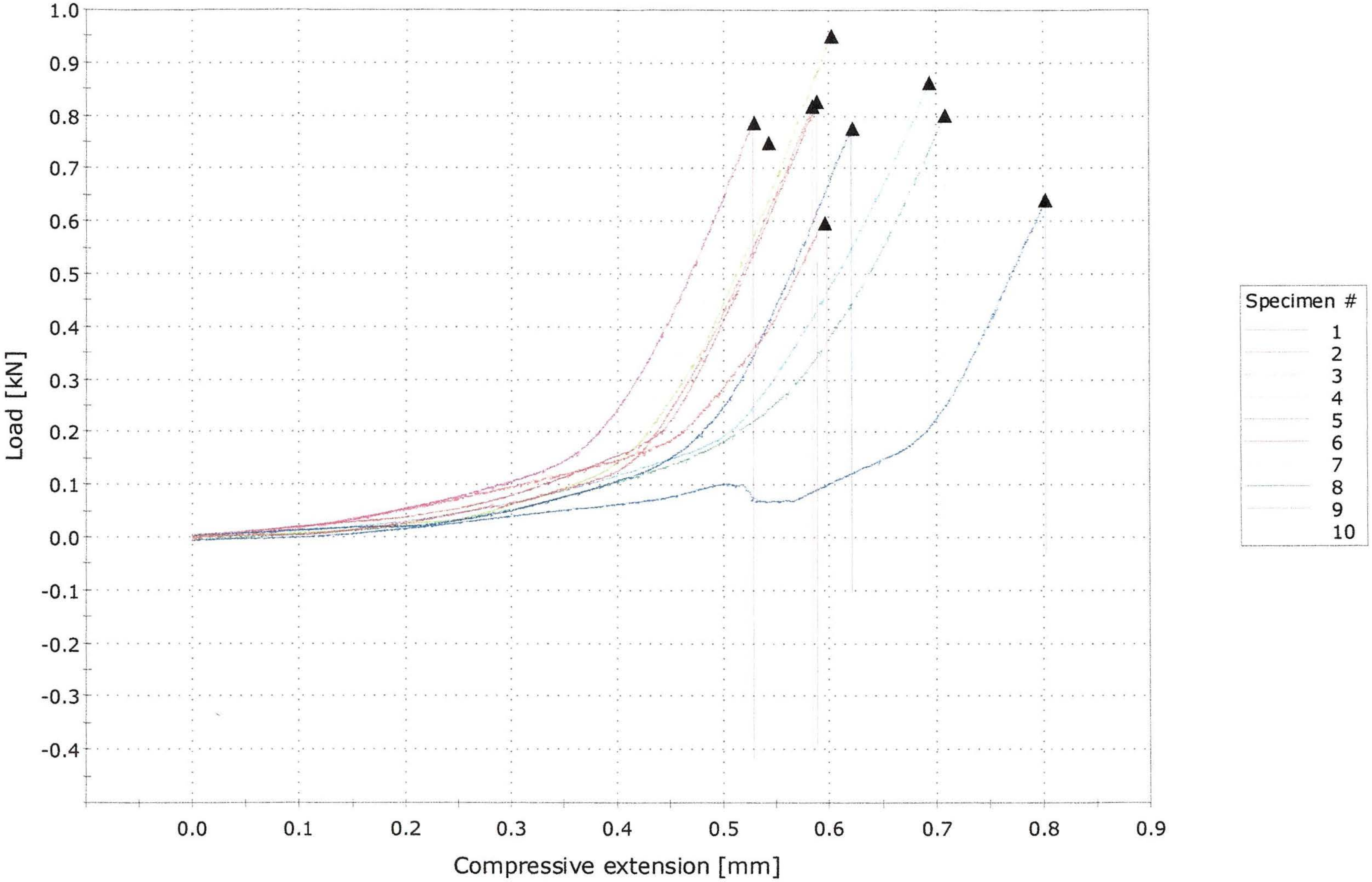
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
Load [kN]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Compressive extension [mm]
Specimen #
1
2
3
4
5
6
7
8
9
10

Specimen 1 to 10



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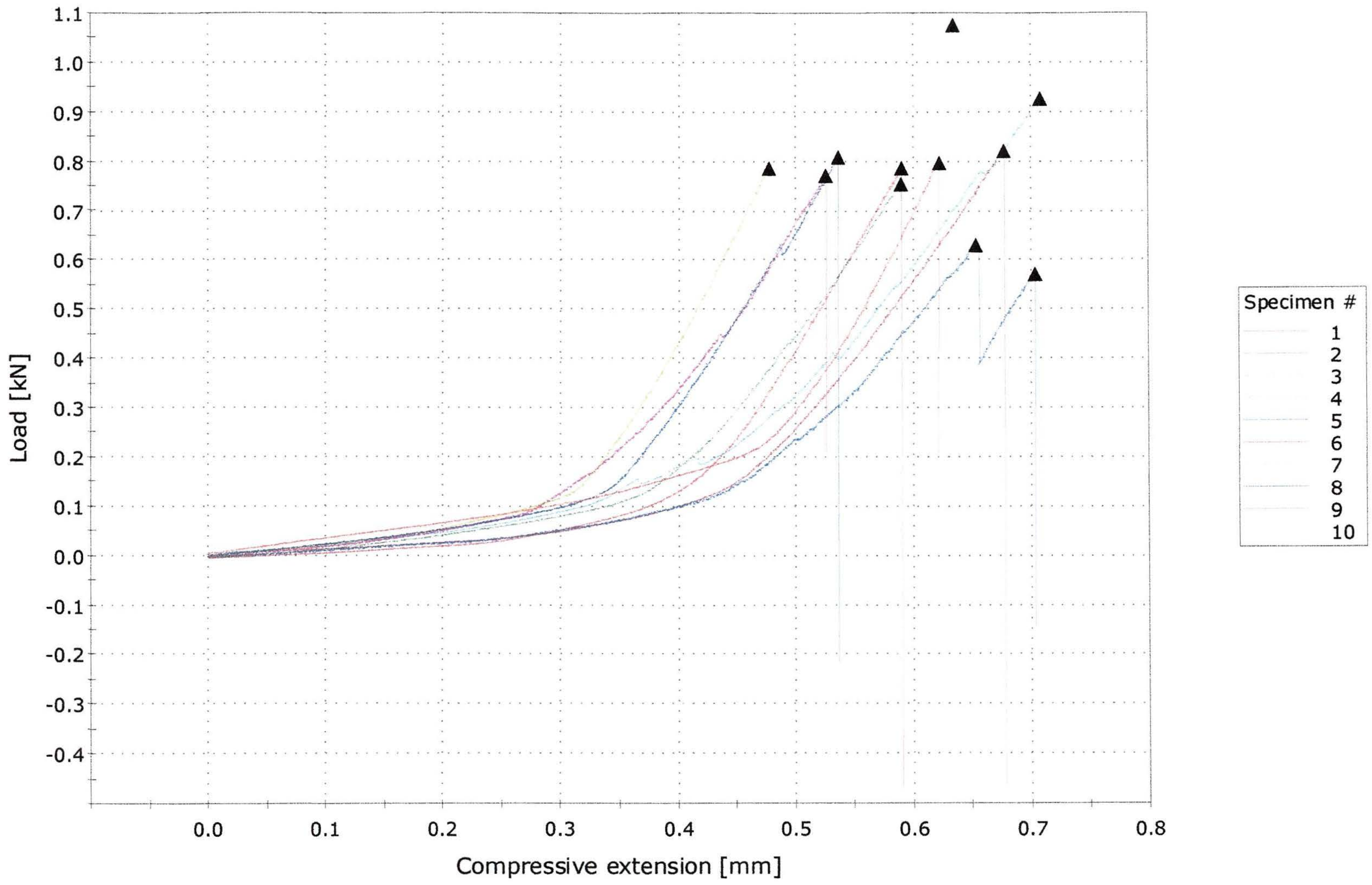

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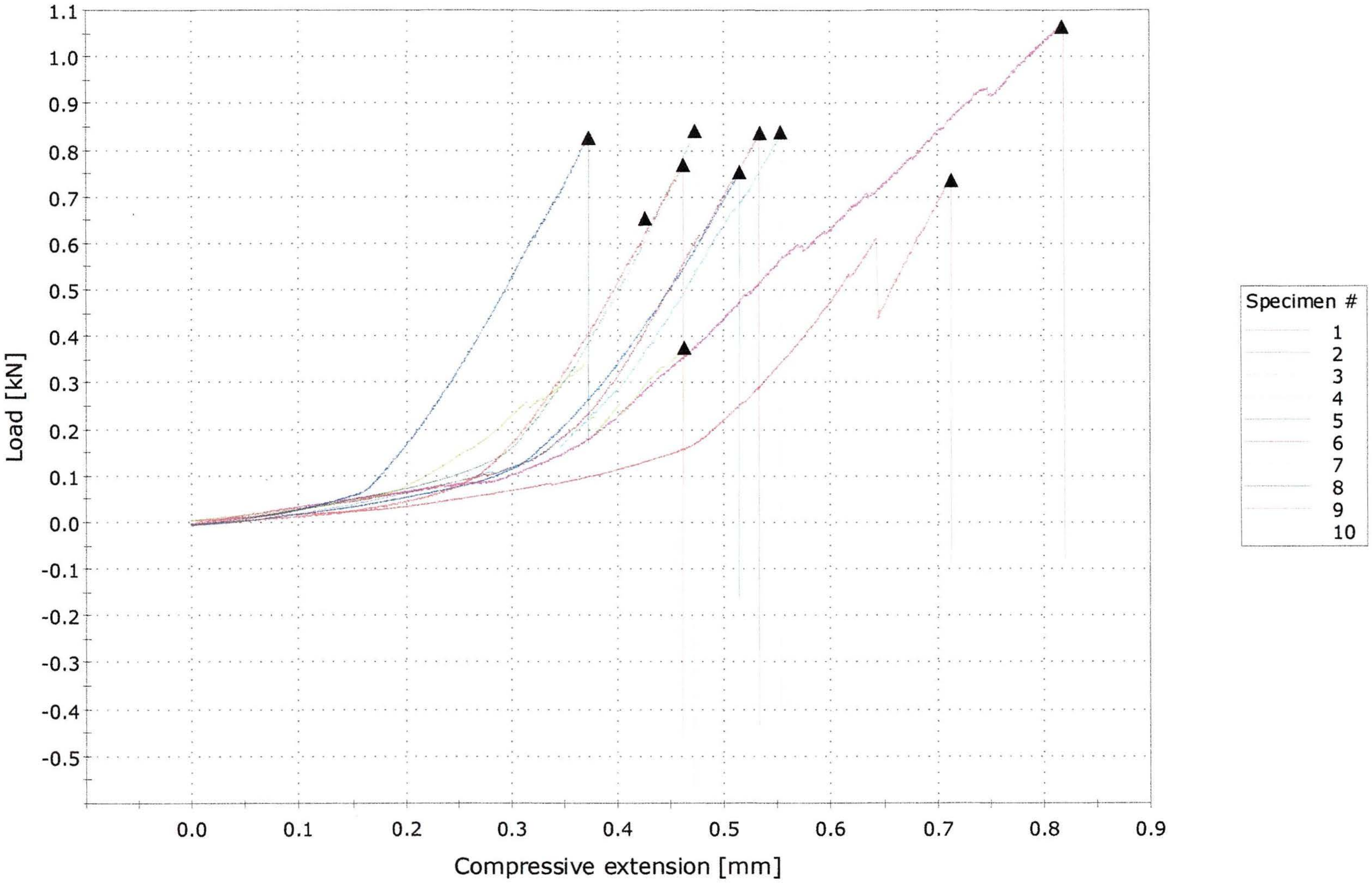

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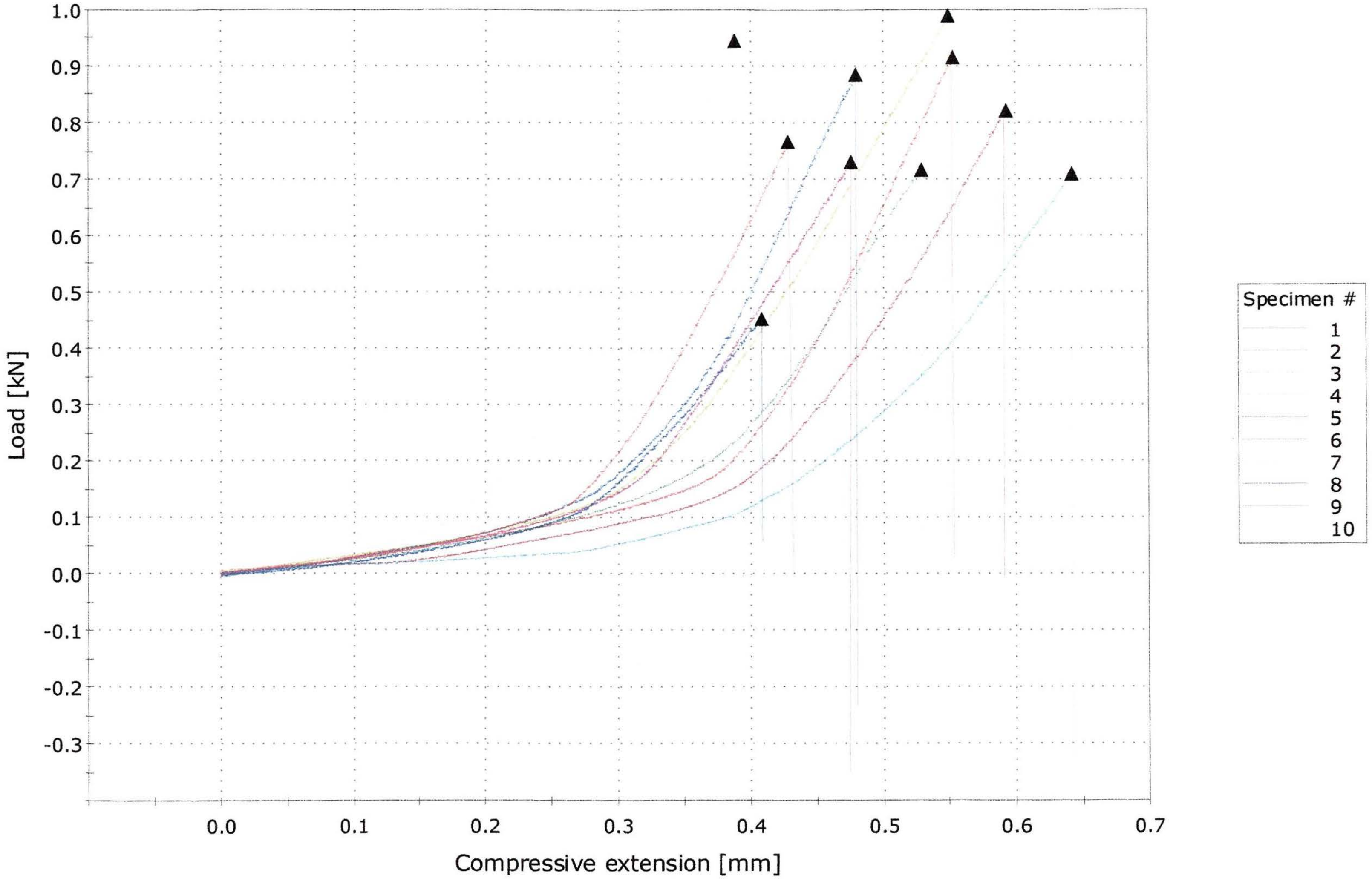

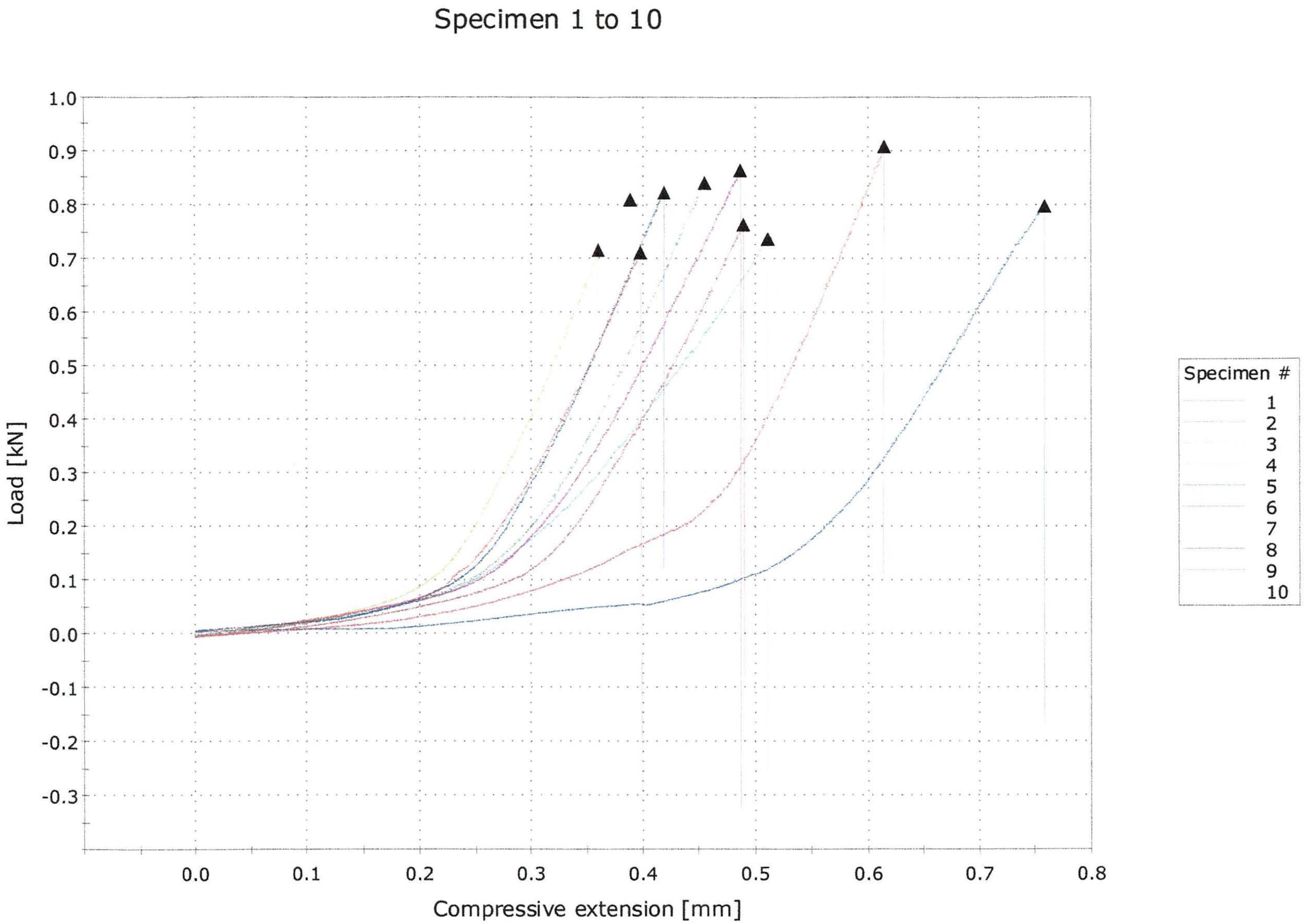
Specimen 1 to 10
Load [kN]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Compressive extension [mm]
Specimen #
1
2
3
4
5
6
7
8
9
10

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