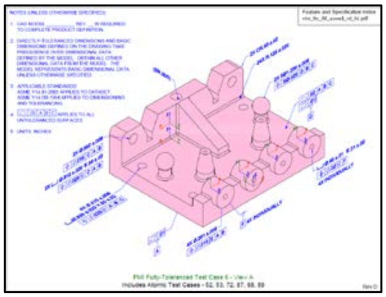
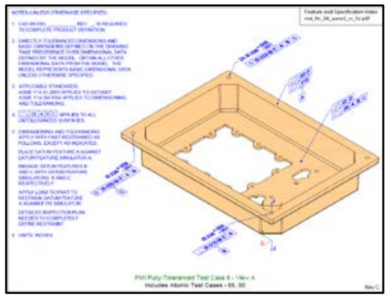
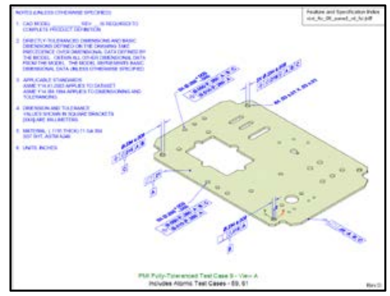
NIST GCR 15-999

Measuring the PMI Modeling Capability in CAD Systems: Report 3 - Fully-Toleranced Test Case Verification

Douglas C. Cheney
International TechneGroup Inc.

Bryan R. Fischer
Advanced Dimensional Management LLC

This publication is available free of charge from:
http://dx.doi.org/10.6028/NIST.GCR.15-999

National Institute of Standards and Technology
U.S. Department of Commerce

NIST GCR 15-999

Measuring the PMI Modeling Capability in CAD Systems: Report 3 - Fully-Toleranced Test Case Verification

Prepared for
U.S. Department of Commerce
Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

By
Douglas C. Cheney
International TechneGroup Inc.

Bryan R. Fischer
Advanced Dimensional Management LLC

This publication is available free of charge from:
http://dx.doi.org/10.6028/NIST.GCR.15-999

October 2015

U.S. Department of Commerce
Penny Pritzker, Secretary

National Institute of Standards and Technology
Willie May, Under Secretary of Commerce for Standards and Technology and Director

Preface

The National Institute of Standards and Technology (NIST) has created a test system to measure conformance of Computer-Aided Design (CAD) software to American Society of Mechanical Engineers (ASME) standards for product and manufacturing information (PMI), specifically geometric dimensioning and tolerancing (GD&T) information. The test system has three main components: test cases, test CAD models, and verification and validation test results. The verification and validation results measure PMI implementation capabilities in CAD software and derivative STEP, JT, and 3D PDF files.

All of the test cases, test models, test results, and other presentations are available from the project website: http://www.nist.gov/el/msid/infotest/mbe-pmi-validation.cfm

This report is the third of three reports about the test system. The reports can be read independently of each other.

- Measuring the PMI Modeling Capability in CAD Systems: Report 1 - Combined Test Case Verification
- Measuring the PMI Modeling Capability in CAD Systems: Report 2 - Test Case Validation
- Measuring the PMI Modeling Capability in CAD Systems: Report 3 - Fully-Toleranced Test Case Verification

Disclaimers

The reports were prepared for the Engineering Laboratory of the National Institute of Standards and Technology under the following contracts:

- SB1341-12-SE-0860, RECON Services Inc., "PMI Conformance Testing Models"
- SB1341-12-SE-0853, International TechneGroup Inc., "PMI and Composite Information Validation and Conformance Testing"
- SB1341-14-SE-0061, International TechneGroup Inc., "PMI Test Cases and Models, Validation and Conformance Testing"

The contents of the reports do not necessarily reflect the views of NIST. NIST and the authors do not make any warranty, expressed or implied, nor assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, product, or process included in the reports.

Any mention of commercial products is for information purposes only; it does not imply recommendation or endorsement by NIST. The test system can be used without any restrictions. Its use in other software or hardware products does not imply a recommendation or endorsement by NIST of those products.

Project Participants

- International TechneGroup Inc. (ITI) - test model creation, expert review, verification, validation, and documentation
- Advanced Dimensional Management LLC - test case definition and expert review
- RECON Services Inc., Neilsoft Ltd. - test model creation and expert review
- Department of Energy Kansas City Plant (operated by Honeywell FM&T), RECON Services Inc., Sigmetrix - expert review

Cover image: Fully-toleranced test cases

Table of Contents

List of Figures

List of Tables

1 Introduction

A methodology for measuring the product and manufacturing information (PMI) modeling capability of computer-aided design (CAD) systems has been developed to measure technology readiness and to track progress as functionality gaps are closed. A measurement methodology will enhance the ability of discrete-part manufacturing companies to implement a model-based enterprise (MBE) [1-5]. The use of a clear capability assessment will accelerate MBE technology development by CAD software vendors. This can increase the business opportunities for both manufacturing companies and technology providers.

Common practice in discrete-part manufacturing companies is to use CAD systems to create three-dimensional (3D) models that precisely define the shape of their products. The companies derive two-dimensional (2D) drawings from the 3D model that detail the product's dimensions, tolerances, and other manufacturing information. Manufacturing organizations have typically considered the drawings to be the master product definition for all downstream processes such as simulation, manufacturing, and inspection. Often a 3D model is recreated from the drawing in one or more downstream processes, especially when performed by external suppliers. In some cases, the original 3D model is released with the drawing as a reference document [6].

As the drawing goes through several engineering changes, the 3D model may become outdated because it is not the master design document. Therefore, model recreation from the drawing tends to increase as a product matures. Downstream consumers of the drawing visually interpret the dimensions, tolerances, and other manufacturing information and manually reenter this information into downstream systems. Manually reentering information is a potentially error-prone process. This human interpretation is repeated for each engineering change.

Global business requirements are driving companies to produce better and cheaper products in less time to market. Management initiatives target the reduction of risk due to variation and the elimination of all non-value-added tasks throughout the engineering, manufacturing, and sustainment phases of a product's lifecycle. A leading process improvement initiative today is the concept of MBE [7].

1.1 Model-Based Enterprise and Model-Based Definition

A model-based enterprise (MBE) builds on the foundation that all product data may be integrated into a single model-based definition (MBD). This eliminates the need for 2D drawing generation, the recreation of 3D models, and/or the visual interpretation of drawing data in downstream processes. It improves product quality by eliminating drawing-to-model inconsistencies, unintentional model changes during recreation, and drawing interpretation errors. It decreases overall time to market by enabling direct reuse of the digital product model in downstream software systems.

A key component of an MBD is the integration of all the product and manufacturing information (PMI) into the 3D model. Dimensions, tolerances, notes, and other data previously found on a drawing are displayed in the model with direct links to the affected portion of the model's shape definition or 3D geometry. The data is grouped into multiple saved views to aid visual consumption. More importantly, the visual data is linked to an internal representation that is well defined and structured for automated consumption in downstream software systems. Derivative models, such as STEP (ISO 10303 –known informally as the STandard for Exchange of Product model data) [8-10], JT [11-13] and 3D PDF [14-16] files, are created as needed for downstream consumers who do not have direct access to the CAD system in which the native MBD model is defined.

1.2 MBD Verification and Validation

In a drawing-based product lifecycle, the drawing is manually checked by a person before release and then visually interpreted by a person during downstream reuse. This results in processes that tolerate low-level variation in the digital data while being fairly controlled. In a model-based process, the checking task is often eliminated on the assumption that a precise native model should be directly reusable in downstream systems without error. This results in processes that are less tolerant of digital data variation while being less controlled. However, if a company is going to rely on an MBD model throughout its product's lifecycle, the model must be reliable. Therefore, quality checking of the geometry and PMI in the master model, and their equivalent entities in all derivatives, is critical before release to downstream processes.

Various automotive, aerospace, and defense industry groups have identified precise geometry and PMI quality criteria for native MBD models and their derivatives. These include:

- Strategic Automotive Special Interest Group (SASIG) Product Data Quality (PDQ) team [17]
- PDES, Inc. [18] and ProSTEP iViP [19] collaboration for Long-Term Archival (LOTAR) [20]
- Department of Defense's MBE team [1]

Each group has recently documented these requirements in international, regional, and domestic standards such as:

- Managed Model-based 3D Engineering - STEP ISO 10303-242 [21, 22]
- CAD mechanical 3D Explicit geometry information - EN9300-110 [23]
- DoD Standard Practice: Technical Data Packages - MIL-STD-31000A [24]

These groups generally agree that the process of quality checking a native CAD model should be called verification. This process verifies that the product definition data is complete, consistent, and conformant to relevant standards. They recommend that the process of determining whether the data in a derivative model is equivalent to the native model should be called validation. This process validates that all data has been translated with any digital variation within acceptable limits specified by the anticipated downstream processes.

Due to the complexity of MBD data, it is unrealistic to implement verification or validation using an interactive, manual process. Several CAD applications have been developed to automate verification and validation using the criteria referenced above. While these applications make MBD quality control feasible, they impose an important requirement on the CAD modeling systems: that all MBD data, including 3D geometry and PMI, must be accessible through an application programming interface (API) to third-party developers.

1.3 PMI Representation and Presentation

An MBD must contain sufficient PMI representation so that automated systems, such as machining and inspection, can reuse the information efficiently and correctly in all downstream processes. PMI representation (also known as semantic PMI) includes all information necessary to represent GD&T without any graphical presentation elements. The PMI presentation should also be clearly presented for visual (human) consumers so that they understand and trust the model-based definition. PMI presentation (also known as graphical PMI) consists of geometric elements such as lines and arcs preserving the exact appearance (color, shape, positioning) of the GD&T annotations. The internal PMI representation should be structured and defined so each element is clear, complete, and consistent. The PMI presentation should be organized into saved views with annotations that support cross-highlighting of affected geometry.

These two aspects of PMI, representation and presentation, are best understood by considering how their key characteristics are applied to the various components of an MBD. Table 1 and Table 2 list the characteristics of PMI representation and presentation, respectively. The following is an explanation how they apply to the product geometry, coordinate systems, supplemental geometry, annotations, and saved views in an MBD.

Table 1: Characteristics of PMI representation

Annotation structure
Annotation parameters
Annotation geometry
Coordinate system structure
Coordinate system parameters
Supplemental geometry structure
Supplemental geometry parameters

Table 2: Characteristics of PMI presentation

Annotation visibility
Annotation color
Annotation name
Annotation layout
Annotation location
Annotation orientation
Annotation lines
Annotation text
Coordinate system visibility
Coordinate system color
Coordinate system name
Coordinate system text
Supplemental geometry visibility
Supplemental geometry color
Saved view structure
Saved view name
Saved view frustum

MBD product geometry is structured to differentiate the geometric entities that define the 3D shape of the product from other entities used as reference, context, or supplemental geometry for annotations. For most discrete-part product models, a solid (closed volume) or shell (open surface) definition provides the highest level of definition for downstream processes. The parametric definition of the model is complete, correct, and useful for revisioning. The explicit definition of topology and geometry is free of defects that impede downstream reuse. The meta-data properties associated with the product model capture basic product management data, such as ownership and lifecycle state. The visibility status and display color of the product geometry are appropriate for visual interpretation by downstream users.

MBD annotations have a specified type (dimension, feature control frame, note, etc.) and named parameters (nominal value, tolerance, material modifier, etc.) that facilitate automated interpretation downstream. An annotation's associated geometry includes all affected surfaces in the product geometry and any supplemental geometry. It does not include any extraneous geometry. This facilitates both automated consumption and visual interpretation, also known as cross-highlighting. The visibility, layout, location, and orientation of the annotation in saved views, along with its color, display name, lines, and text, are appropriate for visual interpretation by downstream users.

MBD coordinate systems have explicit named associations with the feature control frames that rely on the datum reference frames they represent. Each coordinate system's location and orientation accurately represent the datum reference frame. The coordinate system's visibility in each saved view corresponds to the visibility of its associated annotations. Its color, name, and display text are appropriate for visual interpretation by downstream users.

Supplemental geometry is geometric elements that do not belong to the shape of a part. The geometric elements are used to create other shapes or contain information about part features such as hole centerlines. MBD supplemental geometry entities have the correct form or structure for the annotations that references them. For example, the limited area for a datum target defines the portion of the underlying solid face or surface that is inside versus outside. The location, orientation, and size of each supplemental geometry entity complete the conceptual definition of its associated annotations. Its visibility in saved views corresponds to the visibility of its associated annotations. Supplemental geometry color is appropriate for visual interpretation by downstream users.

A saved view facilitates the presentation of the model and associated PMI by defining a subset of the PMI and an orientation from which it is viewed. MBD saved views are structured to contain a related set of annotations, with their associated supplemental geometry and coordinate systems, along with the appropriate product geometry. Each saved view may contain the complete geometric definition of the product or a portion defined by a cross section. The contents of a saved view are displayed within a frustum, or pyramid of vision, that is intuitive for visual interpretation by downstream users.

1.4 PMI Verification and Validation

The process of querying PMI data in an MBD model for verification is straightforward as long as the CAD API provides sufficient access to the data. First, the type and properties of each annotation entity are retrieved and compared with those specified in the test case documentation. Second, any relationships between the annotation and other annotations or geometry entities are queried and compared with the specification. Since an MBD model may contain multiple annotations with similar types and properties, it may be necessary also to query the graphic presentation data in order to match reliably each annotation with its specification and to confirm its relationships are correct.

The process of comparing PMI constructs between MBD models in dissimilar CAD systems for equivalence validation is more complex. The primary challenge is to correctly match corresponding annotation entities before comparing their characteristics. Because all of the presentation characteristics can vary significantly without changing the meaning or representation, these cannot be reliably used for matching purposes. The test model images in Figures 6-9 illustrate the typical variation between the CAD systems used for this assessment. Reliable annotation matching requires that all product and supplemental geometry entities be matched. Then the subset of annotations entities associated with each set of matching geometry entities are matched and compared. Annotations that have been added, removed, or had their geometry associations changed will remain unmatched.

Some PMI constructs make automation of the above verification and validation processes difficult (see section 3.4). The various CAD systems use different modeling methodologies for these constructs that are each considered valid within the ASME standards. Until the CAD systems converge toward common methodologies, or the standards are modified to require this, the MBD verification and validation technologies must implement advanced reasoning and exception handling to accommodate this allowable variation in PMI definition.

2 Methodology for PMI Modeling Capability Assessment

The PMI modeling capability of the CAD systems commonly used by discrete-part manufacturing companies to support MBE was assessed using a formal methodology [25], shown in Figure 1, involving:

1. Test case definition and expert review
2. Test CAD model creation based on the test case definitions
3. Verification of the CAD models against the test case definitions
4. Generation of derivative STEP, JT, and 3D PDF files by the Implementor Forums [12, 14, 26]
5. Validation of the derivative files against the CAD models and test case definitions

This report is concerned with steps 1-3 of the PMI modeling capability assessment. The validation of the derivative files is documented in second report of this series [27]. The verification of other test cases is documented in the first report of this series [28].

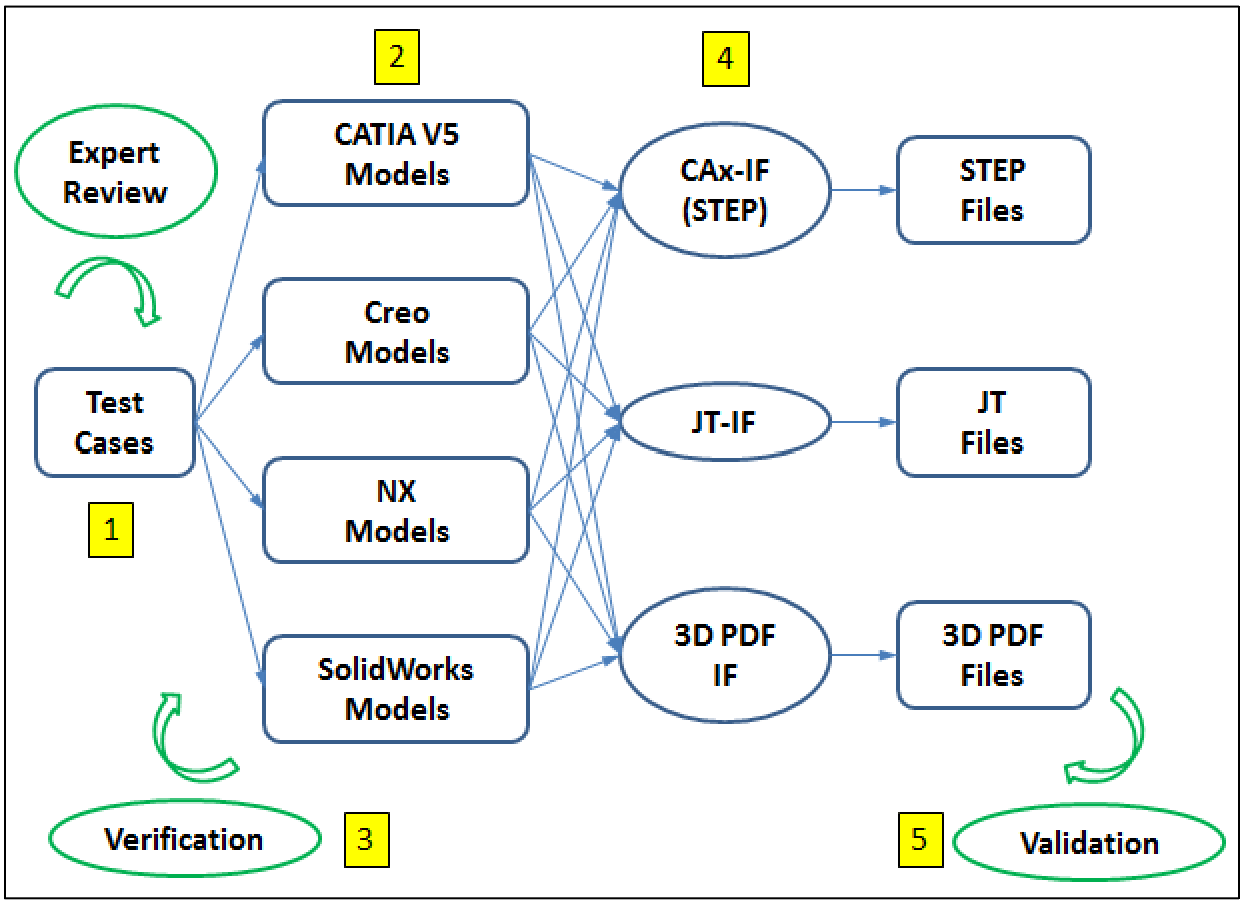


Figure 1: Methodology for PMI modeling capability assessment

2.1 Test Case Definition

For test case generation, an industry expert in geometric dimensioning and tolerancing (GD&T) defined representative PMI constructs allowed by the American Society of Mechanical Engineers (ASME) standards for 2D drawings Y14.5-1994 [29] and 3D models Y14.41-2003 [30]. (Newer versions of both standards are available.) A PMI construct is a group of annotation entities which define an elemental concept, for example: defining a datum feature with a datum feature symbol (one annotation) or controlling the variation of a hole with a size dimension, a feature control frame, and its associated datum features (3 to 5 annotations). Figure 2 shows the presentation of a typical GD&T annotation [31].

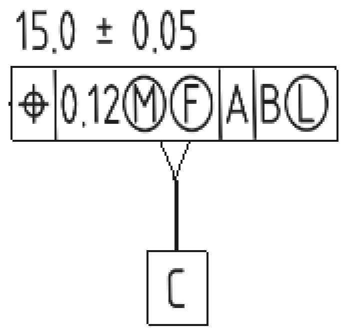


Figure 2: Typical presentation of a GD&T annotation

The constructs defined for this assessment are listed in Appendix A. The constructs were applied to three discrete-part geometry models, with the intent that all geometric features would be fully-toleranced, i.e. controlled and constrained, and account for all hierarchical interrelationships.

Each fully-toleranced test case (FTC) is documented with a set of drawings and explanatory text, as shown in Figures 3-5. Drawings of other views of each test case are in Appendix B.

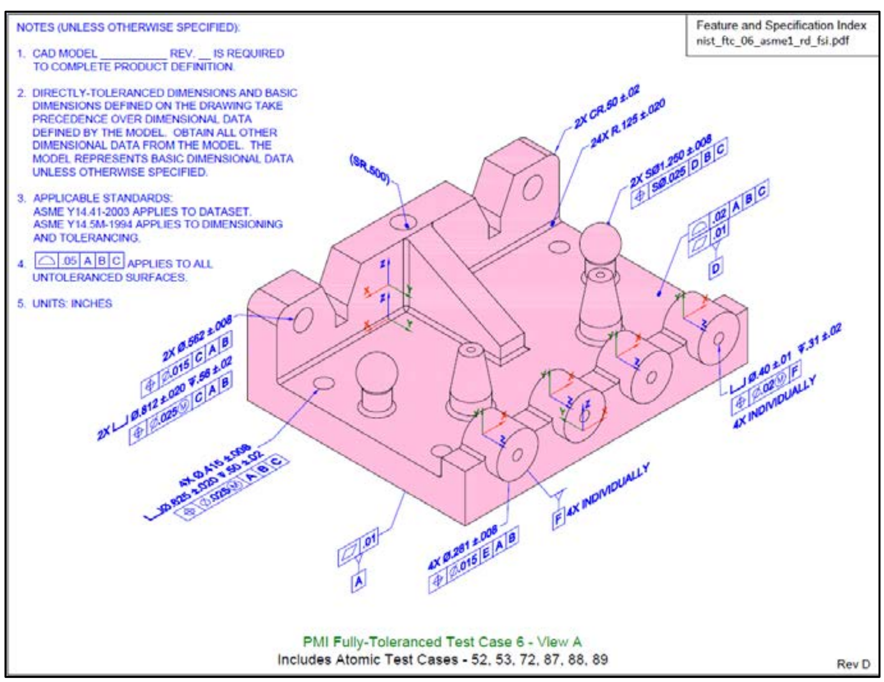


Figure 3: Fully-toleranced test case 6 (FTC 6) drawing

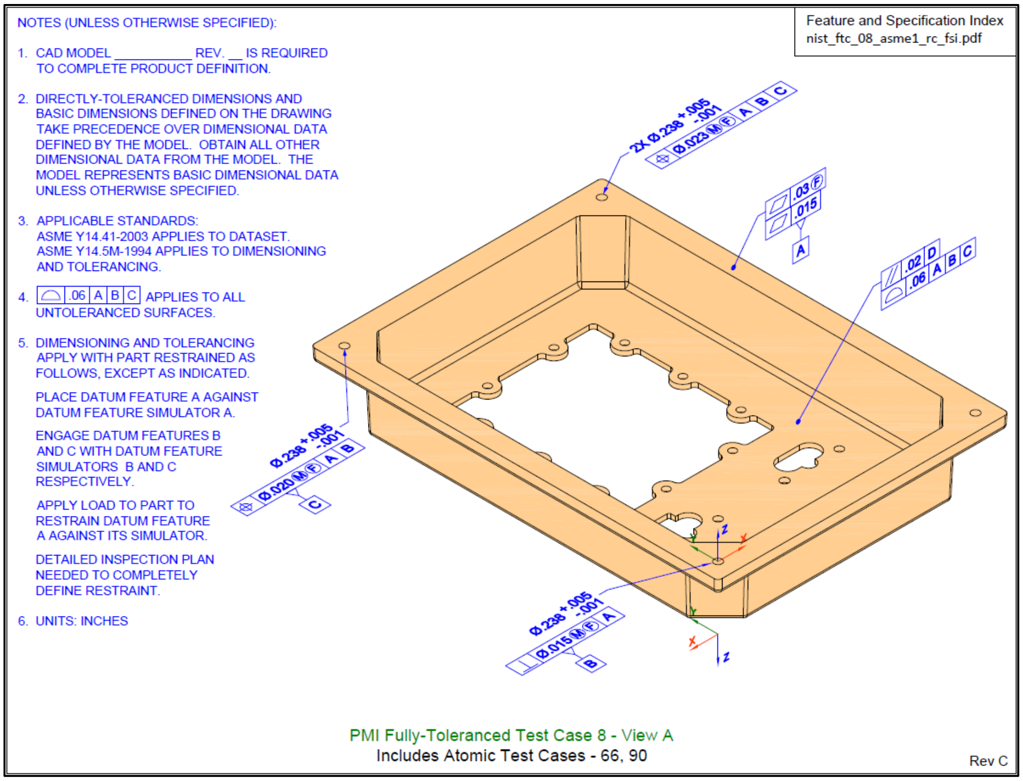


Figure 4: Fully-toleranced test case 8 (FTC 8) drawing

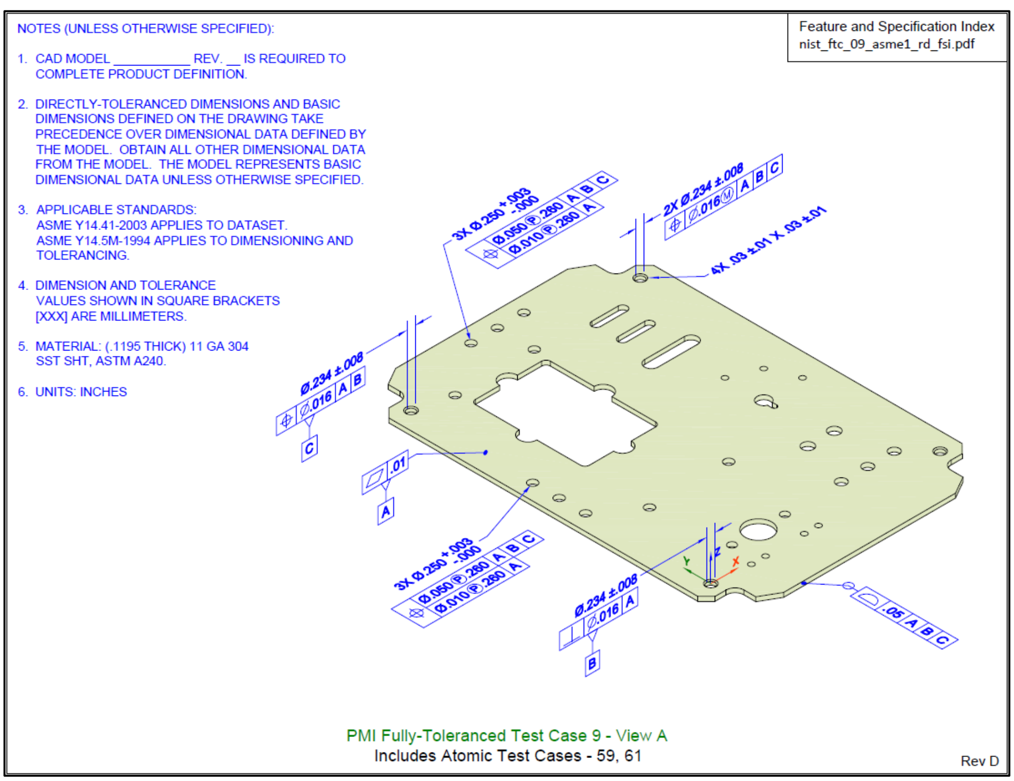


Figure 5: Fully-toleranced test case 9 (FTC 9) drawing

Other industry GD&T experts reviewed the three FTCs for clarity and correctness. The FTCs were refined based on the expert feedback. All experts agreed that the FTCs are not intended to be functional for production tolerance purposes. The test cases are also not intended to represent best practice in how to apply GD&T to a part. Simpler GD&T strategies could have been used. The test cases are intended to exercise valid presentations of GD&T defined in the ASME Y14 standards.

2.2 Test Model Creation

A team of CAD experts created CAD models for each FTC in four CAD systems that were available in late 2014:

- CATIA V5 R24 (aka V5-6R2014) from Dassault Systemes [32]
- Creo 3.0 from PTC [33]
- NX 9.0 from Siemens PLM [34]
- SOLIDWORKS 2015 from Dassault Systemes [35]

The CAD experts used the above PMI representation and presentation criteria to create models with equivalent meaning, and negligible graphical variation. When it was not possible to satisfy both sets of criteria, the representation was given precedence over the presentation. Figures 6-9 show fully-toleranced test case 6 (FTC 6) modeled in each of the four CAD systems. Images of each test model, each with multiple saved views, are shown in Appendix C.

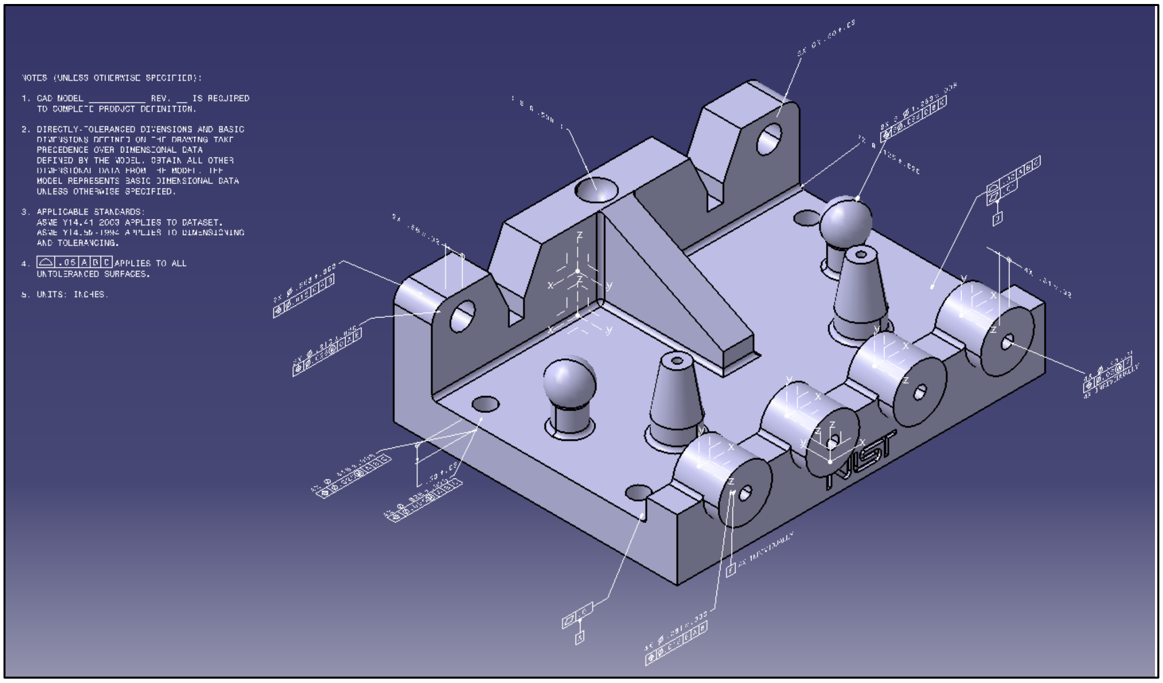


Figure 6: Fully-toleranced test case 6 (FTC 6) modeled in CATIA V5 R24

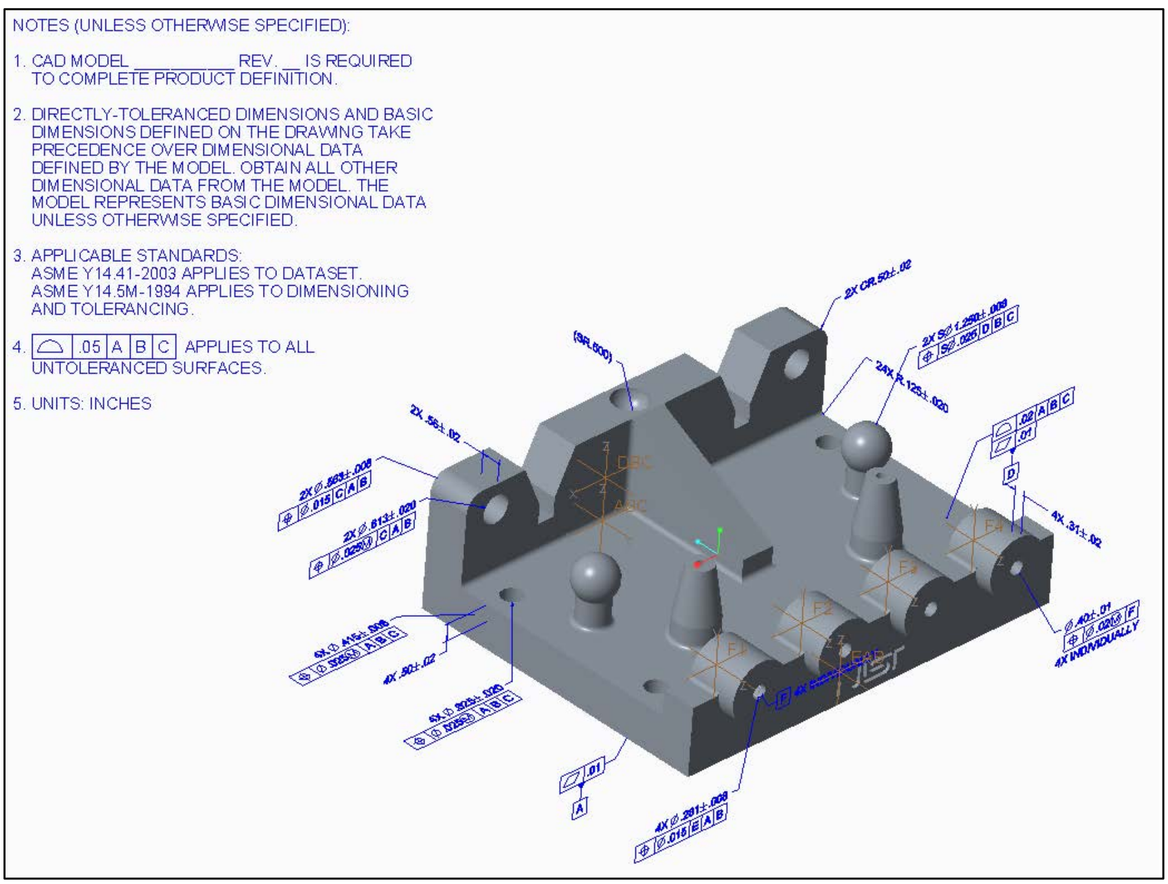


Figure 7: Fully-toleranced test case 6 (FTC 6) modeled in Creo 3.0

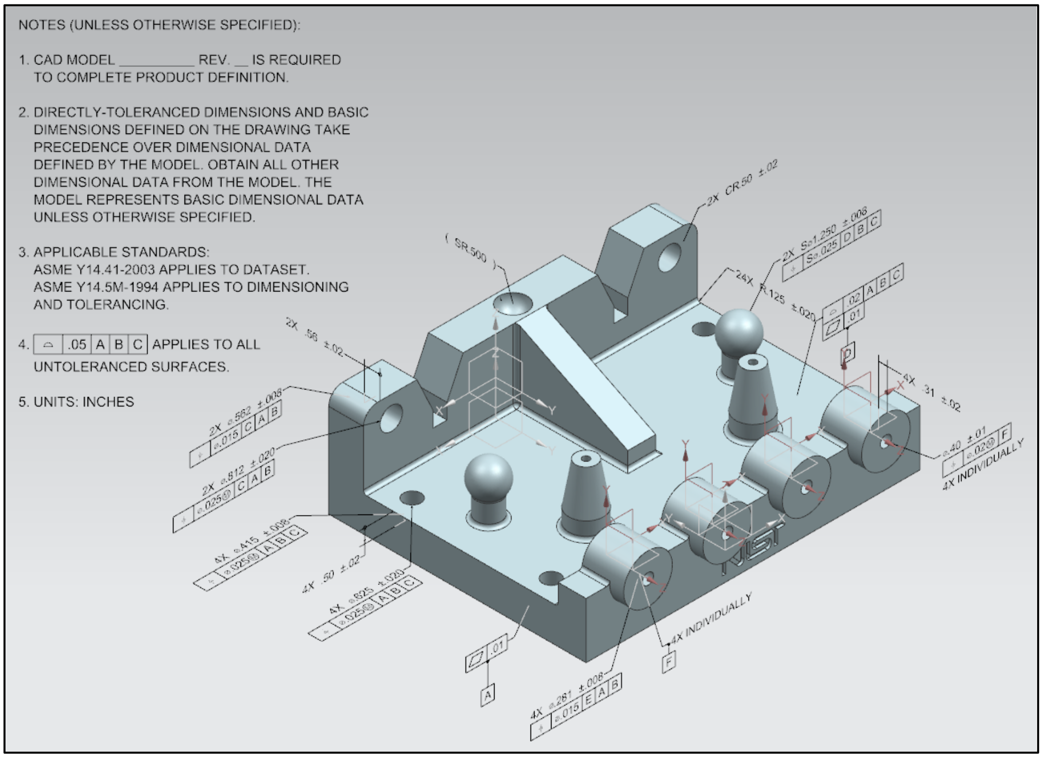


Figure 8: Fully-toleranced test case 6 (FTC 6) modeled in NX 9.0

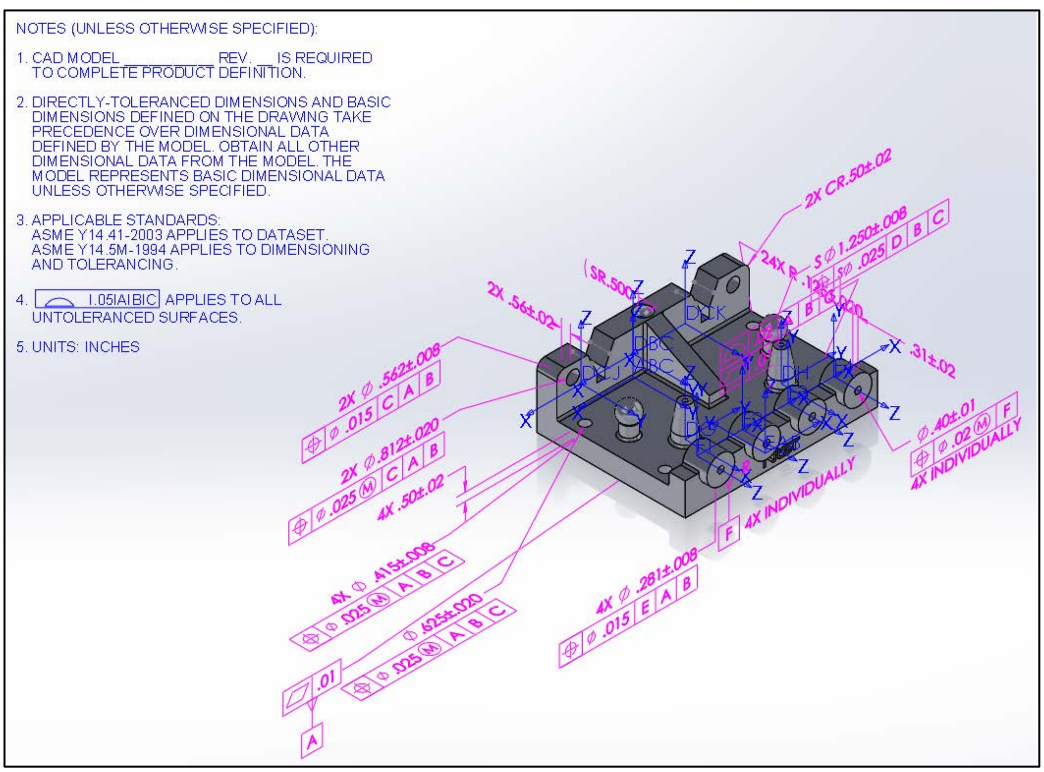


Figure 9: Fully-toleranced test case 6 (FTC 6) modeled in SOLIDWORKS 2015

2.3 Test Model Verification

The CAD validation software CADIQ 8.0 [36] was used to query the PMI representation and presentation data in a 3D model using the API of each CAD system. The software developer for CADIQ developed and refined algorithms for matching and comparing each data element between models in different CAD systems that were based on the same test case definition.

After the models were complete, a CAD validation specialist manually compared the data queried for each PMI element in the three models for one CAD system to the three test case definitions. Significant discrepancies or deficiencies were documented. Once the CAD modeling team resolved the identified issues in the models, the data set was designated as the reference set. Using the multi-CAD PMI validation technology, the specialist automatically compared each model from the other three CAD systems to the reference model.

Each discrepancy between the PMI in a model pair was compared with the test case to determine which model was inconsistent. Then, interactive CAD system queries were used to determine whether the discrepancy was due to measurement error in the validation tool or a difference in the test model. The validation software vendor resolved measurement errors while the CAD modeling team resolved model discrepancies within the limitations of the CAD system.

After several iterations of model refinement and verification, the outstanding discrepancies were documented as system limitations and the test models were released to the CAD software vendor representatives in the CAx Implementor Forum (CAx-IF) [26] for review. The CAD software vendors provided additional feedback to resolve any outstanding modeling issues.

3 PMI Modeling Capability Results

The testing methodology was used to determine whether the representation and presentation of each PMI element (i.e., annotation, coordinate system, supplemental geometry entitiy, saved view) in each test model were well defined. The PMI element counts for this representative data set are shown in Table 3.

Table 3: PMI element counts by type and test case

	Element Count per Test Case			
PMI Element	**FTC 6**	**FTC 8**	**FTC 9**	**Total**
Annotation	66	52	64	182
Coordinate System	15	9	9	33
Supplemental Geometry Entity	6	2	8	16
Saved View	3	4	4	11
Total:	90	67	85	**242**

All PMI elements with a representation limitation were counted, by element type, across all test models for each CAD system. These counts were used to calculate a “Representation Limitation” percentage using this formula:

$$Limitation\ Percentage = 100\ x\ \frac{Limitation\ Count}{Element\ Count}$$

All PMI elements with only a presentation limitation were counted and likewise divided by the element count to produce a “Presentation Limitations Only” percentage. If an element had both a representation and a presentation limitation, it was included only in the representation percentage. If an element had two or more representation and/or presentation limitations, it was counted only once in the appropriate calculation. Elements with neither type of limitation were counted in a “No Limitations” percentage, thus:

$$No\ Limitations = 100\% - (Representation\ Limitations + Presentation\ Limitations)$$

These three modeling capability percentages for each CAD system are shown in Figure 10. The names of the CAD systems have been generalized to give the end-user community an overall summary of their capabilities without impugning any particular CAD vendor. The technical details have been shared separately with each CAD vendor so they know their opportunity for improvement in the MBE domain.

	CAD A	CAD B	CAD C	CAD D
No Limitations	89%	69%	82%	52%
Presentation Limitations only	3%	12%	12%	30%
Representation Limitations	8%	19%	7%	18%
Representation Level	92%	81%	93%	82%

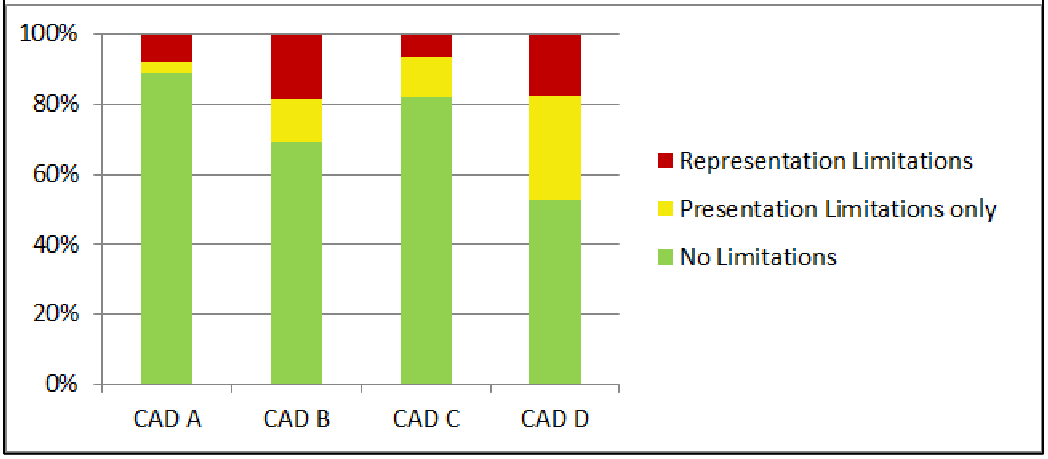


Figure 10: PMI modeling capability results by CAD system

In Figure 10, the "No Limitations" percentage can be interpreted as a measure of the capability of the CAD system to satisfy both the automated and visual consumption requirements of downstream MBE processes relative to the functional coverage of PMI constructs of this set of test cases. The "Representation Level" percentage, calculated as 100% less the "Representation Limitations" percentage, indicates the CAD system's ability to satisfy only automated consumption requirements.

The representation and presentation limitations for each CAD system were then subtotaled by characteristic and divided by the count of PMI elements of the type appropriate for that characteristic using this formula:

$$Verification\ Percentage = 100\ x\ \frac{Element\ Count - Limitation\ Count}{Element\ Count}$$

For example, the count of annotation structure limitations for all models in each CAD system was divided by the count of annotations in the test case using the above formula. The verification percentages for each element type in each CAD system are shown in Tables 4 and 5.

Table 4 shows that all four CAD systems correctly represented the coordinate systems and supplemental geometry specified in the test cases. Each system was unable to represent a small portion of the annotation information.

Table 4: PMI representation limitations by characteristic and CAD system

Representation Limitations	Element Count	CAD A	CAD B	CAD C	CAD D
Annotation structure	182	97%	**89%**	97%	99%
Annotation parameters	182	96%	92%	95%	91%
Annotation geometry	182	97%	95%	100%	**86%**
Coordinate system parameters	33	100%	100%	100%	100%
Supplemental geometry structure	16	100%	100%	100%	100%
Supplemental geometry parameters	16	100%	100%	100%	100%

Table 5 shows a much broader variation in the types of presentation limitations across CAD systems. One of the systems (CAD D) was unable to adequately present coordinate system, supplemental geometry and saved view characteristics, which accounts for its large "Presentation Limitations only" percentage relative to the other systems shown in Figure 10.

Table 5: PMI presentation limitations by characteristic and CAD system

Presentation Limitations	Element Count	CAD A	CAD B	CAD C	CAD D
Annotation visibility	182	100%	100%	100%	98%
Annotation color	182	100%	100%	100%	100%
Annotation name	182	100%	100%	100%	100%
Annotation layout	182	96%	91%	96%	94%
Annotation location	182	100%	99%	92%	98%
Annotation orientation	182	99%	98%	99%	99%
Annotation lines	182	99%	97%	98%	97%
Annotation text	182	96%	91%	99%	92%
Coordinate system visibility	33	100%	100%	100%	**42%**
Coordinate system color	33	100%	100%	100%	100%
Coordinate system name	33	100%	100%	100%	100%
Coordinate system text	33	100%	100%	100%	100%
Supplemental geometry visibility	16	100%	100%	100%	**0%**
Supplemental geometry color	16	100%	100%	100%	100%
Saved view structure	11	100%	100%	100%	**0%**
Saved view name	11	100%	100%	100%	100%
Saved view frustum	11	100%	100%	100%	**0%**

3.1 Representation Limitations

For each characteristic, there were often multiple types of limitations. Appendix D shows one example of each type of PMI representation limitation. The graphics in the appendices have been generalized to avoid identifying the specific CAD system involved. Figure 11 shows one example from Appendix D. Table 7 tabulates the count of representation limitations by characteristic and type across all CAD systems. Table 6 explains the PMI entity abbreviations used in Table 7.

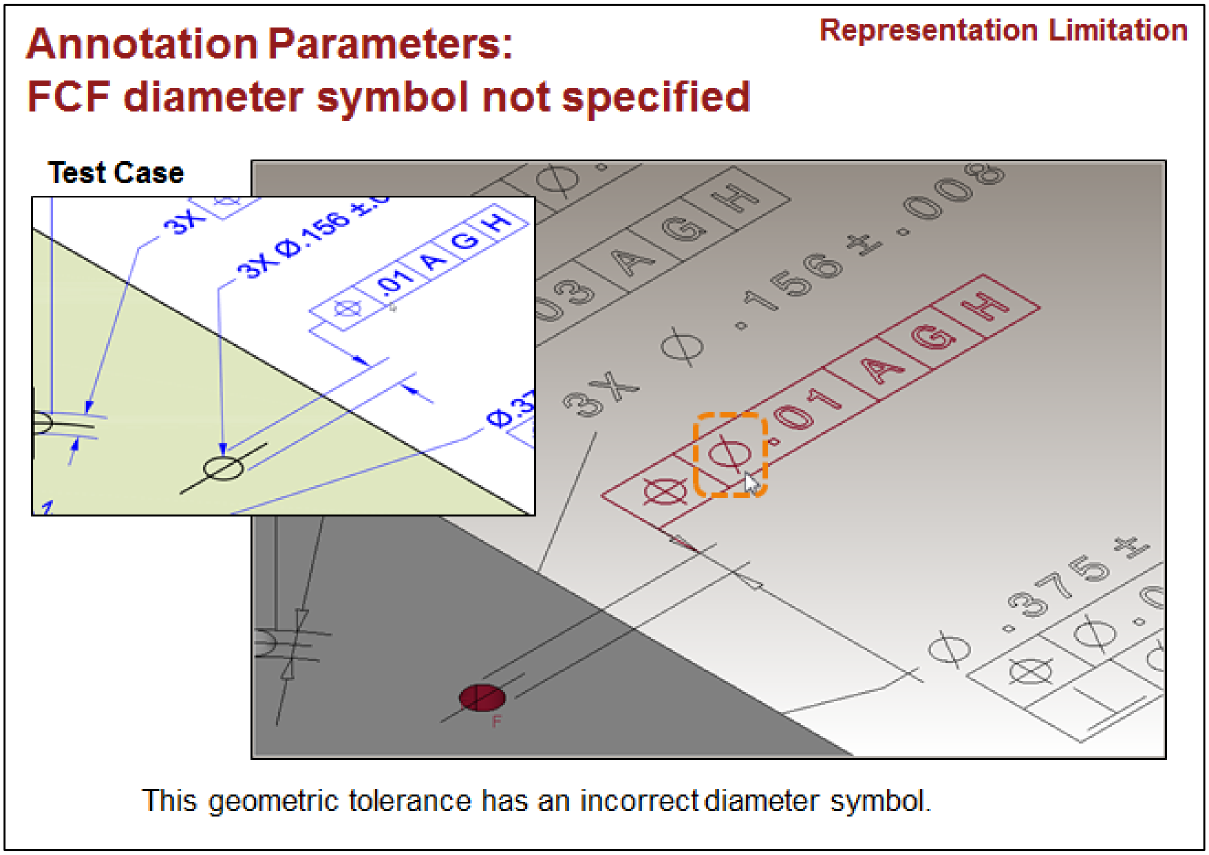


Figure 11: Example of a representation limitation

Table 6: PMI entity abbreviations

Abbrev	Definition
AN	Annotation
CS	Coordinate system
DFS	Datum feature symbol
DIM	Dimension
DRF	Datum reference frame
DTS	Datum target symbol
FCF	Feature control frame
PG	Product geometry
SG	Supplemental geometry
VW	View

Table 7: Representation limitation counts by characteristic and type

Representation Limitations	**133**
Annotation structure	**38**
FCF extension lines defined as separate DIM	18
FCF missing composite layout	4
FCF not defined	1
FCF projected tolerance zone defined as separate DIM	2
FCF text defined as separate note	12
FCF text duplicated	1
Annotation parameters	**51**
Chamfer DIM width not defined	1
DIM conic surfaces defined with encoded text	4
DIM controlled radius defined with encoded text	2
DIM missing dual dimension tolerance	1
DIM not defined as reference DIM	3
DIM origin not defined	4
DIM radius defined with encoded text	1
DIM slot radius defined with encoded text	6
DIM spherical diameter defined with encoded text	3
DIM spherical radius defined with encoded text	4
DIM tapered center defined with encoded text	4
FCF between-basis defined with encoded text	4
FCF diameter symbol not specified	6
FCF dual dimension defined with encoded text	2
FCF free state defined with encoded text	1
FCF missing all-around designation	2
FCF missing tangent plane modifier	1
FCF spherical diameter defined with encoded text	2
Annotation geometry	**44**
DFS not associated with complete set of faces	5
DIM associated with incorrect face	1
DIM not associated with complete set of faces	5
DIM not associated with edge	2
DIM not associated with face	2
DTS not associated with SG curve	6
FCF associated with incorrect face	1
FCF extension line DIM not associated with correct face	3
FCF not associated with complete set of faces	2
FCF not associated with SG curve	17

3.2 Presentation Limitations

Appendix E shows one example of each type of presentation limitation. Figure 12 shows one example from Appendix E. Table 8 tabulates the count of representation limitations by characteristic and type across all CAD systems. Table 6 explains the PMI entity abbreviations used in Table 8.

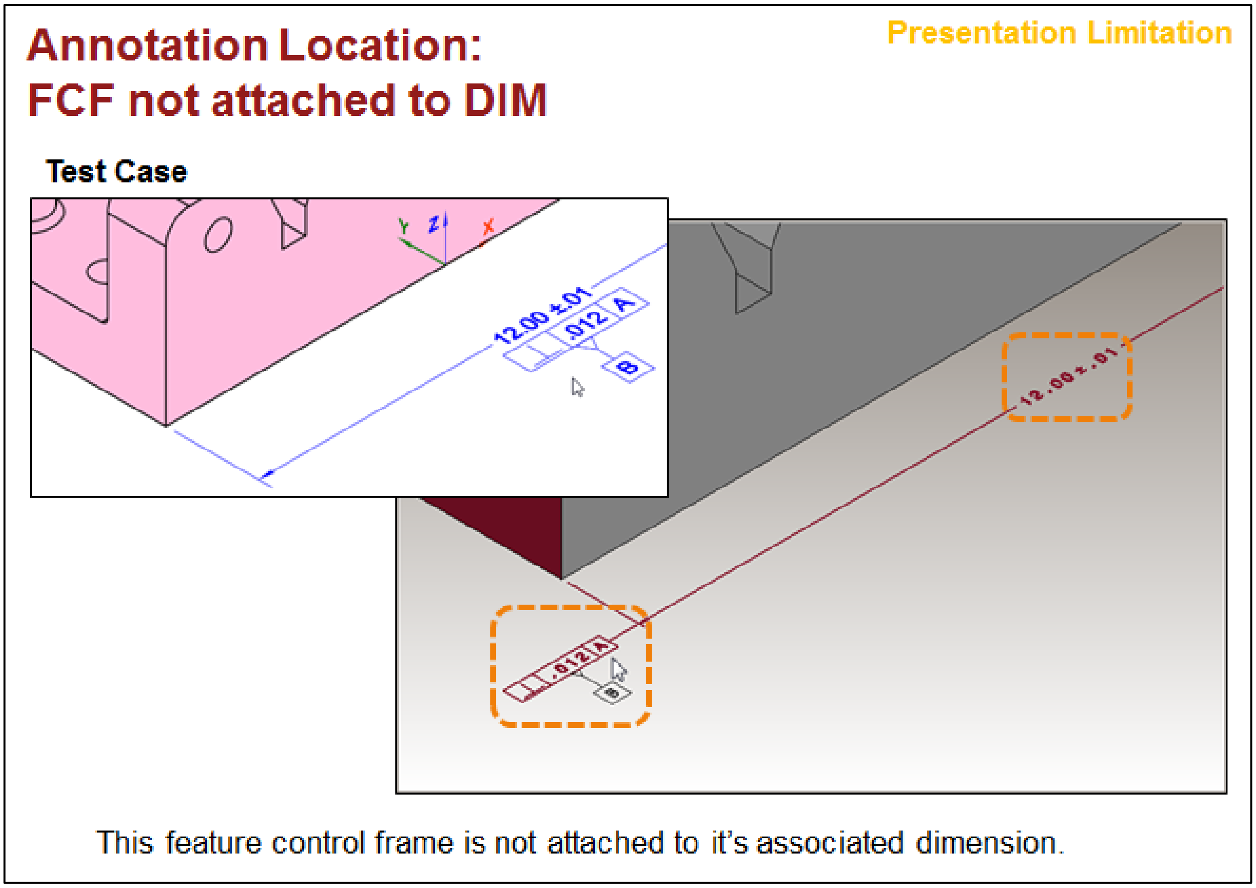


Figure 12: Example of a presentation limitation

Table 8: Presentation limitation counts by characteristic and type

Presentation Limitations	**198**
Annotation visibility	**4**
DFS is extraneous when DTS is defined	4
Annotation layout	**43**
Counterbore DIM defined as two separate DIM's	12
Countersink DIM defined as two separate DIM's	3
DIM dual dimension bracket size very small	1
DIM dual dimension position is incorrect	1
DIM not stacked correctly	4
DIM text misaligned	2
FCF defined separate from general note text	2
FCF instance count not in front	2
FCF modifiers reversed	1
FCF stack order reversed	2
Hole DIM defined as two separate DIM's	8
Slot DIM defined as two separate DIMs	5
Annotation location	**19**
DFS not attached to FCF	17
FCF not attached to DIM	2
Annotation orientation	**8**
DIM view plane rotated	6
FCF view plane rotated	2
Annotation lines	**15**
DFS missing extension line	5
DIM leader line is extraneous	1
FCF divider line cuts through symbol	1
FCF leader line passes through FCF	1
FCF missing dual leader lines	4
FCF radial extension lines defined as SG curves	3
Annotation text	**39**
DFS text is extraneous	6
DIM has extraneous space	7
DIM missing pattern text	2
DIM missing zero tolerance limit negative sign	2
DIM nominal value rounded incorrectly	4
DIM pattern text is extraneous	1
DIM pattern text is incorrect	1
FCF extension line DIM text is extraneous	6
FCF missing projected tolerance zone length	2
FCF pattern text is extraneous	7
FCF pattern text is incorrect	1
Coordinate system visibility	**19**
CS visible in wrong view	19
Supplemental geometry visibility	**29**
SG curve visible in wrong view	16
SG point visible in wrong view	13
Saved view structure	**11**
View cannot contain annotations on different planes	11
Saved view frustum	**11**
View camera position not defined	11

3.3 Style Differences

In some cases, the representation and presentation for a PMI element were determined by the expert reviewers to be correct yet different between the CAD systems. These variations were categorized as style differences and not included in the representation or presentation limitation calculations. Appendix F documents one example of each type of style difference that was ignored. Figure 13 shows an example from Appendix F. Table 9 tabulates the count of style differences by characteristic and type across all systems. Table 6 explains the PMI entity abbreviations used in Table 9.

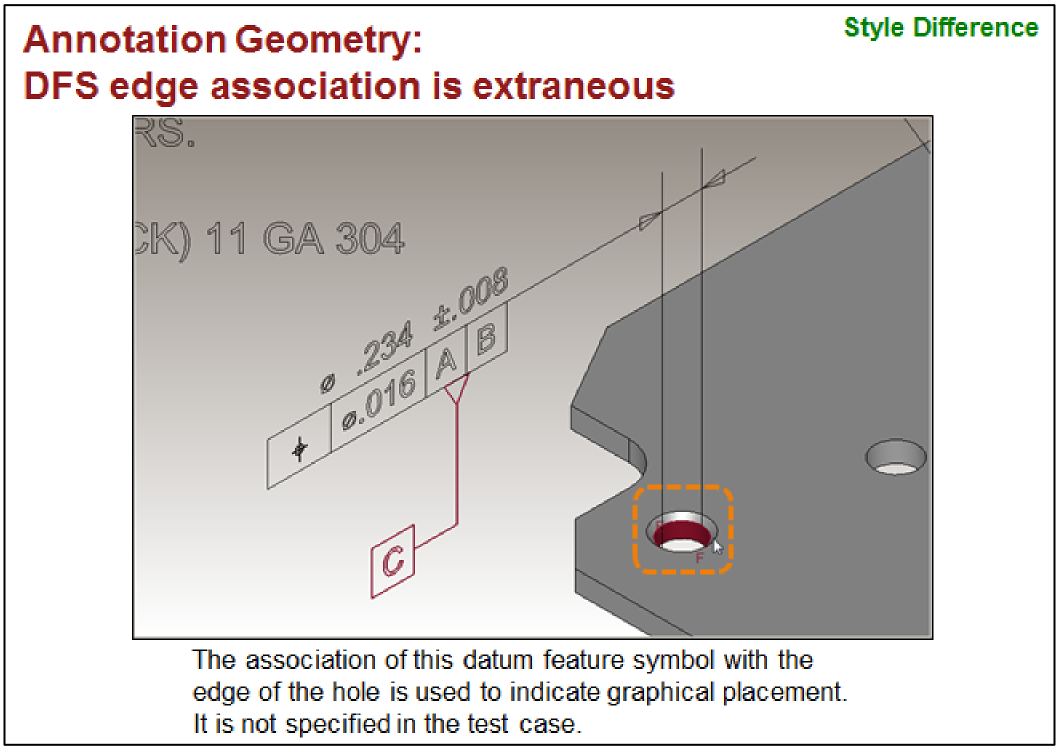


Figure 13: Example of a style difference

Table 9: Style difference counts by characteristic and type

⊟ Style Differences	**36**
⊟ Annotation structure	**12**
DTS requires DFS to be defined	12
⊟ Annotation geometry	**20**
DFS edge association is extraneous	2
DIM edge association is extraneous	8
FCF edge association is extraneous	10
⊟ Supplemental geometry structure	**4**
FCF limited area is non-solid surface on solid face	3
FCF limited area is subdivided solid face	1

3.4 PMI Verification Challenges

A challenging construct is the representation of extension lines for datum feature symbols and feature control frames. In some CAD systems, this construct is represented as dimension entities that are separate from the attached annotation, as shown in Figure 14. These extra annotations introduce parameters (nominal value and limits) that must be ignored during verification.

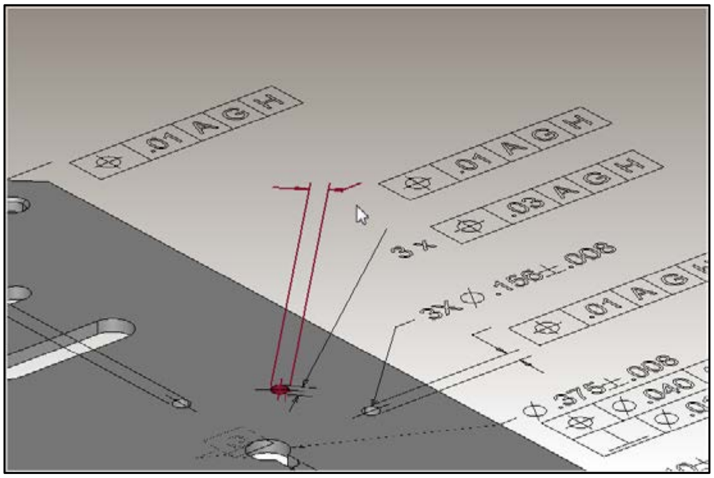


Figure 14: Extension lines represented as separate dimension annotations

Another challenging construct is the representation of datum target symbols shown in Figure 15. Some CAD systems consider that these symbols completely define a datum feature while others require datum feature symbols also to be defined. This modeling difference creates a structural difference (number of annotations) that must be accommodated during verification.

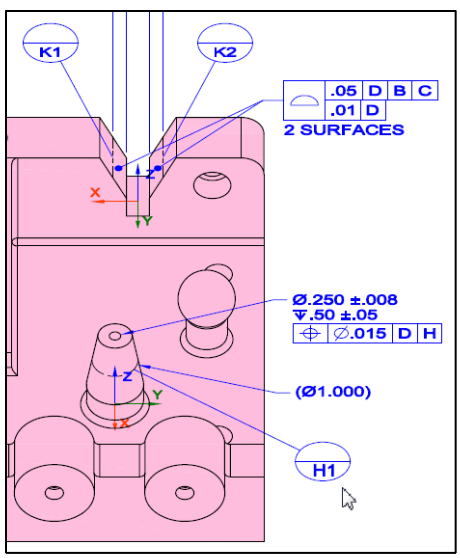


Figure 15: Datum targets specified in a test case

Finally, when a PMI construct is specified with a limited area, such as a datum target or geometric tolerance, the portion of the product shapes that is within the target area is represented differently. Some CAD systems define a non-solid surface overlaid on the solid while others subdivide the portion of the solid face into a separate face shown in Figure 16. Still others indicate the area with a region defined by wireframe geometry. These modeling differences create significant variability that must be accounted for during annotation matching and comparison.

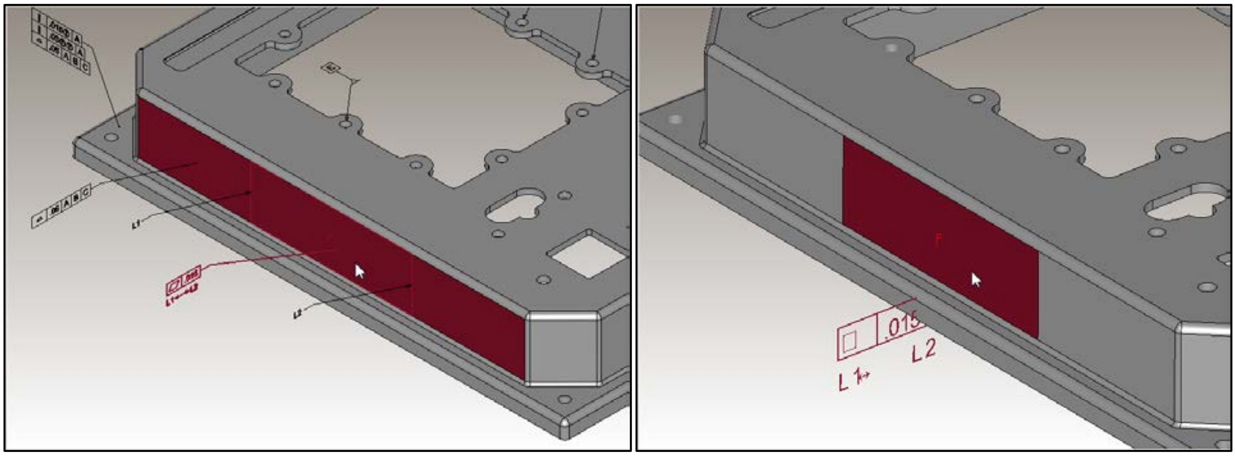


Figure 16: Different target area representations

4 Discussion

Using a formal methodology, implemented with advanced verification and validation technology, the MBE modeling capability of four leading CAD systems was quantified relative to the PMI requirements captured in three fully-toleranced test cases.

- Two of the four CAD systems, tested at 2014 release levels, were able to represent more than 90% of the PMI elements. The other two CAD systems had twice as many representation limitations and were therefore only able to represent 80% of the PMI elements.
- One of the CAD systems had relatively few presentation-only limitations (3%). Two systems had presentation limitations for 12% of the PMI elements that did not also have representation limitations.
- One of the CAD systems had almost three times as many elements (30%) affected by its presentation limitations.

The specific PMI representation and presentation system limitations identified by this assessment have been clearly documented and communicated to the CAD vendors.

The specific test of the PMI capabilities in CAD systems documented in this report is a snapshot in time. Specific test cases were developed using particular versions of the ASME Y14 tolerancing standards and PMI constructs. The test cases were modeled in particular versions of four CAD systems with a specific modeling methodology to give precedence to PMI representation over PMI presentation. The CAD models were compared to each other with a particular version of CAD validation software. Results for PMI representation and presentation capabilities were reported based on four categories of PMI elements: annotations, coordinate systems, supplemental geometry, and saved views.

For a company that is transitioning from 2D drawings to 3D models to implement model-based design, this report can be used to identify the characteristics of PMI representation and presentation and the capabilities of CAD software that are important to achieve an MBD workflow. The test cases may or may not be representative of the types of PMI that might be typically used. The versions of the CAD systems and tolerancing standards might be newer or older than what a company requires. However, the report clearly identifies a wide variety of PMI representation and presentation issues that can be used to evaluate CAD software that is used in an MBD environment.

5 References

[1] *Model Based Enterprise - Exploring the Digital Tapestry*, http://www.model-based-enterprise.org/.

[2] J. Lubell, K. Chen, J. Horst, S. Frechette, and P. Huang, "Model Based Enterprise / Technical Data Package Summit Report," NIST Technical Note 1753, 2012.

[3] J. Lubell, S. P. Frechette, R. R. Lipman, F. M. Proctor, J. A. Horst, M. Carlisle, and P. J. Huang, "Model-Based Enterprise Summit Report," National Institute of Standards and Technology, NIST Technical Note 1820, 2013.

[4] *Model-Based Enterprise Summit 2013*, National Institute of Standards and Technology, http://www.nist.gov/el/msid/mbe_2013_presentations.cfm.

[5] *Model-Based Enterprise Summit 2014*, National Institute of Standards and Technology, http://www.nist.gov/el/msid/mbe2014presentations.cfm.

[6] V. Quintana, L. Rivest, R. Pellerin, F. Venne, and F. Kheddouci, "Will Model-based Definition replace engineering drawings throughout the product lifecycle? A global perspective from aerospace industry," *Computers in Industry*, vol. 61, pp. 497-508, 2010.

[7] M. Alemanni, F. Destefanis, and E. Vezzetti, "Model-based definition design in the product lifecycle management scenario," *The International Journal of Advanced Manufacturing Technology*, vol. 52, pp. 1-14, 2011.

[8] ISO 10303-1:1994, "Industrial automation systems and integration - Product data representation and exchange - Part 1: Overview and fundamental principles," International Organization for Standardization, Geneva, Switzerland.

[9] M. J. Pratt, "Introduction to ISO 10303—the STEP standard for product data exchange," *Journal of Computing and Information Science in Engineering*, vol. 1, pp. 102-103, 2001.

[10] *STEP Application Handbook, ISO 10303, Version 3*, SCRA, 2006, https://pdesinc.org/downloadable_files/STEPapplicationhandbook63006BF.pdf.

[11] *JT Open*, Siemens, http://www.plm.automation.siemens.com/en_us/products/open/jtopen/.

[12] *JT Implementor Forum*, ProSTEP iViP, http://www.prostep.org/en/projects/jt-implementor-forum.html.

[13] ISO 14306:2012, "Industrial automation systems and integration - JT file format specification for 3D visualization," International Organization for Standardization, Geneva, Switzerland.

[14] *3D PDF Consortium*, http://www.3dpdfconsortium.org/.

[15] ISO 24517-1:2008, "Document management -- Engineering document format using PDF -- Part 1: Use of PDF 1.6 (PDF/E-1)," International Organization for Standardization, Geneva, Switzerland.

[16] ISO 14739-1:2014, "Document management -- 3D use of Product Representation Compact (PRC) format -- Part 1: PRC 10001," International Organization for Standardization, Geneva, Switzerland.

[17] ISO/PAS 26183:2006, "SASIG Product data quality guidelines for the global automotive industry," International Organization for Standardization, Geneva, Switzerland.

[18] *PDES, Inc. - Advancing the Digital Enterprise*, https://pdesinc.org/.

[19] *ProSTEP iViP Association*, http://prostep.org/.

[20] *LOTAR - Long Term Archiving and Retrieval*, http://www.lotar-international.org/.

[21] *Development of a Convergent Modular STEP Application Protocol Based on AP 203 and AP 214: STEP AP 242 – Managed Model Based 3D Engineering*, ASD Strategic Standardization Group, 2009, http://www.ap242.org/.

[22] ISO 10303-242:2014, "Industrial automation systems and integration - Product data representation and exchange - Part 242: Application protocol: Managed Model-based 3D Engineering," International Organization for Standardization, Geneva, Switzerland.

[23] *ASD Strategic Standardization Group - Long Term Archiving and Retrieval - LOTAR*, http://www.asd-ssg.org/lotar.

[24] MIL-STD-31000A, "DoD Standard Practice: Technical Data Packages," U.S. Department of Defense, 2013.
[25] S. P. Frechette, A. T. Jones, and B. R. Fischer, "Strategy for Testing Conformance to Geometric Dimensioning & Tolerancing Standards," *Procedia CIRP*, vol. 10, pp. 211-215, 2013.
[26] *CAx Implementor Forum*, http://www.cax-if.org/.
[27] D. Cheney and B. Fischer, "Measuring the PMI Modeling Capability in CAD Systems: Report 2 - Test Case Validation," National Institute of Standards and Technology, NIST-GCR 15-998, 2015.
[28] D. Cheney and B. Fischer, "Measuring the PMI Modeling Capability in CAD Systems: Report 1 - Combined Test Case Verification," National Institute of Standards and Technology, NIST-GCR 15-997, 2015.
[29] ASME Y14.5-1994, "Dimensioning and Tolerancing - Engineering Drawing and Related Documentation Practices," American Society of Mechanical Engineers, 1994, New York.
[30] ASME Y14.41-2003, "Digital Product Definition Data Practices - Engineering Drawing and Related Documentation Practices," American Society of Mechanical Engineers, 2003, New York.
[31] R. Lipman and J. Lubell, "Conformance checking of PMI representation in CAD model STEP data exchange files," *Computer-Aided Design*, vol. 66, pp. 14-23, 2015.
[32] *CATIA*, Dassault Systemes, http://www.3ds.com/products-services/catia/.
[33] *Creo*, PTC, http://www.ptc.com/product/creo.
[34] *NX*, Siemens, www.plm.automation.siemens.com/en_us/products/nx/.
[35] *SOLIDWORKS*, Dassault Systemes, http://www.solidworks.com/.
[36] *CADIQ*, ITI TranscenData, http://www.transcendata.com/products/cadiq/.

Appendix A: PMI Constructs

PMI Constructs in FTC 6

Feature ID	Feature Description	Specification	Ano ID	Comments
F1	Datum Feature A	Flatness .01	T1	
		Datum Feature Symbol A	DF1	
F2	Datum Feature B	12.00 ±.01	D1	
		Perpendicularity .012|A	T2	
		Datum Feature Symbol B	DF2	
F3	Datum Feature C	Perpendicularity .012|A|B	T3	
		Datum Feature Symbol C	DF3	
F4	Datum Feature D	Profile Surface .02|A|B|C	T4	
		Flatness .01	T5	
		Datum Feature Symbol D	DF4	
F5	Datum Feature E	Profile Surface .02|A|B|C	T6	
		Flatness .01	T7	
		Datum Feature Symbol E	DF5	
F6-F9	Datum Feature F	4X Ø.281 ±.008	D2	
		Position Ø.015|E|A|B	T8	
		Datum Feature Symbol F	DF6	
		4X INDIVIDUALLY	STR1	
F10	Datum Target G1	Datum Target Symbol G1	DT1	
		Represented line element	RLE1	Circular line element for datum target G1 and controlled element
		(Ø1.000)	D3	Defines RLE1
F11-F12	Datum Target H1	Datum Target Symbol H1	DT2	
		Represented line element	RLE2	Circular line element for datum target H1 and controlled element
		(Ø1.000)	D4	Defines RLE2
F12-F13	Datum Target J1, J2	Datum Target Symbols J1-J2	DT3, DT4	
		Profile Surface .05|D|B|C Profile Surface .01|D	T9	Surfaces are grouped
		2 SURFACES	STR2	Groups surfaces for T9
		Represented line element	RLE3	
		Represented line element	RLE4	
		(1.106)	D5	Applies to datum target lines
F14-F15	Datum Target K1, K2	Datum Target Symbols K1-K2	DT5, DT6	
		Profile Surface .05|D|B|C Profile Surface .01|D	T10	Surfaces are grouped
		2 SURFACES	STR3	Groups surfaces for T10
		Represented line element	RLE5	
		Represented line element	RLE6	
		(1.106)	D6	Applies to datum target lines
F16-F17	Spherical Diameter Surfaces	2X SØ 1.250 ±.008	D7	
		Position SØ.025|D|B|C	T11	
F18-21	Counterbored Holes - Set 1	4X Ø.415 ±.008	D8	
F22-F25		⌴Ø.625 ±.020	D9-1	
		Position Ø.025Ⓜ|A|B|C	T12	Applies to F18-F28
F26-F29		↧.50 ±.02	D9-2	
F30-F31	Counterbored Holes - Set 2	2X Ø.562 ±.008	D10	
		Position Ø.015|C|A|B	T13	
F32-F33		2X ⌴ Ø.812 ±.020	D11-1	
		Position Ø.025Ⓜ|C|A|B	T14	
F34-F35		↧.56 ±.02	D11-2	

F36-F39	Counterbored Holes - Set 3	⌴Ø.40 ±.01	D12-1	
		Position Ø.02Ⓜ|F	T15	Applies individually to 4 holes
F40-F43		↧.31 ±.02	D12-2	
		4X INDIVIDUALLY	STR4	
F44-F67	Fillets	24X R.125 ±.020	D13	

Feature ID	Feature Description	Specification	Ano ID	Comments
F68	Spherical Cutout	(SR.500)	D14	Reference Dimension
F69-F70	Large External Rounds	2X CR.50 ±.02	D15	
F71	Tapered Center Rib Surface	⊿ 1.00 : 2.00	D16	Basic Dimension
		Profile Surface .04|A|B|C	T16	
F72-F73	Conic Surfaces	2X 1.00 : 3.00 ▷	D17	Basic Dimension
	Cone w/ G1	Profile Surface .05|D|B|C Profile Surface .01|D	T17	Applies to cone and cylinder
F74	Cylindrical Cone Support	Profile Surface .05|D|B|C Profile Surface .01|D	T17	Applies to cone and cylinder
	Cone w/ H1	Profile Surface .05|D|B|C Profile Surface .01|D	T18	Applies to cone and cylinder
F75	Cylindrical Cone Support	Profile Surface .05|D|B|C Profile Surface .01|D	T18	Applies to cone and cylinder
F76	Cylindrical hole in cone w/ G1	Ø.250 ±.008	D18	
		Position Ø.015|D|G	T19	
F77	Bottom of Hole	↧.50 ±.05	D19	
F78	Cylindrical hole in cone w/ H1	Ø.250 ±.008	D20	
		Position Ø.015|D|H	T20	
F79	Bottom of Hole	↧.50 ±.05	D21	
F80	Width feature of size @ J1-J2	.500 ±.008	D22	
		Position .025|D|C|J	T21	
F81	Width feature of size @ K1-K2	.500 ±.008	D23	
		Position .025|D|C|K	T22	
-	General Profile Tolerance 1	Profile Surface .05|A|B|C	T23	
MCS1	MCS for Views 1, 2, 3		CS1-1	Main MCS for model
	MCS for DRF A		CS1-2	" " " "
	MCS for DRF A|B		CS1-3	" " " "
	MCS for DRF A|B|C		CS1-4	" " " "
	MCS for DRF C|A|B		CS1-5	" " " "
MCS2	MCS for DRF D|B|C		CS2	
MCS3	MCS for DRF E|A|B		CS3	
MCS4	MCS for DRF F1		CS4	First of 4 individual datum reference frames for F
MCS5	MCS for DRF F2		CS5	Second of 4 individual datum reference frames for F
MCS6	MCS for DRF F3		CS6	Third of 4 individual datum reference frames for F
MCS7	MCS for DRF F4		CS7	Fourth of 4 individual datum reference frames for F
MCS8	MCS for DRF D|G		CS8	
MCS9	MCS for DRF D|H		CS9	
MCS10	MCS for DRF D|C|J		CS10	
MCS11	MCS for DRF D|C|K		CS11	
-	General Notes	NOTES...	STR5	Flat to screen

PMI Constructs in FTC 8

Feature ID	Feature Description	Specification	Ano ID	Comments
F1	Datum Feature A	Flatness .03Ⓕ	T1	Applies in free state
		Flatness .015	T2	
		Datum Feature Symbol A	DF1	
F2	Datum Feature B	Ø.238 +.005/-.001	D1	
		Perpendicularity Ø.015ⓂⒻ|A	T3	Applies in free state
		Datum Feature Symbol B	DF2	
F3	Datum Feature C	Ø.238 +.005/-.001	D2	
		Position Ø.020ⓂⒻ|A|B	T4	Applies in free state
		Datum Feature Symbol C	DF3	
F4	Datum Feature D	Parallelism .03|A	T5	
		Profile .06|A|B|C	T6	
		Datum Feature Symbol D	DF4	
F5	Datum Feature E	Datum Feature Symbol E	DF5	Controlled by D3 and T7
F6	Datum Feature F	Datum Feature Symbol F	DF6	Controlled by D3 and T7
F5-F14	Pattern of PCB Mtg Holes	10X Ø.213 +.005/-.001	D3	Controls DF E and DF F
		Position Ø.04Ⓜ|D|B|C Position Ø.02Ⓜ|D|B|C	T7	Controls DF E and DF F
F15-F16	Datum Feature G	2X Ø.250 +.006/-.001	D4	
		Position Ø.03|D|B|C	T8	
		Datum Feature Symbol G	DF7	
F17	Datum Feature H	Ø.228 +.005/-.001	D5	
		Position Ø.050Ⓜ|D|B|C Position Ø.020Ⓜ|D|B|C SIM REQT 1	T9	
		Datum Feature Symbol H	DF8	
F18	Datum Feature J	Ø.242 +.005/-.001	D6	
		Position Ø.050Ⓜ|D|B|C Position Ø.020Ⓜ|D|B|C SIM REQT 1	T10	
		Datum Feature Symbol J	DF9	
F19	Datum Feature K	Ø.228 +.005/-.001	D7	
		Position Ø.050Ⓜ|D|B|C Position Ø.020Ⓜ|D|B|C SIM REQT 2	T11	
		Datum Feature Symbol K	DF10	
F20	Datum Feature L	Ø.242 +.005/-.001	D8	
		Position Ø.050Ⓜ|D|B|C Position Ø.020Ⓜ|D|B|C SIM REQT 2	T12	
		Datum Feature Symbol L	DF11	
F21-F22	Pattern of 2 Other Main Mtg Holes	2X Ø.238 +.005/-.001	D9	
		Position Ø.023ⓂⒻ|A|B|C	T13	Applies in free state
F23	Bottom Inside Surface	Parallelism .02|D	T14	
		Profile .06|A|B|C	T15	

F24	Surface Opposite Datum Feature A	Parallelism .015Ⓣ|A	T16	
		Parallelism .03ⒻⓉ|A	T17	Applies in free state
		Profile .05|A|B|C	T18	
F25	External Sidewall in -X Direction	Profile .06|A|B|C	T19	
F25.1	Limited Area on External Sidewall in -X Direction	Flatness .015 L1◄─► L2	T20	Tolerance applies between line elements L1 and L2
		Represented line element	RLE1	L1
		Represented line element	RLE2	L2

Feature ID	Feature Description	Specification	Ano ID	Comments
		Leader-Directed Note L1	LDN1	Labels RLE 1 that bounds limited area
		Leader-Directed Note L2	LDN2	Labels RLE 2 that bounds limited area
F26	Recess for Placard	Parallelism .015Ⓣ|D	T21	
		Profile .035|D|B|C	T22	
F27	Cutout for PCB Mtg	Profile .04|D|E-F All Around	T23	
F28	Square hole cutout	(□1.100)	D10	
		Profile .015|D|GⓂ All Around	T24	
F29	Cutout for E Stop	Profile .040|D|B|C Profile .005|D|B|C All Around	T25	
F30	Cutout for Middle Switch on -X Side	Profile .015|D|HⓂ-JⓂ All Around	T26	
F31	Cutout for Middle Switch on +X Side	Profile .015|D|KⓂ|LⓂ All Around	T27	
-	General Profile Tolerance	Profile Surface .06|A|B|C	T28	
MCS1	MCS for Views A, B		CS1-1	Main MCS for model
	MCS for DRF A		CS1-2	Same location as MCS1
	MCS for DRF A|B		CS1-3	Same location as MCS1
	MCS for DRF A|B|C - Free State		CS1-4	Same location as MCS1
	MCS for DRF A|B|C - Restrained		CS1-5	Same location as MCS1
MCS2	MCS for Views C, D		CS2-1	
	MCS for DRF D		CS2-2	Same location as MCS2
	MCS for DRF D|B|C		CS2-3	Same location as MCS2
MCS3	MCS for DRF D|E-F		CS3	
MCS4	MCS for DRF D|GⓂ		CS4	
MCS5	MCS for DRF D|HⓂ-JⓂ		CS5	
MCS6	MCS for DRF D|KⓂ|LⓂ		CS6	
-	General Notes	NOTES...	STR1	Flat to screen

PMI Constructs in FTC 9

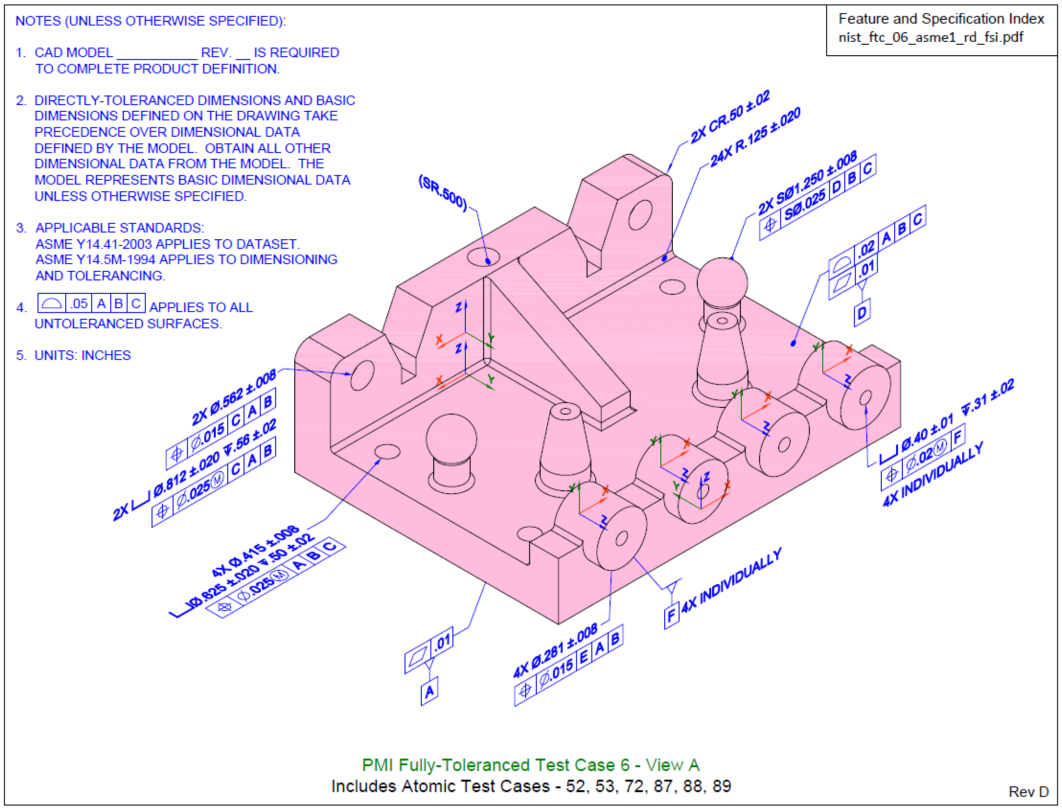
Feature ID	Feature Description	Specification	Ano ID	Comments
F1	Datum Feature A	Flatness .01	T1	
		Datum Feature Symbol A	DF1	
F2	Datum Feature B	Ø.234 ±.008	D1	
		Perpendicularity Ø.016|A	T2	
		Datum Feature Symbol B	DF2	
F3	Datum Feature C	Ø.234 ±.008	D2	
		Position Ø.016|A|B	T3	
		Datum Feature Symbol C	DF3	
F4	Datum Feature D	Ø.750 ±.008	D3	
		Perpendicularity Ø.010|A	T4	
		Position Ø.050|A|B|C	T5	
		Datum Feature Symbol D	DF4	
F5-F6	Datum Feature E	2X Ø.221 ±.008	D4	
		Position Ø.020|A|D|B	T6	
		Datum Feature Symbol E	DF5	
F7-F10	Datum Feature F	4X Ø.250 ±.008	D5	
		Position Ø.030|A|B|C	T7	
		Datum Feature Symbol F	DF6	
F11	Datum Feature G	Ø.375 ±.008	D6	
		Position Ø.040|A|B|C	T8	
		Perpendicularity Ø.010|A	T9	
		Datum Feature Symbol G	DF7	
F12	Datum Feature H	.140 ± .008	D7	SIELD
		Position Ø.010|A|G|B	T10	SIELD
		Datum Feature Symbol H	DF8	
F13	Radial End - Datum Feature H	Profile .008|A|G|H	T11	
F14-F17	Chamfers (cones)	4X .03 ±.01 X .03 ±.01	D8	2 dims and tols in one spec
F18-F19	Hole Pattern 1 - Panel Mounting	2XØ.234 ±.008	D9	Other 2 panel mounting holes
		Position Ø.016Ⓜ|A|B|C	T12	
F20-F23	Hole Pattern 2 - Horizontal	3X Ø.250 +.003/-.000	D10	Holes sized for PEM CLSS-032-3 self-clinching nuts
		Position Ø.050 Ⓟ.260|A|B|C Position Ø.010 Ⓟ.260|A	T13	Composite Position 2 Segments with Projected tolerance zone
F24-F27	Hole Pattern 3 - Vertical	3X Ø.250 +.003/-.000	D11	Holes sized for PEM CLSS-032-3 self-clinching nuts
		Position Ø.050 Ⓟ.260|A|B|C Position Ø.010 Ⓟ.260|A	T14	Composite Position 2 Segments with Projected tolerance zone
F28	Cutout - for FTC10 Insert	Profile .02|A|FⓂ All Around	T15	Cutout for insert into FTC10
F29-F30	Small Slots	2X .25 ±.01	D12	Width
		Position .02Ⓜ|A|B|C	T16	
		BOUNDARY	STR1	
		2X 1.00 ±.02	D13	Length - SIELD
		Position .06Ⓜ|A|B|C	T17	SIELD
		BOUNDARY	STR2	SIELD
		4X R	D14	Ends

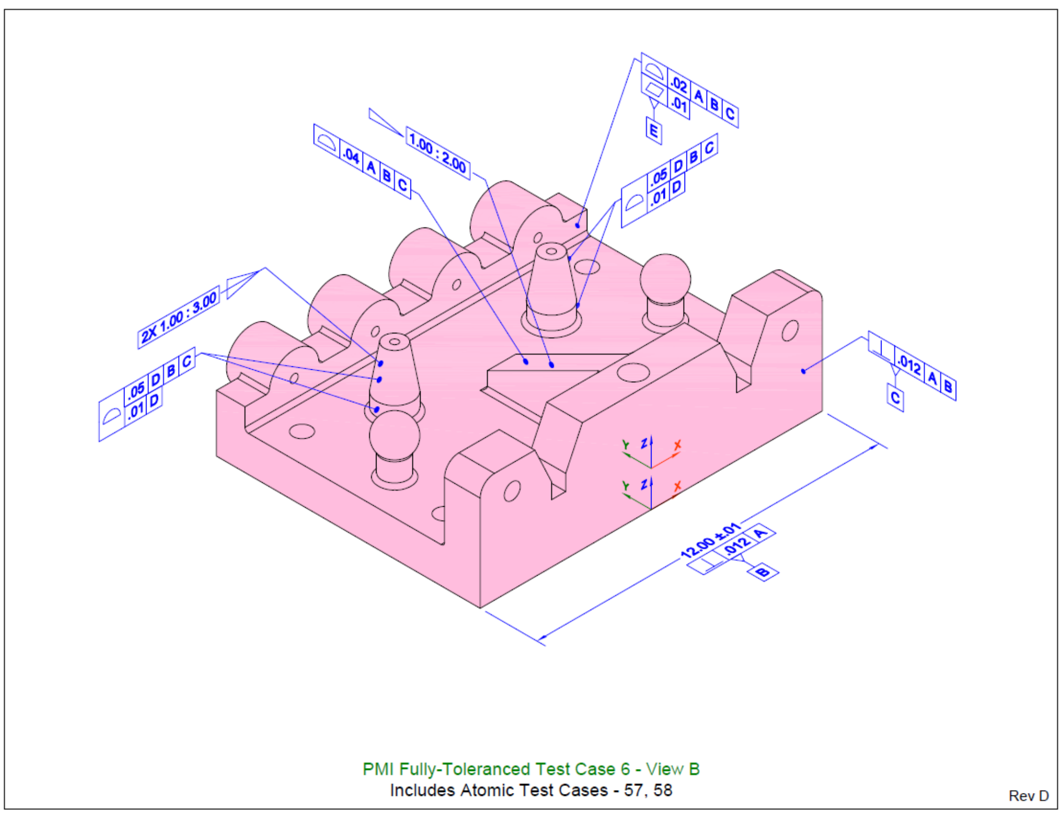
F31	Large Slot	.375 ±.008 X 1.500 ±.012	D15	2 dims and tols in one spec
		Position .030Ⓜ|A|B|C All-Around	T18	
		BOUNDARY	STR3	
		2X R	D16	Ends
F32-F34	Hole Pattern 4 - Polar	3X Ø.156 ±.008	D17	

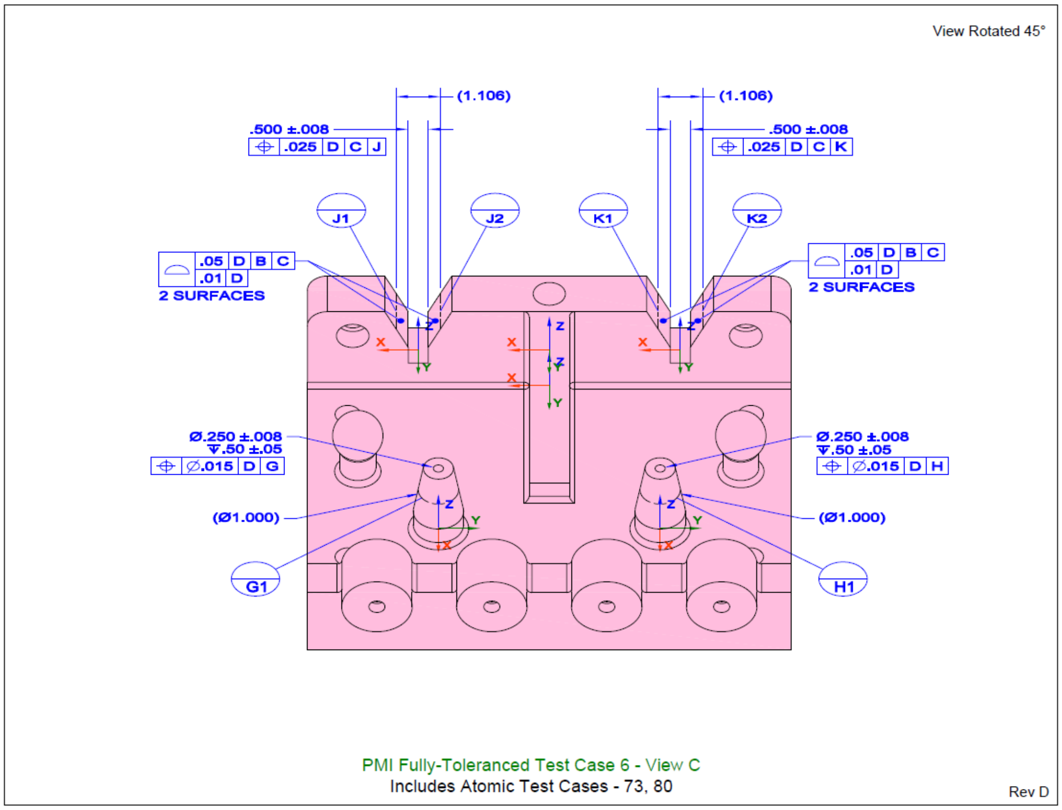
Feature ID	Feature Description	Specification	Ano ID	Comments
		3X Position .03|A|G|H	T19	Radial Direction - SIELD
		Represented line element	RLE1	Curve represents radial path
F32	Polar Hole 1 - Horizontal	Position .01|A|G|H	T20	Applies in X direction - SIELD
		Represented line element	RLE2	Line represents X direction
F33	Polar Hole 2 - Diagonal	Position .01|A|G|H	T21	Applies 45° to X direction - SIELD
		Represented line element	RLE3	Line represents 45° to X direction
F34	Polar Hole 3 - Vertical	Position .01|A|G|H	T22	Applies in Y direction - SIELD
		Represented line element	RLE4	Line represents Y direction
F35-F36	Dual Unit Holes	2X Ø.315 ±.008 [8 ±0.2]	D18	Inch and [mm] per DRM 11th ed.
		Position Ø.030 [0.76]|A|B|C	T23	Inch and [mm] per DRM 11th ed.
F37-F39	Hole Pattern 5 - Bidirectional Tols	3X Ø.281 ±.008	D19	
		Perpendicularity Ø.010|A	T24	
		3X Position .060|A|B|C	T25	Applies in X direction - SIELD
		Represented line element	RLE5	Line represents X direction
		3X Position .020|A|B|C	T26	Applies in Y direction - SIELD
		Represented line element	RLE6	Line represents Y direction
F40-F41	Hole Pattern 6 - SIM REQT LH	2X Ø.156 ±.008	D20	
		Position Ø.025Ⓜ|A|DⓂ|EⓂ	T27	
		SEP REQT	STR4	
F42-F43	Hole Pattern 7 - SIM REQT RH	2X Ø.156 ±.008	D21	
		Position Ø.025Ⓜ|A|DⓂ|EⓂ	T28	
		SEP REQT	STR5	
F44-F67	Profile Tolerance 1	Profile Surface .05|A|B|C All Around	T29	Peripheral (sheared) surfaces
MCS1	MCS for Views A, B, C, D		CS1-1	Main MCS for model
	MCS for DRF A		CS1-2	Same location as MCS1
	MCS for DRF A|B		CS1-3	Same location as MCS1
	MCS for DRF A|B|C		CS1-4	Same location as MCS1
MCS2	MCS for DRF A|D|B		CS2	
MCS3	MCS for DRF A|DⓂ|EⓂ		CS3	Same location as DRF A|D|B
MCS4	MCS for DRF A|FⓂ		CS4	
MCS5	MCS for DRF A|G|B		CS5	
MCS6	MCS for DRF A|G|H		CS6	Same location as DRF A|G|B
-	General Notes	NOTES...	STR6	Flat to screen
-	Identifier for Detail View C		VSI1	

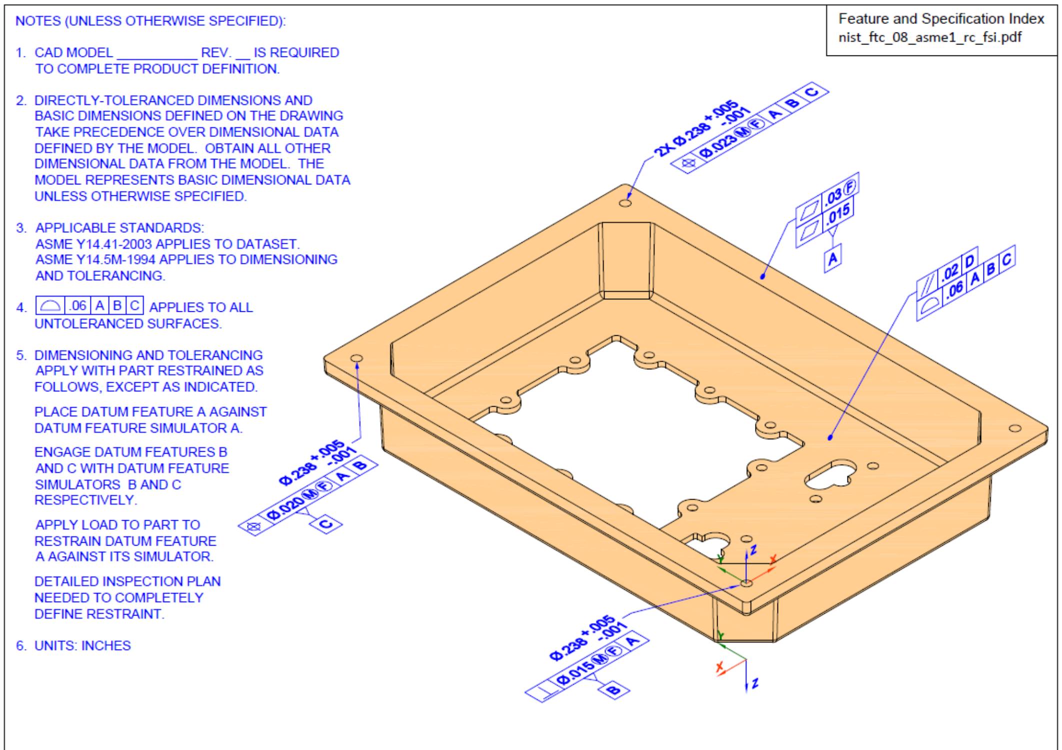
LEGEND	
CS	Coordinate System
D	Dimension
DF	Datum Feature
DT	Datum Target
RLE	Represented Line Element
SIELD	PMI entity contains Semantically-Important Extension Line Direction
STR	String
T	Tolerance

Appendix B: Fully-toleranced Test Case Drawings





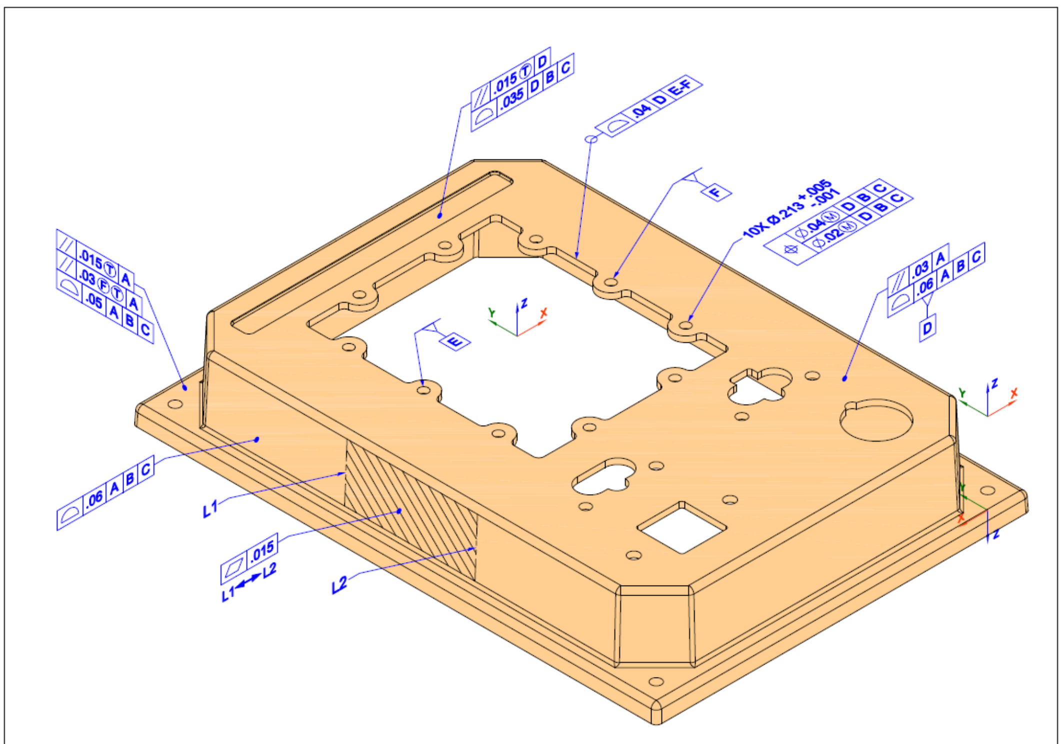

View Rotated 45°
(1.106)
(1.106)
.500 ±.008
.025 D C J
.500 ±.008
.025 D C K
J1
J2
K1
K2
.05 D B C
.01 D
2 SURFACES
.05 D B C
.01 D
2 SURFACES
Ø.250 ±.008
.50 ±.05
Ø.015 D G
Ø.250 ±.008
.50 ±.05
Ø.015 D H
(Ø1.000)
(Ø1.000)
G1
H1
PMI Fully-Toleranced Test Case 6 - View C
Includes Atomic Test Cases - 73, 80
Rev D



PMI Fully-Toleranced Test Case 8 - View A

Includes Atomic Test Cases - 66, 90

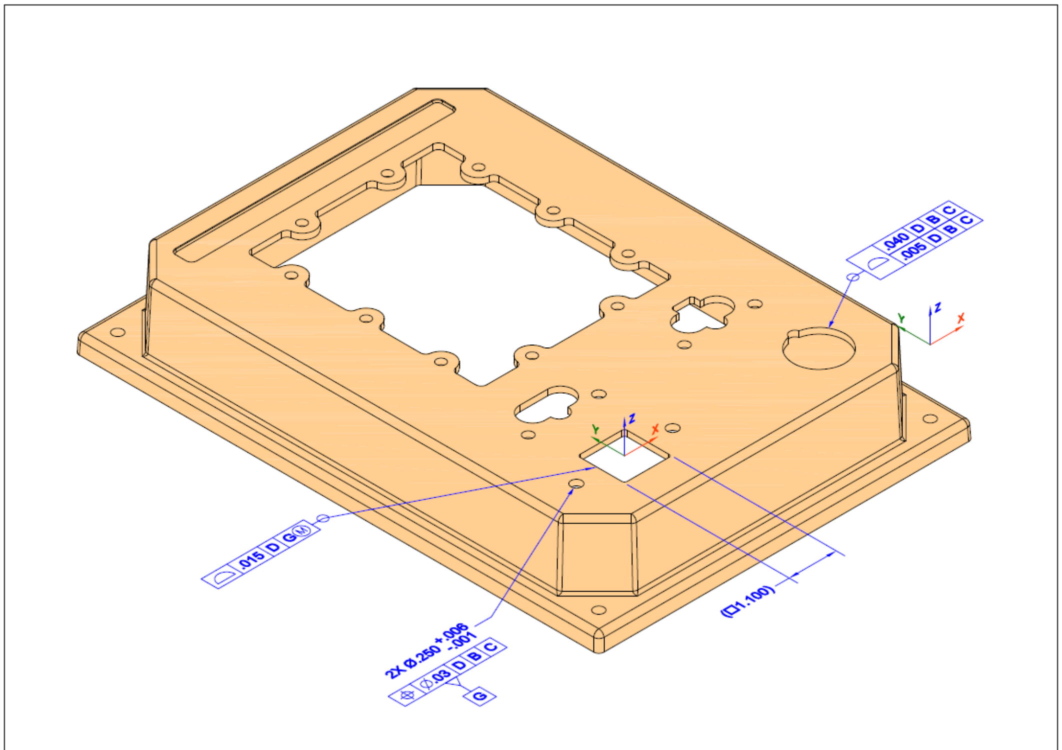
Rev C



PMI Fully-Toleranced Test Case 8 - View B

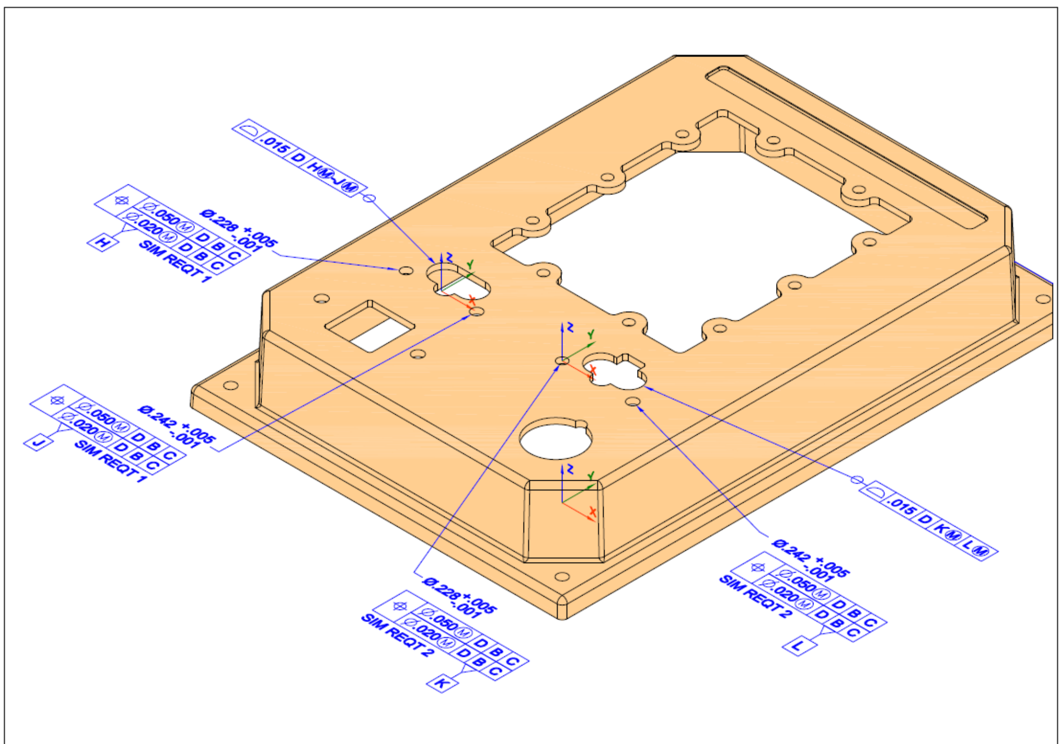
Includes Atomic Test Cases - 68, 76, 94

Rev C



PMI Fully-Toleranced Test Case 8 - View C
Includes Atomic Test Cases - 54

Rev C



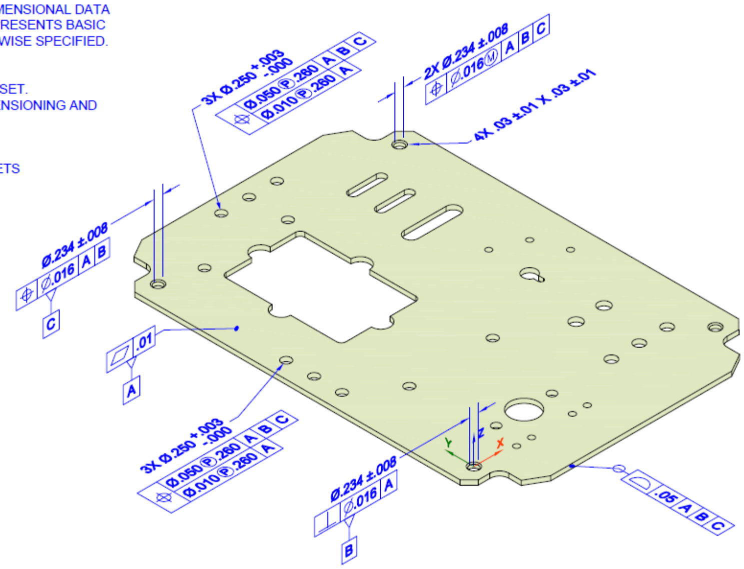
PMI Fully-Toleranced Test Case 8 - View D
Includes Atomic Test Cases - 76, 77, 99

Rev C

NOTES (UNLESS OTHERWISE SPECIFIED):

1. CAD MODEL ___________ REV. __ IS REQUIRED TO COMPLETE PRODUCT DEFINITION.
2. DIRECTLY-TOLERANCED DIMENSIONS AND BASIC DIMENSIONS DEFINED ON THE DRAWING TAKE PRECEDENCE OVER DIMENSIONAL DATA DEFINED BY THE MODEL. OBTAIN ALL OTHER DIMENSIONAL DATA FROM THE MODEL. THE MODEL REPRESENTS BASIC DIMENSIONAL DATA UNLESS OTHERWISE SPECIFIED.
3. APPLICABLE STANDARDS:
   ASME Y14.41-2003 APPLIES TO DATASET.
   ASME Y14.5M-1994 APPLIES TO DIMENSIONING AND TOLERANCING.
4. DIMENSION AND TOLERANCE VALUES SHOWN IN SQUARE BRACKETS [XXX] ARE MILLIMETERS.
5. MATERIAL: (.1195 THICK) 11 GA 304 SST SHT, ASTM A240.
6. UNITS: INCHES

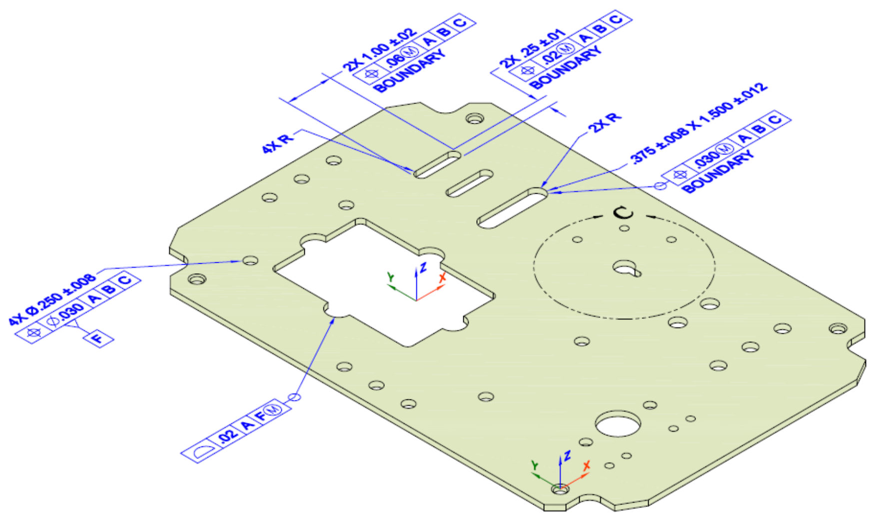
Feature and Specification Index
nist_ftc_09_asme1_rd_fsi.pdf



PMI Fully-Toleranced Test Case 9 - View A

Includes Atomic Test Cases - 59, 61

Rev D



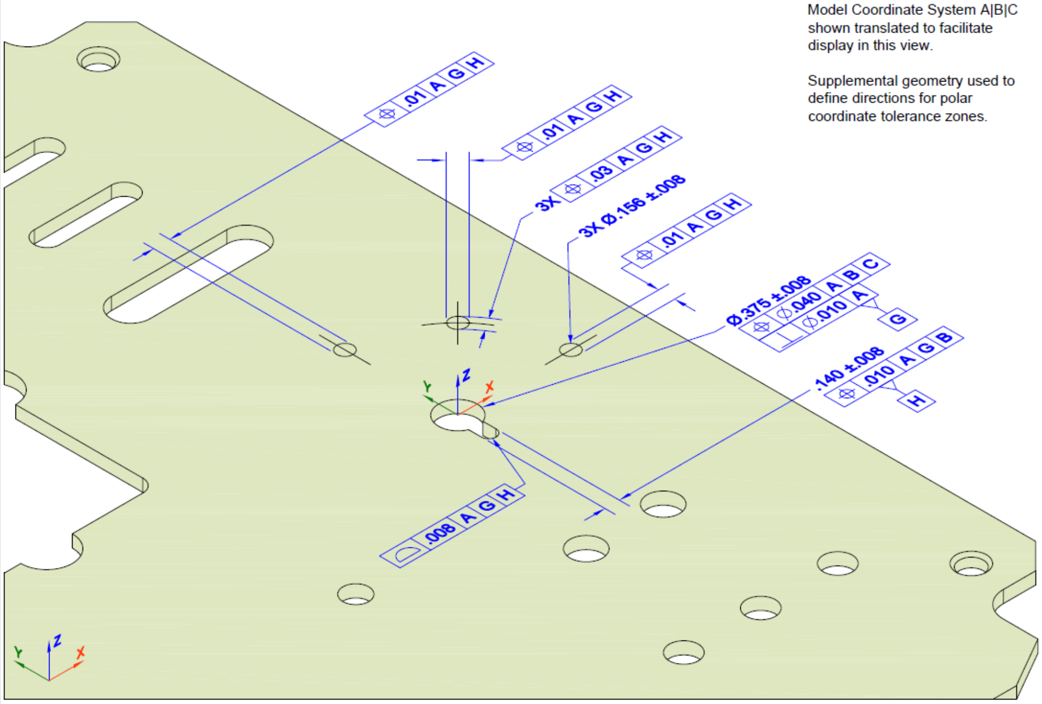
PMI Fully-Toleranced Test Case 9 - View B

Includes Atomic Test Cases - 75, 96, 97

Rev D

Notes -
Model Coordinate System A|B|C shown translated to facilitate display in this view.

Supplemental geometry used to define directions for polar coordinate tolerance zones.

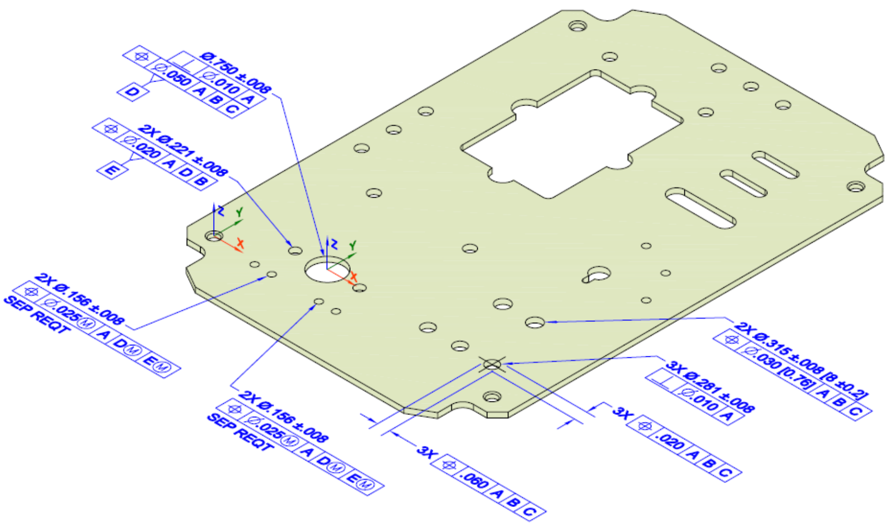


PMI Fully-Toleranced Test Case 9 - View C
Includes Atomic Test Cases - 82

Rev D

Notes -
Dual units used for 2X Ø.315 holes.

Supplemental geometry used to define directions for rectangular coordinate tolerance zones.



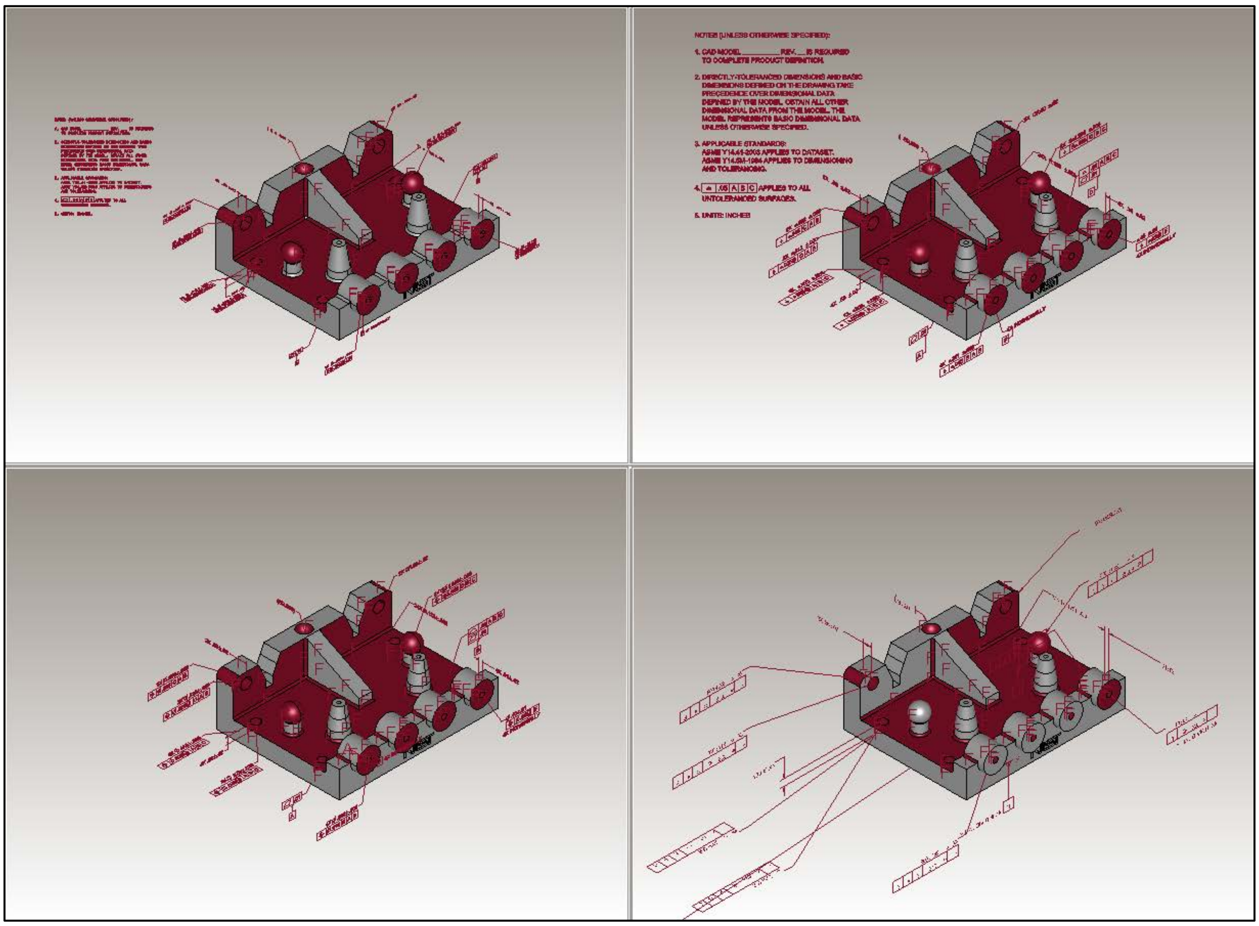
PMI Fully-Toleranced Test Case 9 - View D
Includes Atomic Test Cases - 81, 95, 98

Rev D

Appendix C: Test Model Images

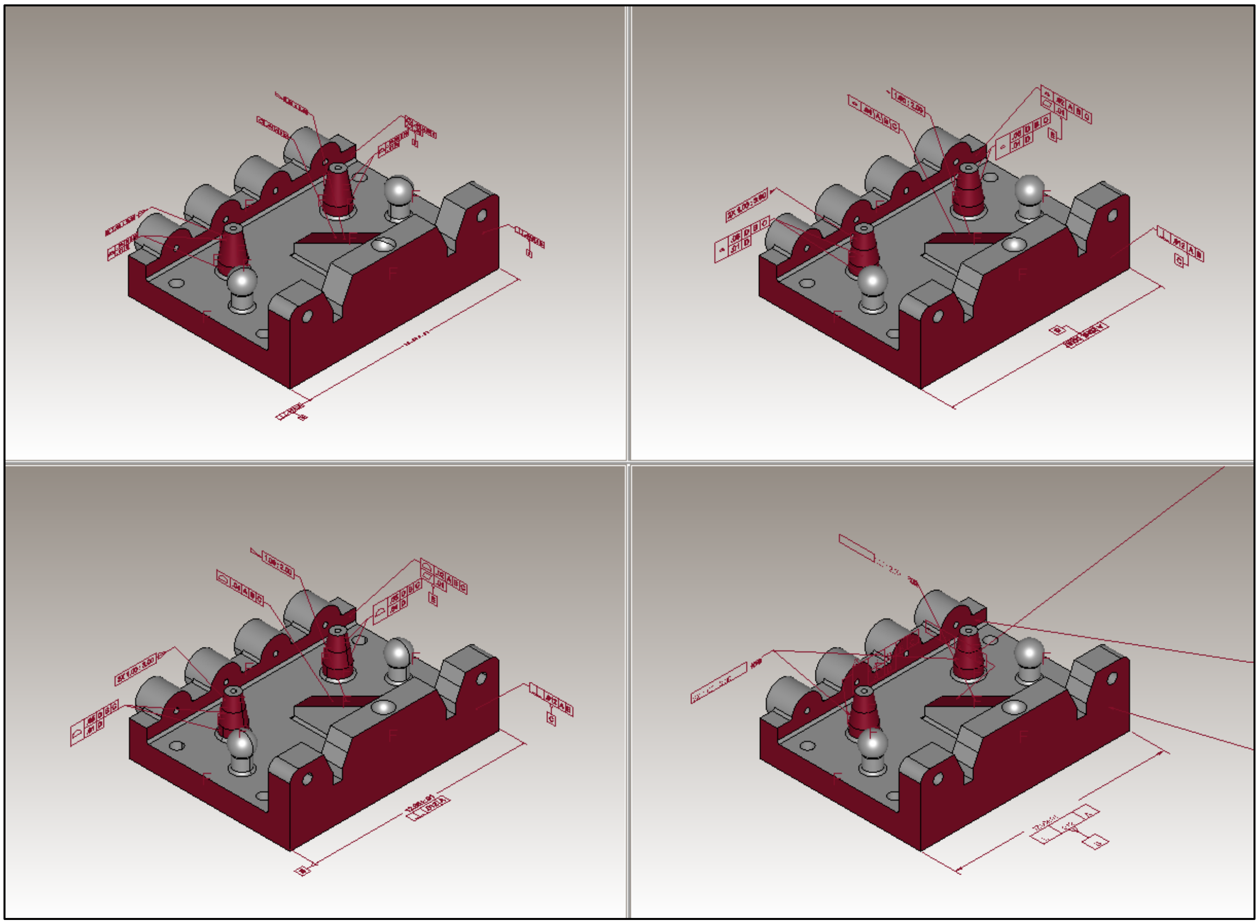
Fully-Toleranced Test Case 6
Saved View MBD_A

- Clockwise from upper left - Test Models for CATIA V5 R24, NX 9.0, SOLIDWORKS 2015 and Creo 3.0
- Screenshot is of each test model displayed in CADIQ
- Annotations and their associated geometry are highlighted in red



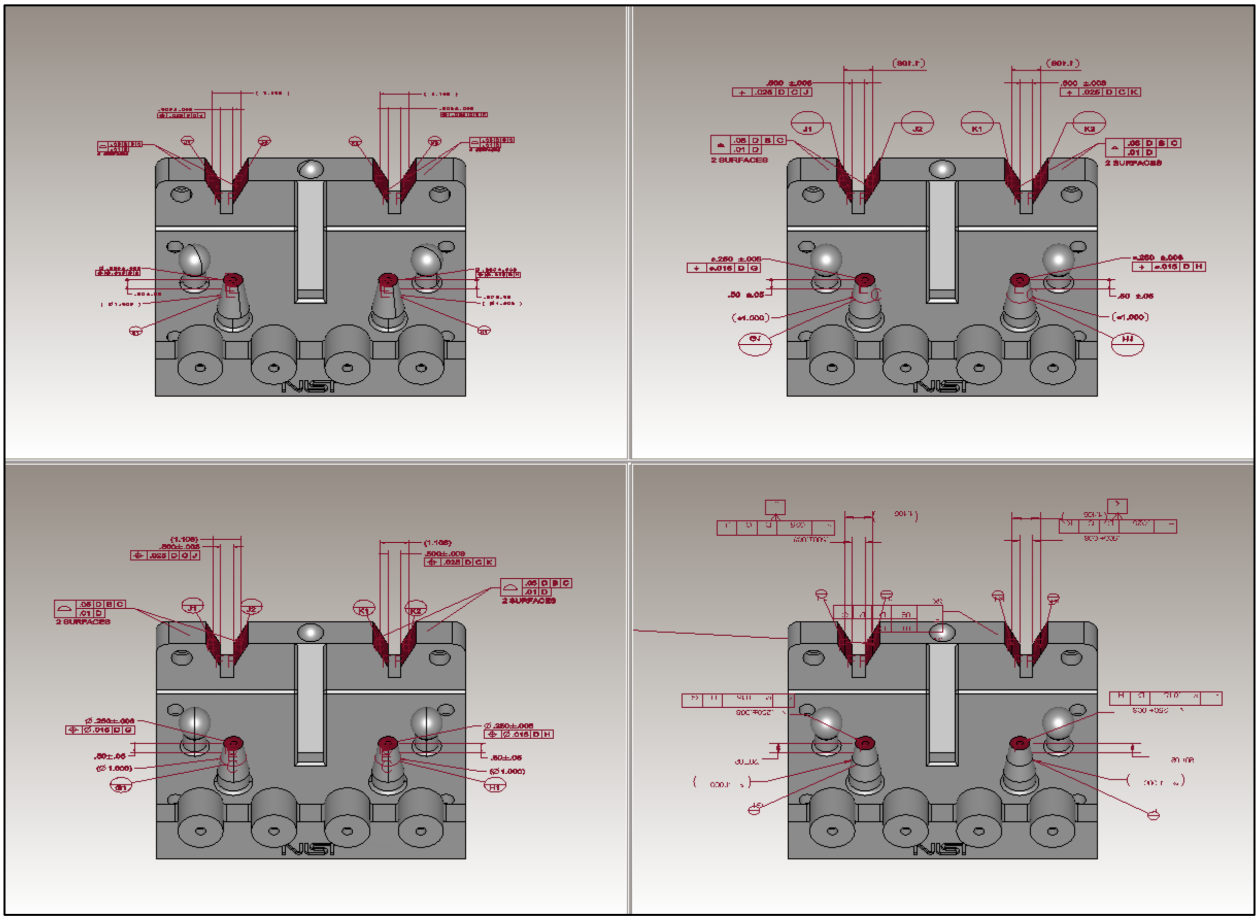
Fully-Toleranced Test Case 6
Saved View MBD_B

- Clockwise from upper left - Test Models for CATIA V5 R24, NX 9.0, SOLIDWORKS 2015 and Creo 3.0
- Screenshot is of each test model displayed in CADIQ
- Annotations and their associated geometry are highlighted in red



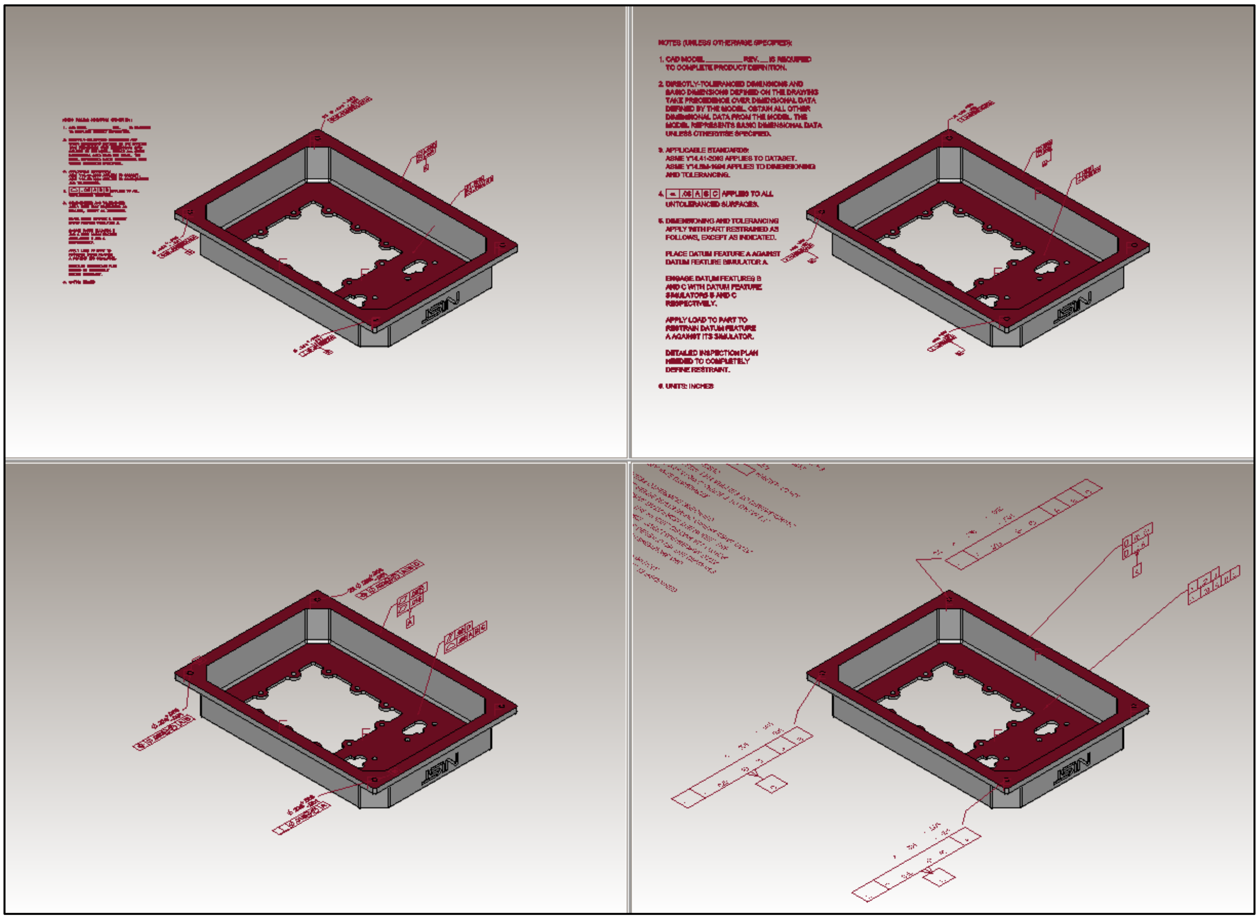
Fully-Toleranced Test Case 6
Saved View MBD_C

- Clockwise from upper left - Test Models for CATIA V5 R24, NX 9.0, SOLIDWORKS 2015 and Creo 3.0
- Screenshot is of each test model displayed in CADIQ
- Annotations and their associated geometry are highlighted in red



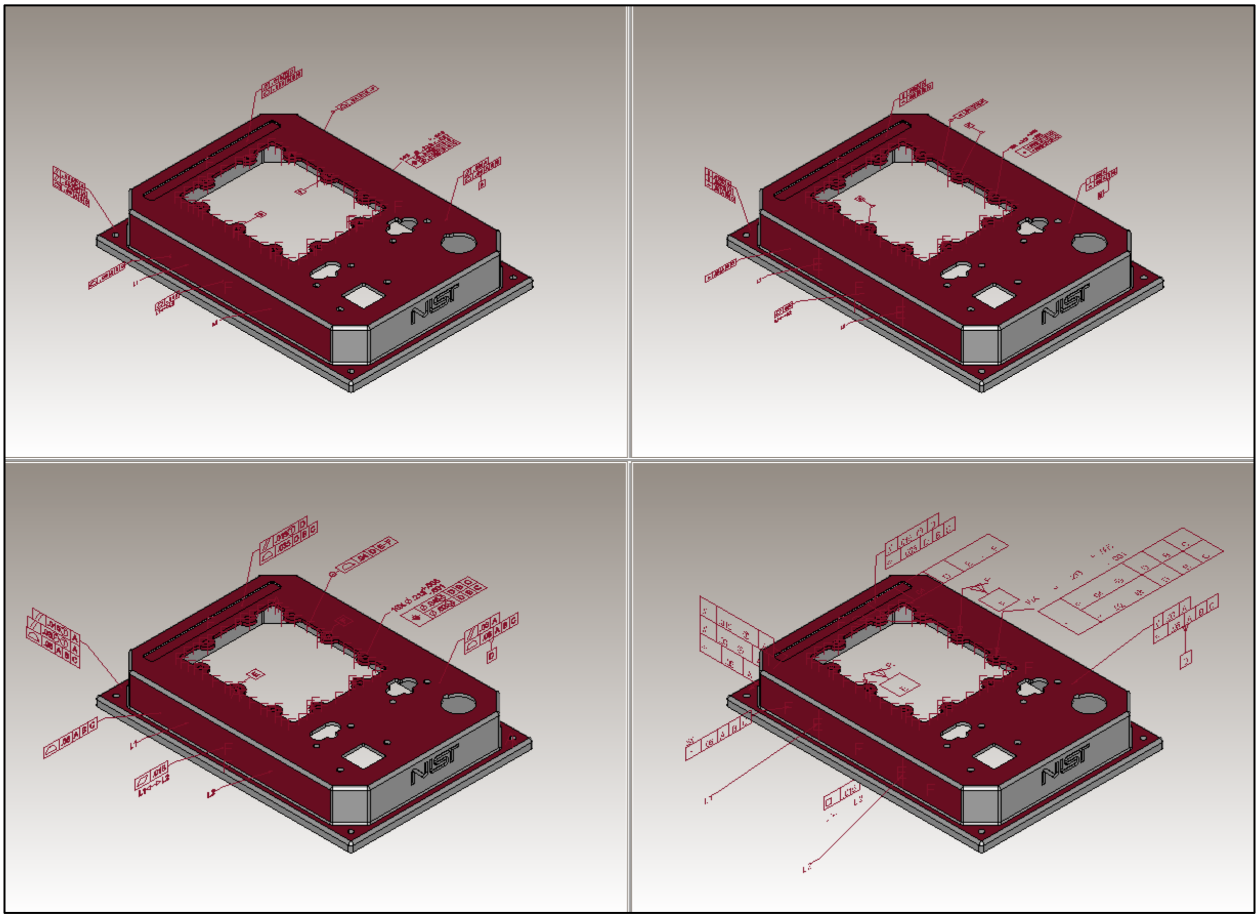
Fully-Toleranced Test Case 8
Saved View MBD_A

- Clockwise from upper left - Test Models for CATIA V5 R24, NX 9.0, SOLIDWORKS 2015 and Creo 3.0
- Screenshot is of each test model displayed in CADIQ
- Annotations and their associated geometry are highlighted in red



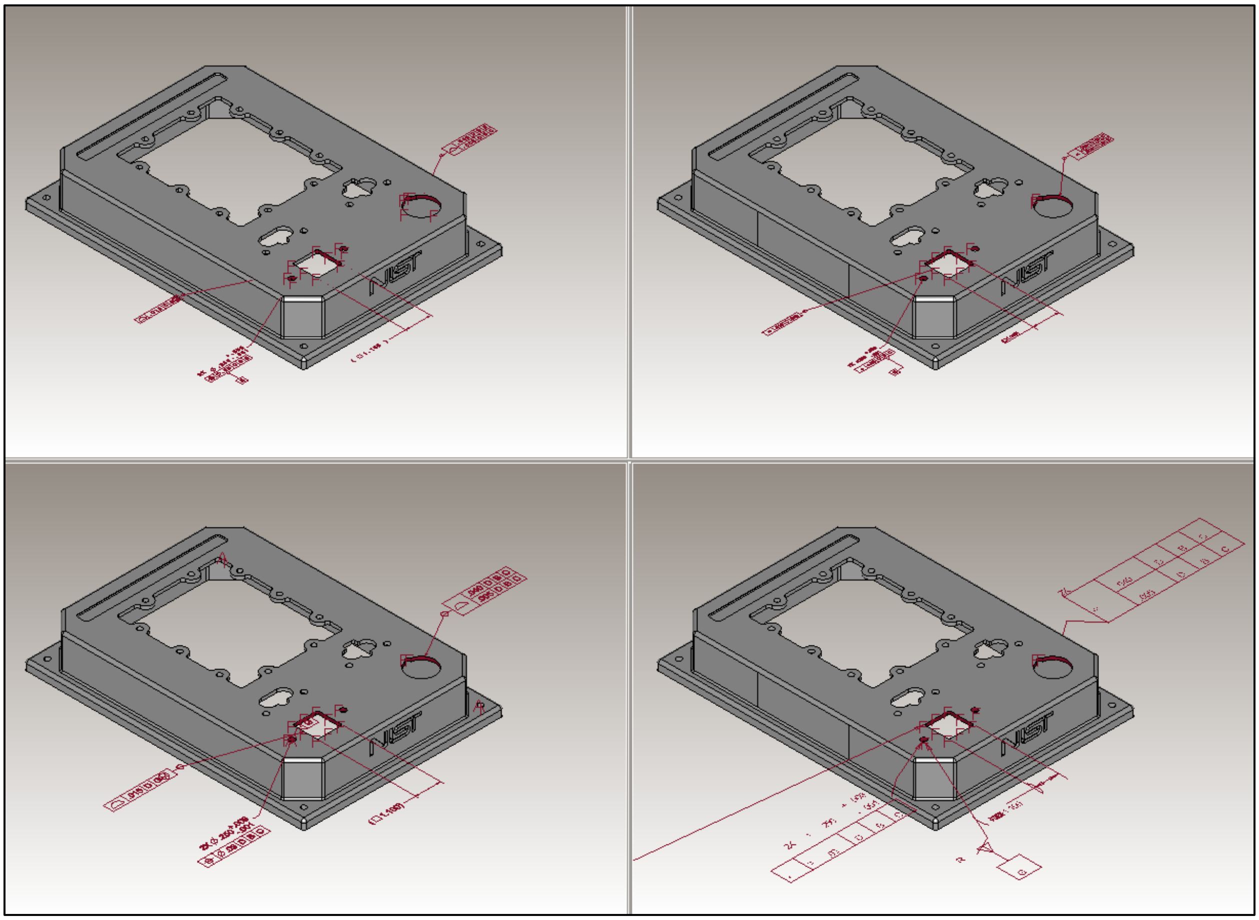
Fully-Toleranced Test Case 8
Saved View MBD_B

- Clockwise from upper left - Test Models for CATIA V5 R24, NX 9.0, SOLIDWORKS 2015 and Creo 3.0
- Screenshot is of each test model displayed in CADIQ
- Annotations and their associated geometry are highlighted in red



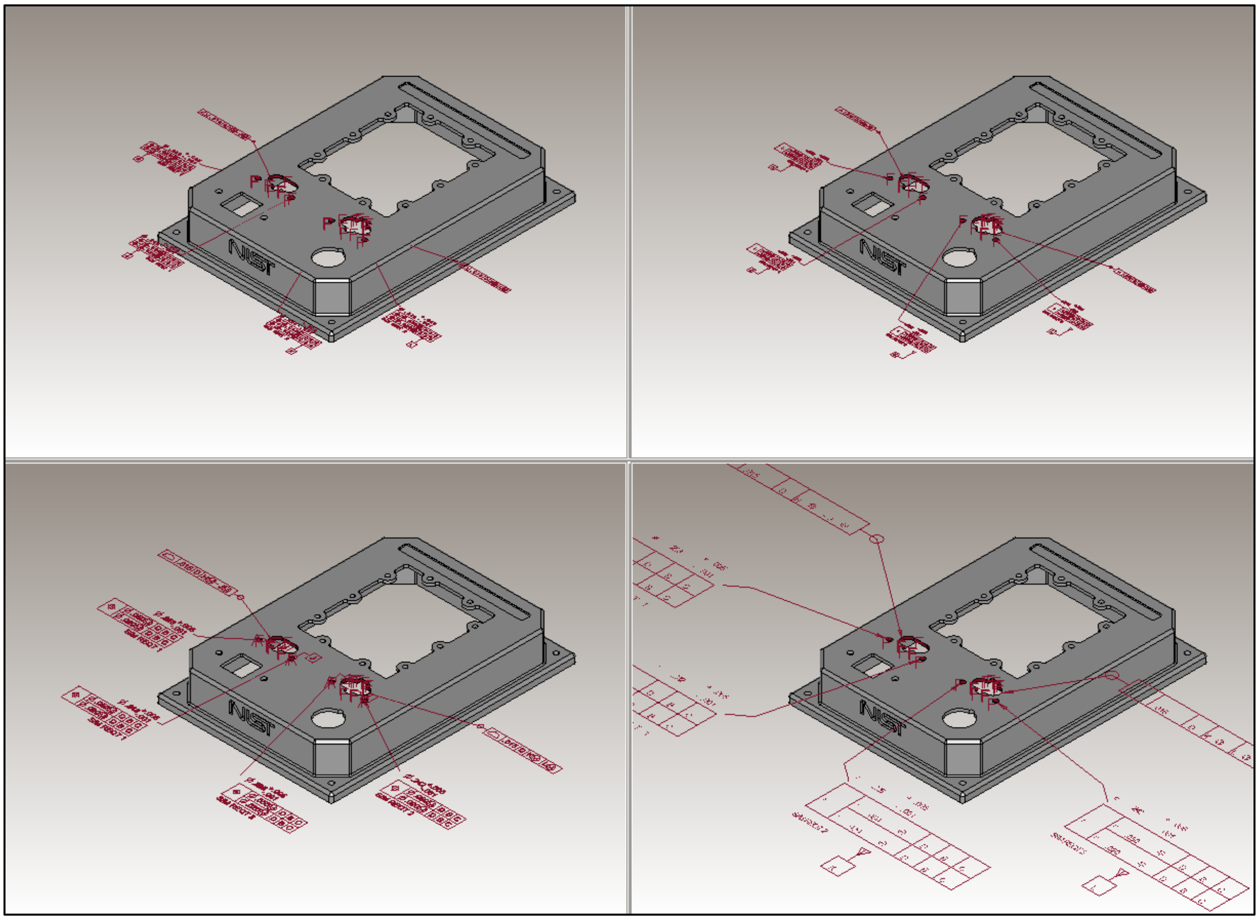
Fully-Toleranced Test Case 8
Saved View MBD_C

- Clockwise from upper left - Test Models for CATIA V5 R24, NX 9.0, SOLIDWORKS 2015 and Creo 3.0
- Screenshot is of each test model displayed in CADIQ
- Annotations and their associated geometry are highlighted in red



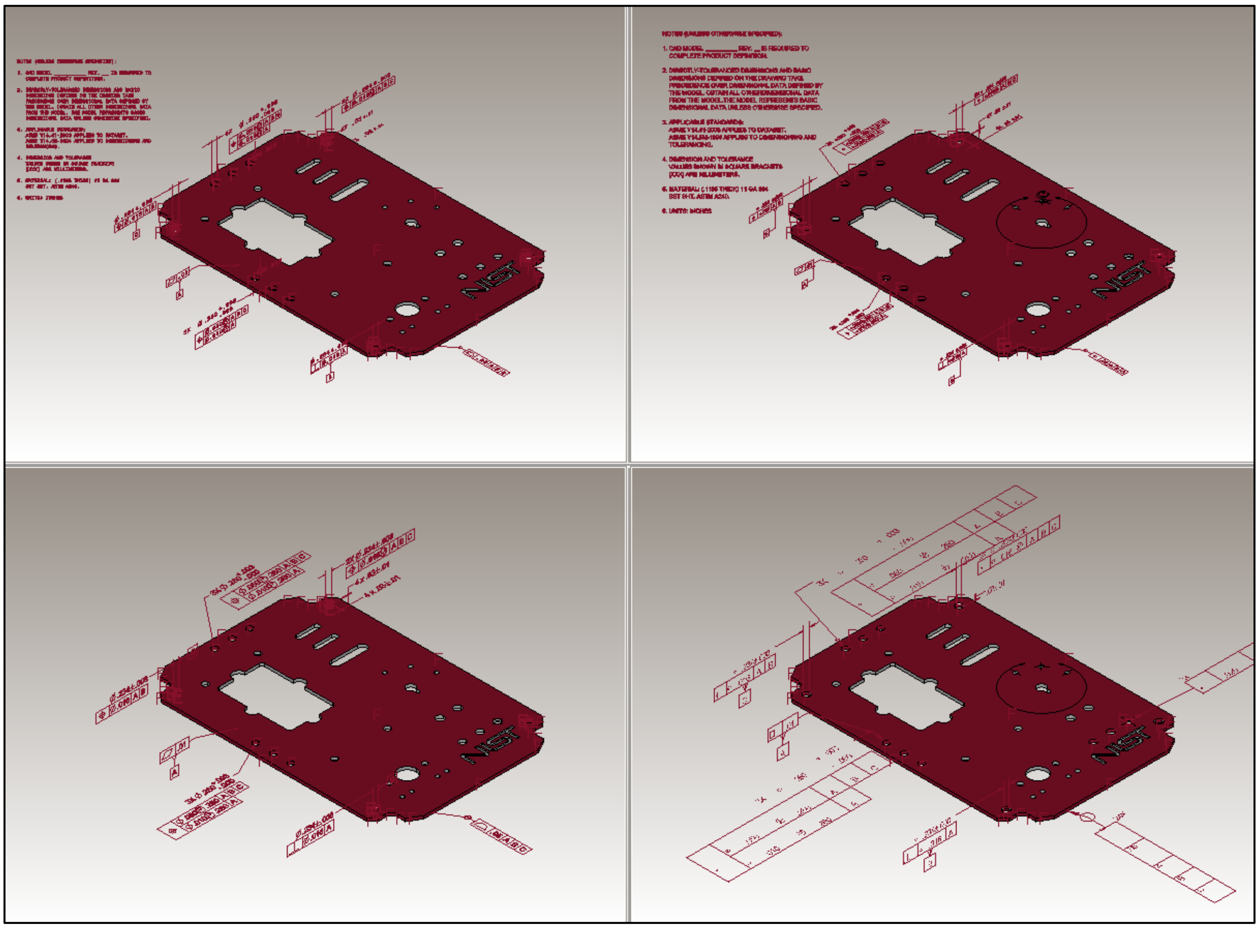
Fully-Toleranced Test Case 8
Saved View MBD_D

- Clockwise from upper left - Test Models for CATIA V5 R24, NX 9.0, SOLIDWORKS 2015 and Creo 3.0
- Screenshot is of each test model displayed in CADIQ
- Annotations and their associated geometry are highlighted in red



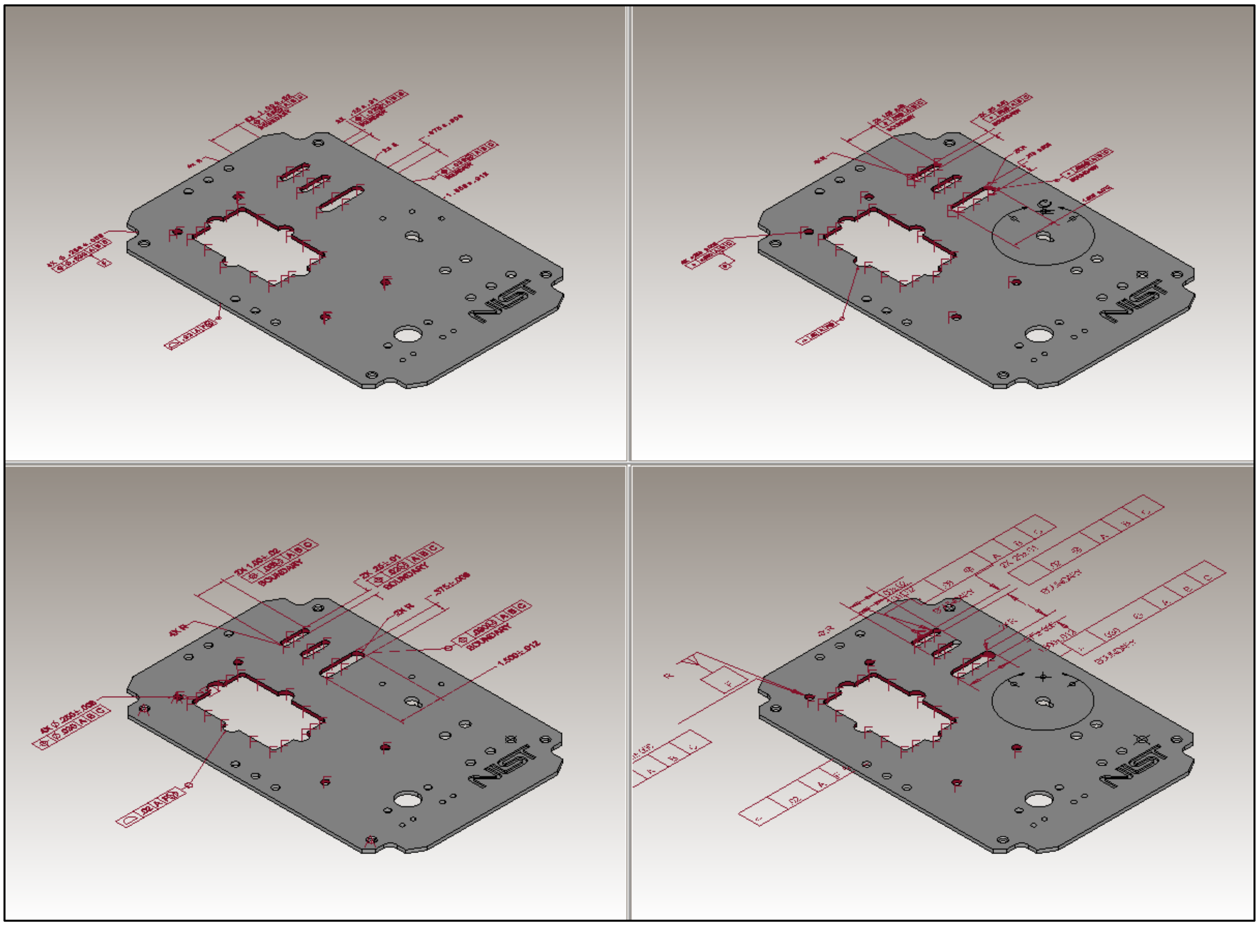
Fully-Toleranced Test Case 9
Saved View MBD_A

- Clockwise from upper left - Test Models for CATIA V5 R24, NX 9.0, SOLIDWORKS 2015 and Creo 3.0
- Screenshot is of each test model displayed in CADIQ
- Annotations and their associated geometry are highlighted in red



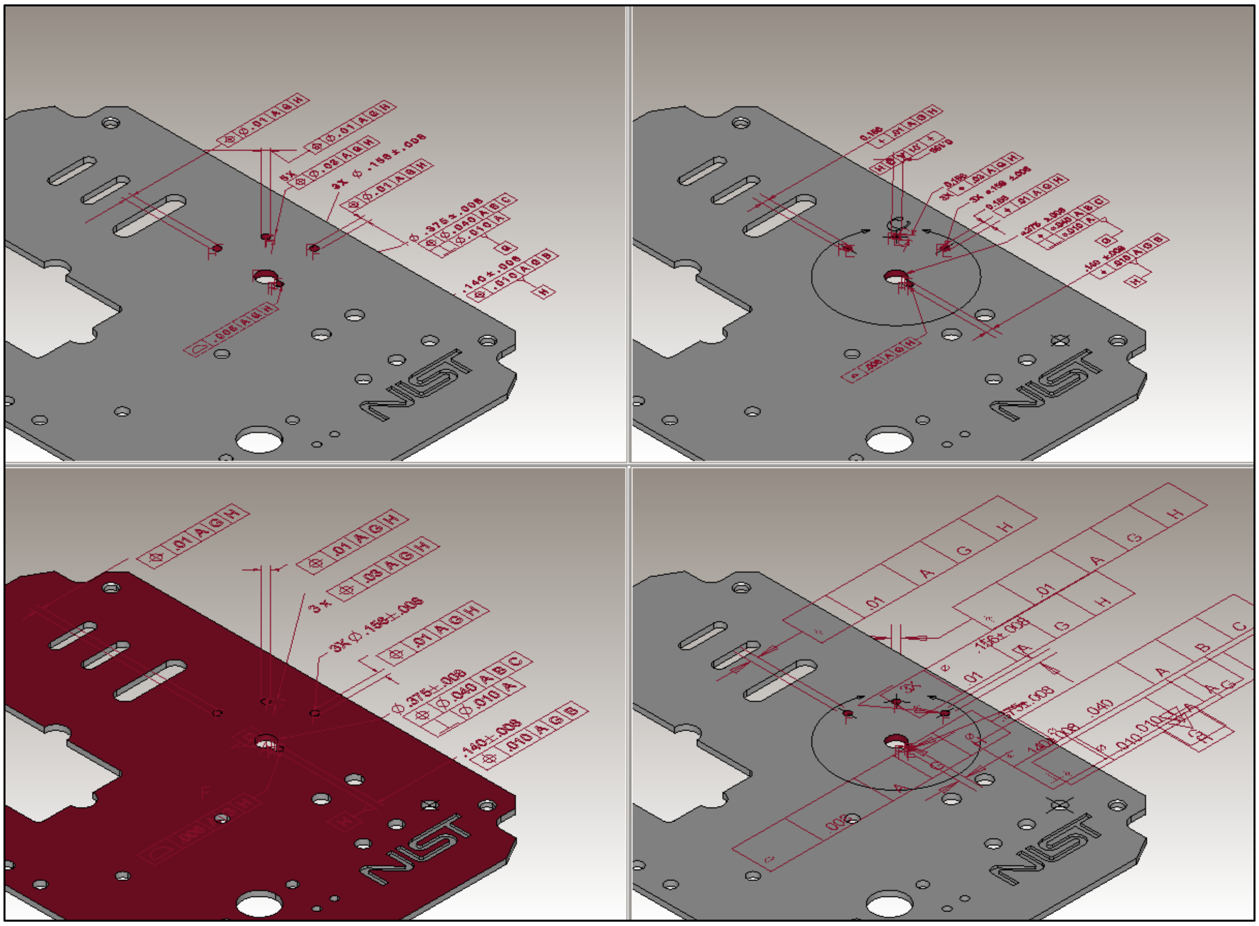
Fully-Toleranced Test Case 9
Saved View MBD_B

- Clockwise from upper left - Test Models for CATIA V5 R24, NX 9.0, SOLIDWORKS 2015 and Creo 3.0
- Screenshot is of each test model displayed in CADIQ
- Annotations and their associated geometry are highlighted in red



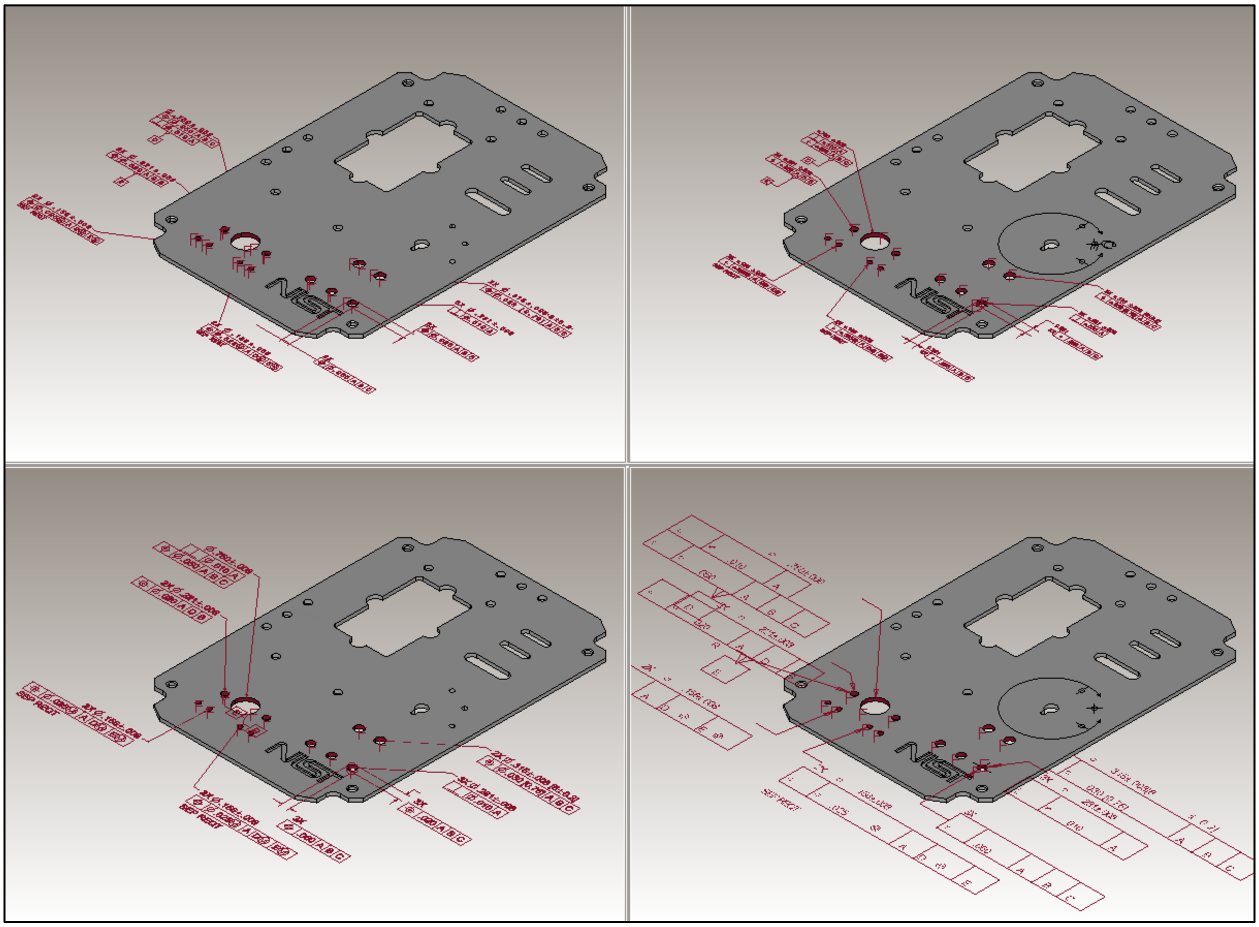
Fully-Toleranced Test Case 9
Saved View MBD_C

- Clockwise from upper left - Test Models for CATIA V5 R24, NX 9.0, SOLIDWORKS 2015 and Creo 3.0
- Screenshot is of each test model displayed in CADIQ
- Annotations and their associated geometry are highlighted in red



Fully-Toleranced Test Case 9
Saved View MBD_D

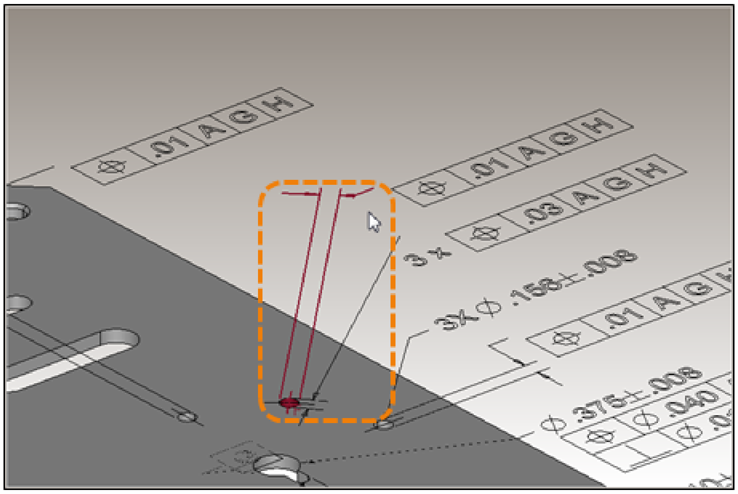
- Clockwise from upper left - Test Models for CATIA V5 R24, NX 9.0, SOLIDWORKS 2015 and Creo 3.0
- Screenshot is of each test model displayed in CADIQ
- Annotations and their associated geometry are highlighted in red



Appendix D: Representation Limitation Examples

Representation Limitation

Annotation Structure:
FCF extension lines defined as separate DIM

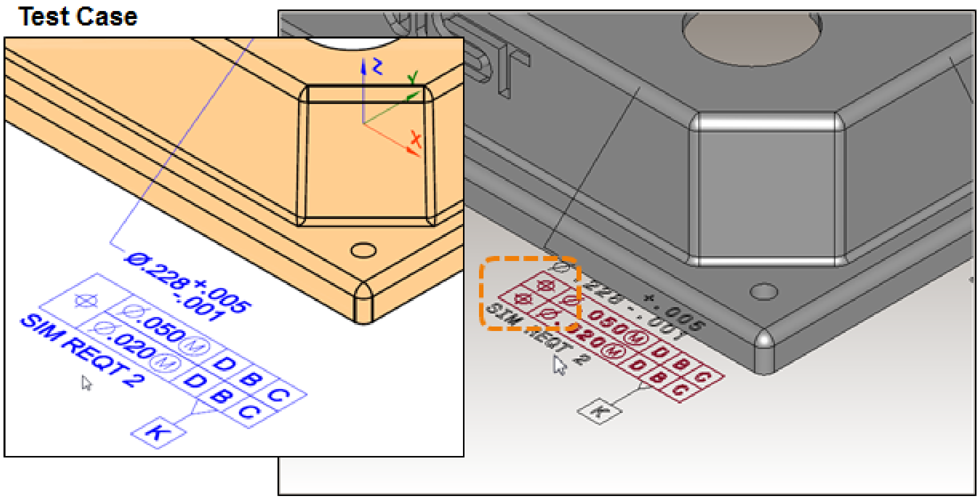


These extension lines are defined as a separate dimension that has no displayed value.

Representation Limitation

Annotation Structure:
FCF missing composite layout

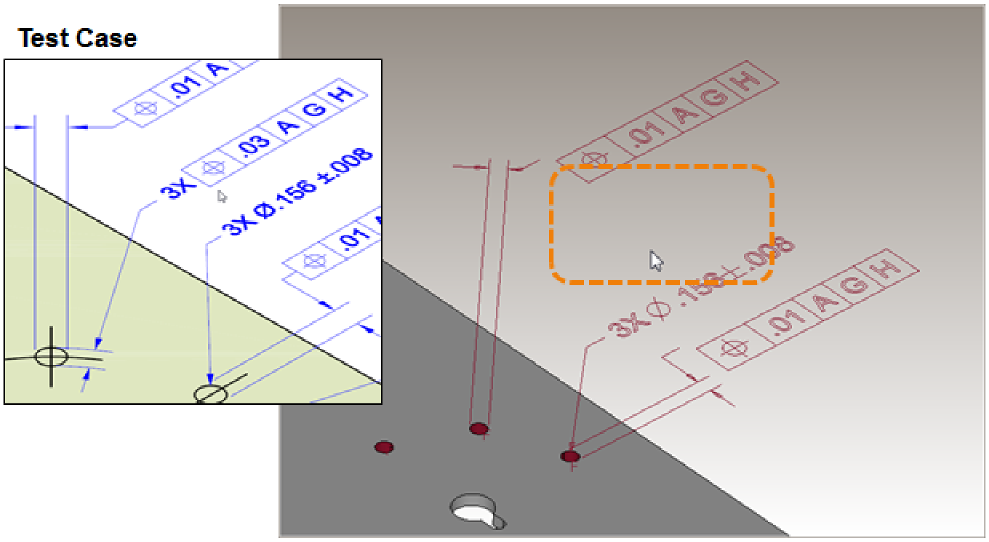
Test Case



This feature control frame lacks the specified composite layout.

Annotation Structure: FCF not defined

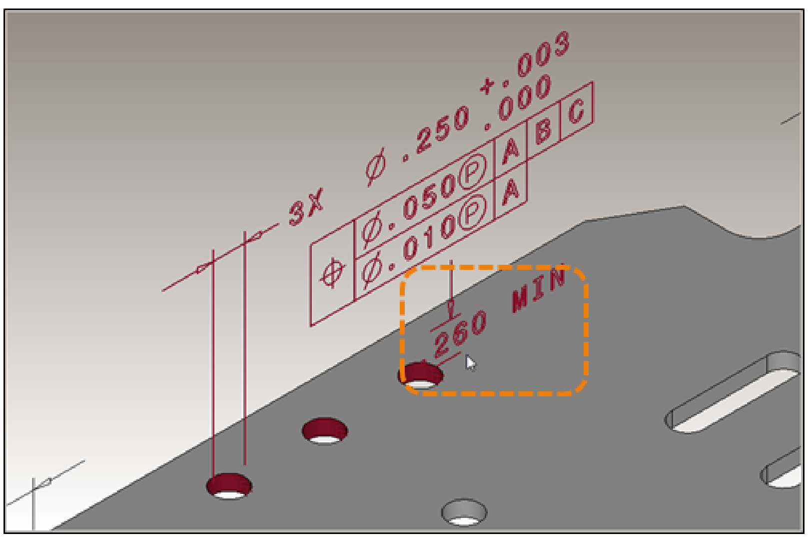
Representation Limitation



This specified feature control frame is defined.

Annotation Structure: FCF projected tolerance zone defined as separate DIM

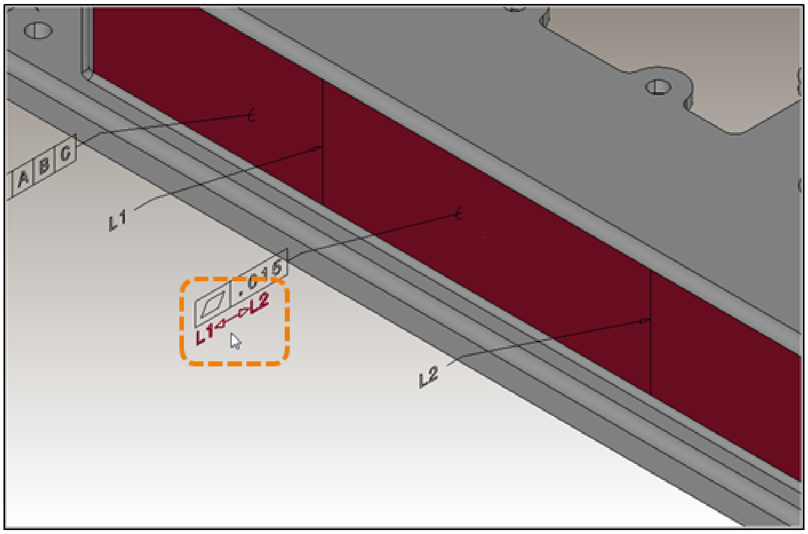
Representation Limitation



The length of the projected tolerance zone for this feature control frame is defined as a separate dimension.

Annotation Structure: FCF text defined as separate note

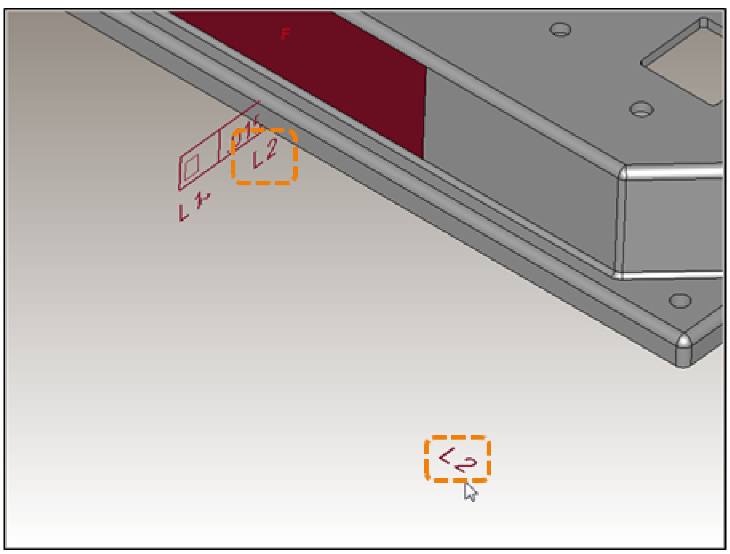
Representation Limitation



The text which defines the between-basis for this feature control frame is defined as a separate note annotation.

Annotation Structure: FCF text duplicated

Representation Limitation

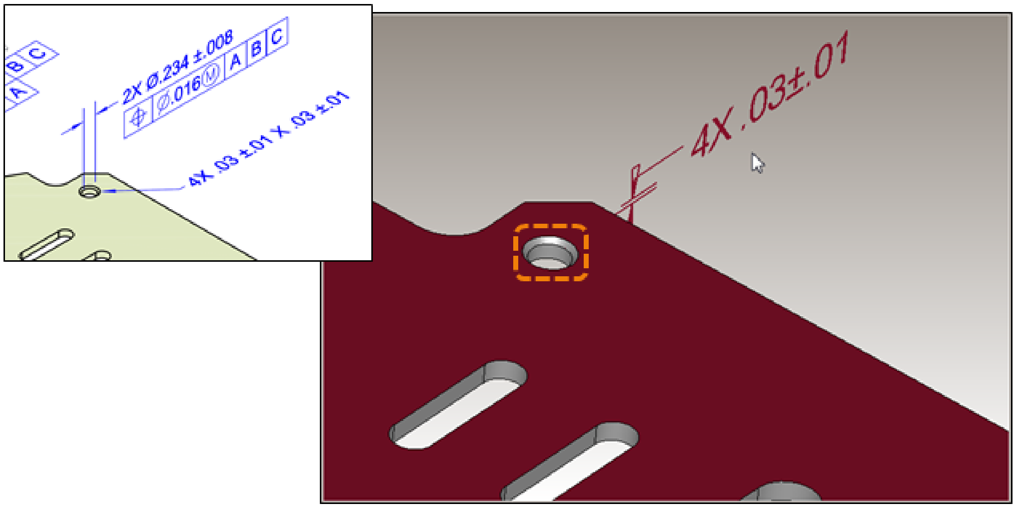


This annotation text is defined twice in the model.

Annotation Parameters: Chamfer DIM width not defined

Representation Limitation

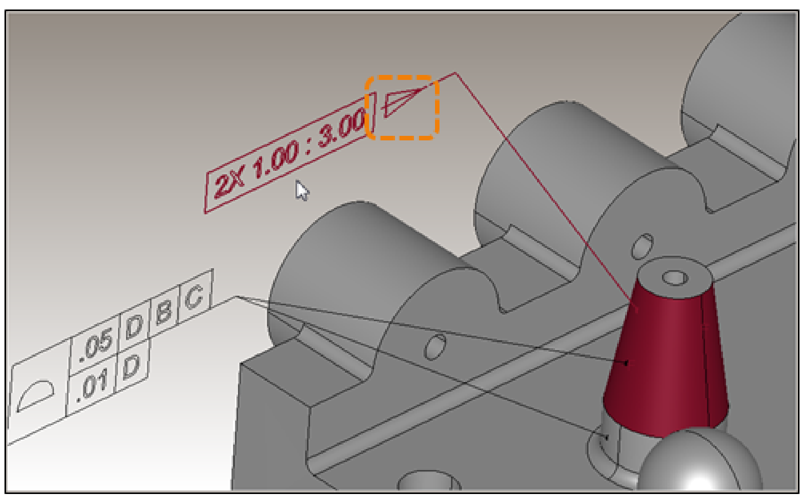
Test Case



This chamfer is missing the dimension that defines its width.

Annotation Parameters: DIM conic surfaces defined with encoded text

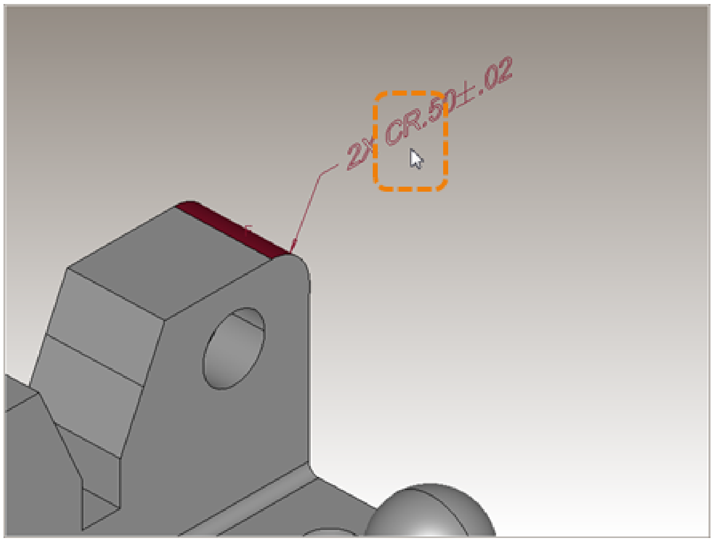
Representation Limitation



The conic surfaces portion of this dimension is defined using encoded text.

Annotation Parameters: DIM controlled radius defined with encoded text

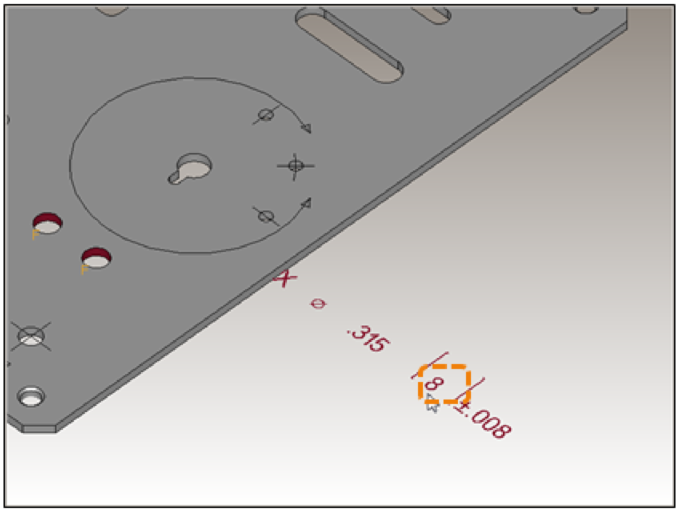
Representation Limitation



The controlled radius parameter of this dimension is defined using encoded text.

Annotation Parameters: DIM missing dual dimension tolerance

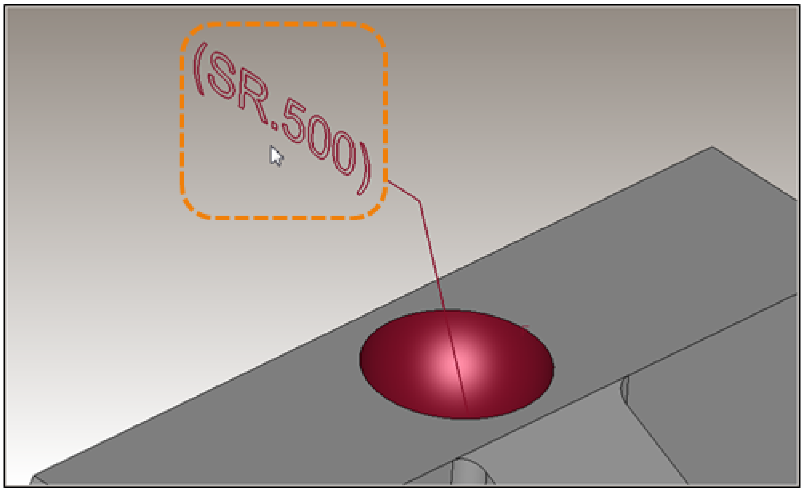
Representation Limitation



This dual dimension is missing a tolerance value.

Representation Limitation

Annotation Parameters:
DIM not defined as reference DIM



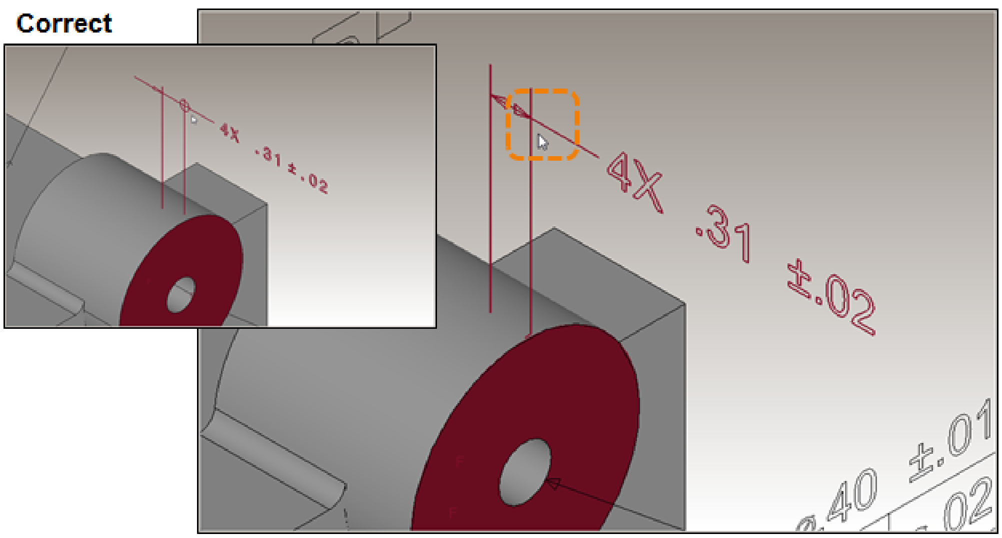
This dimension has parentheses, as specified, but is not defined as a reference dimension.

Representation Limitation

Annotation Parameters:
DIM origin not defined

Incorrect

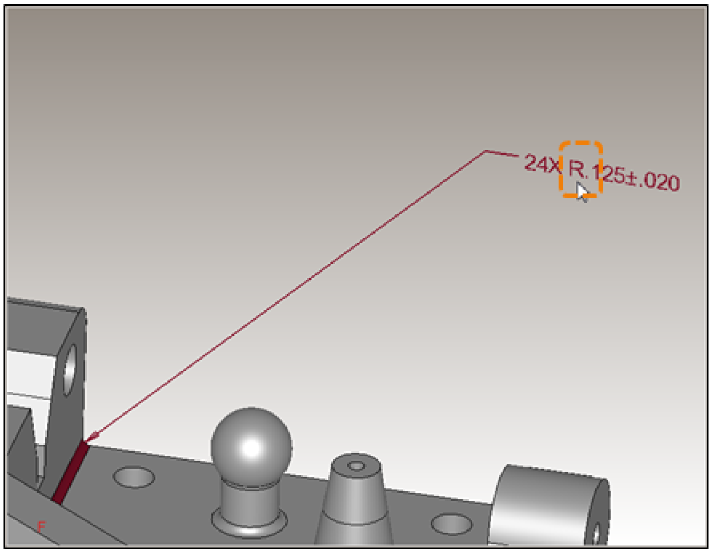
Correct



The origin for this oriented dimension is not defined.

Annotation Parameters: DIM radius defined with encoded text

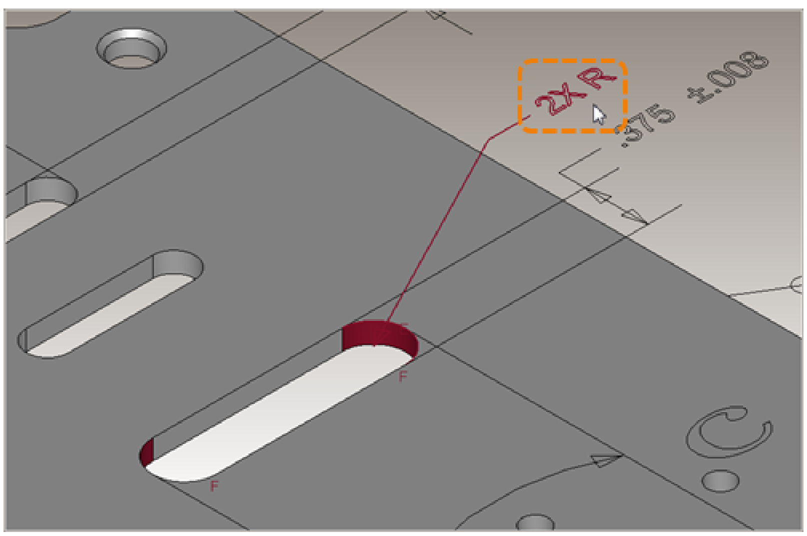
Representation Limitation



The radius parameter of this dimension is defined using encoded text.

Annotation Parameters: DIM slot radius defined with encoded text

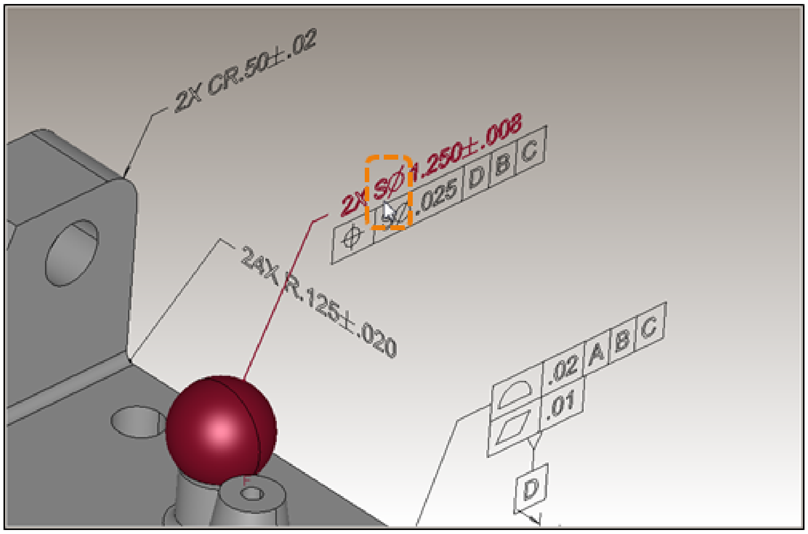
Representation Limitation



The radius parameter of this dimension is defined using encoded text.

Annotation Parameters: DIM spherical diameter defined with encoded text

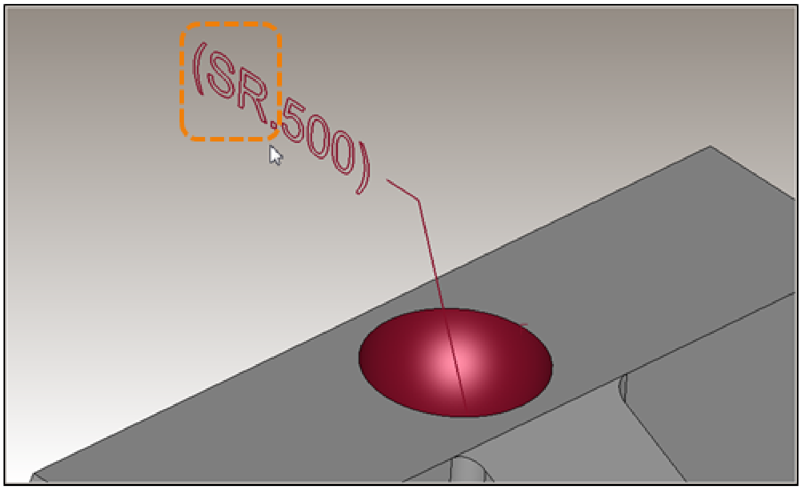
Representation Limitation



The spherical diameter parameter of this dimension is defined using encoded text.

Annotation Parameters: DIM spherical radius defined with encoded text

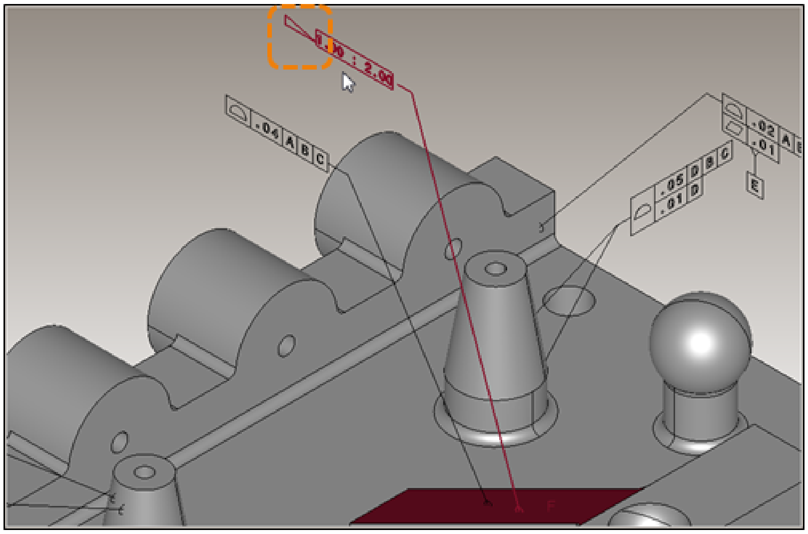
Representation Limitation



This spherical radius parameter of this dimension is defined using encoded text.

Representation Limitation

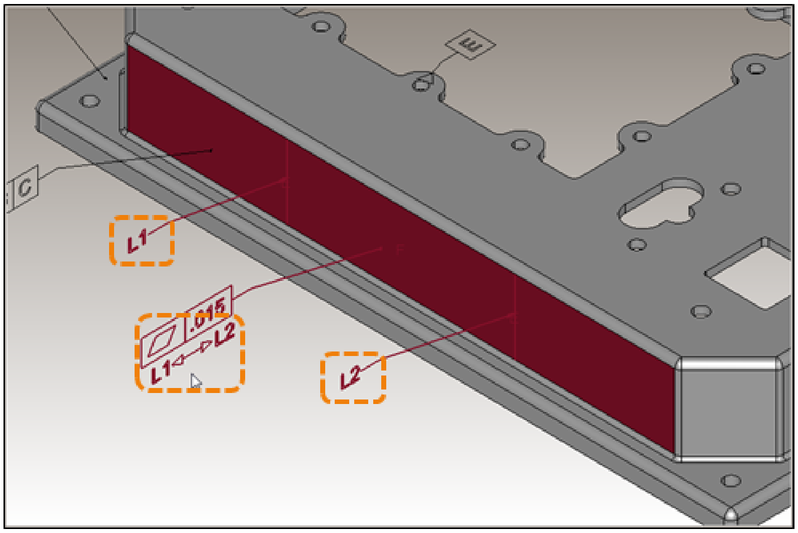
Annotation Parameters:
DIM tapered center defined with encoded text



The tapered center parameter of this dimension is defined using encoded text.

Representation Limitation

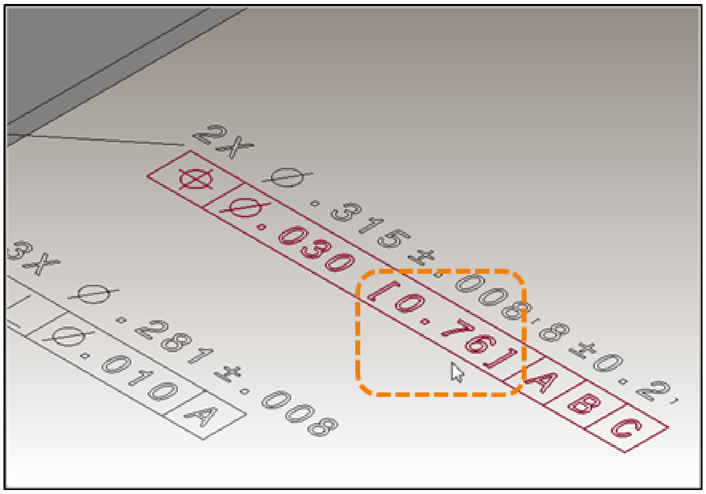
Annotation Parameters:
FCF between-basis defined with encoded text



The between-basis for this feature control frame is defined as encoded text and not with named parameters.

Representation Limitation

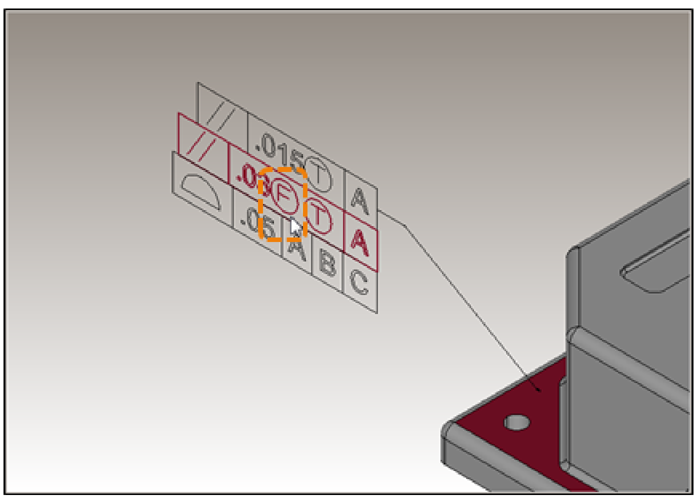
Annotation Parameters: FCF dual dimension defined with encoded text



This dual dimension is defined using encoded text.

Representation Limitation

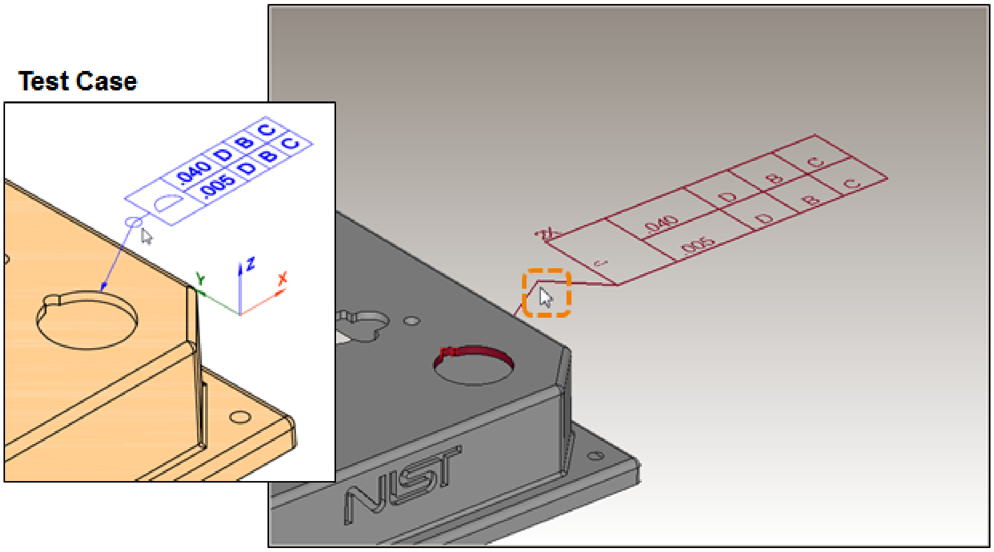
Annotation Parameters: FCF free state defined with encoded text



This free state tolerance modifier is defined using encoded text.

Representation Limitation

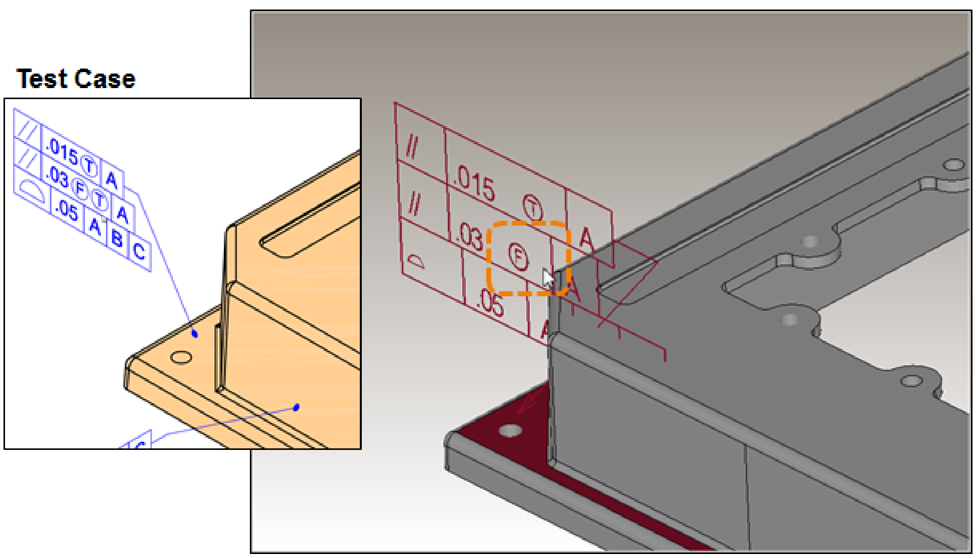
Annotation Parameters: FCF missing all-around designation



This feature control frame is missing an all-around symbol.

Representation Limitation

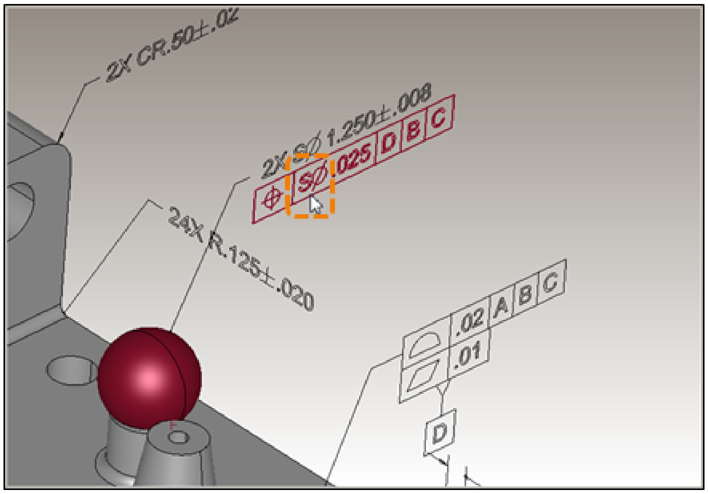
Annotation Parameters: FCF missing tangent plane modifier



This feature control frame is missing the specified tangent plane modifier.

Annotation Parameters: FCF spherical diameter defined with encoded text

Representation Limitation



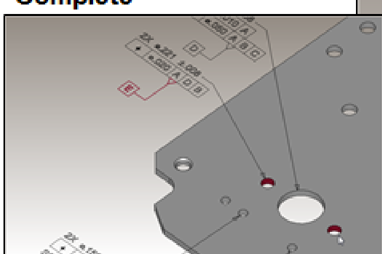
This spherical diameter tolerance zone symbol is defined using encoded text.

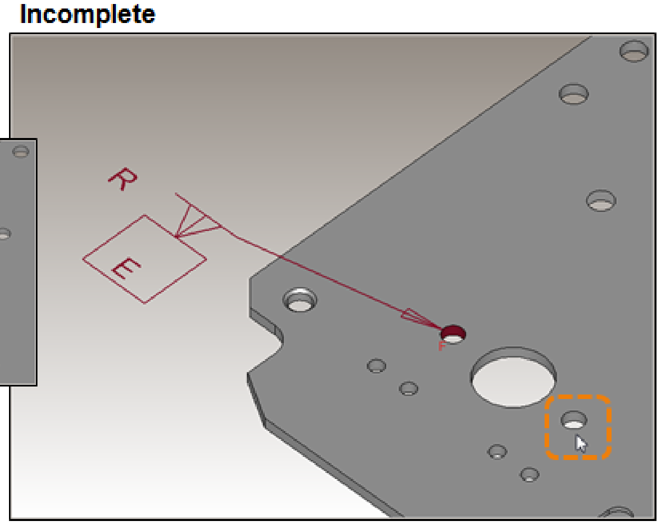
Annotation Geometry: DFS not associated with complete set of faces

Representation Limitation

Incomplete

Complete

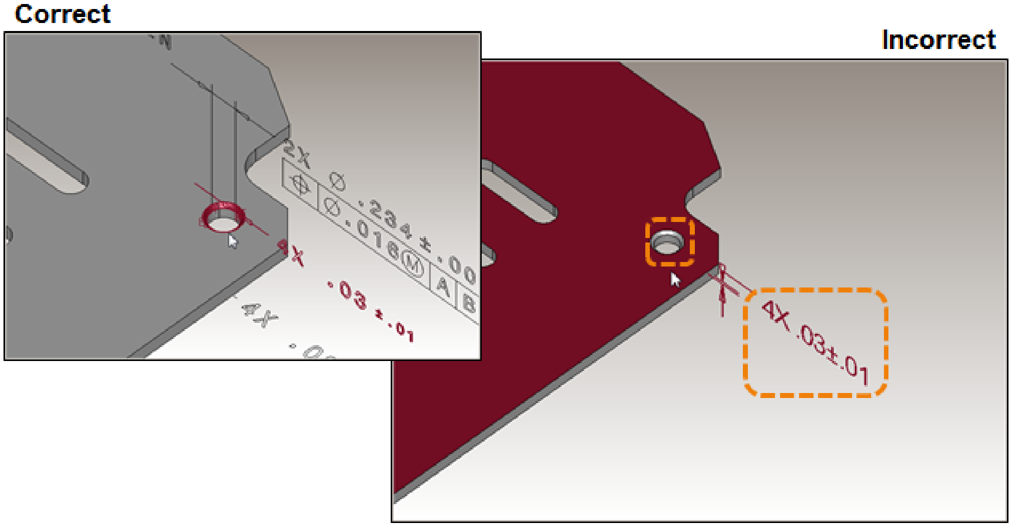




This datum feature symbol is not associated with all of the specified faces.

Annotation Geometry: DIM associated with incorrect face

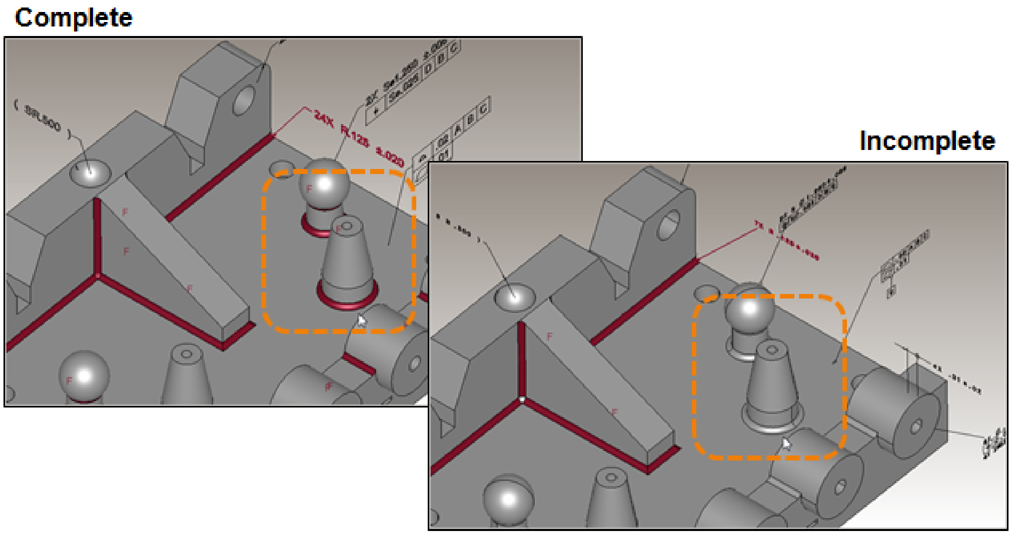
Representation Limitation



This dimension is not associated with the correct specified face.

Annotation Geometry: DIM not associated with complete set of faces

Representation Limitation



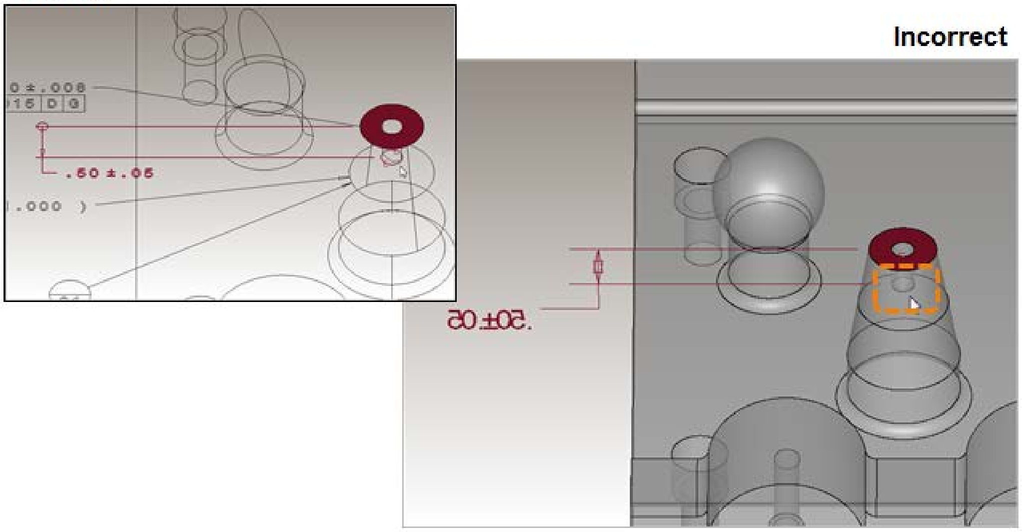
This dimension is only associated with some of the specified faces.

Annotation Geometry: DIM not associated with edge

Representation Limitation

Correct

Incorrect



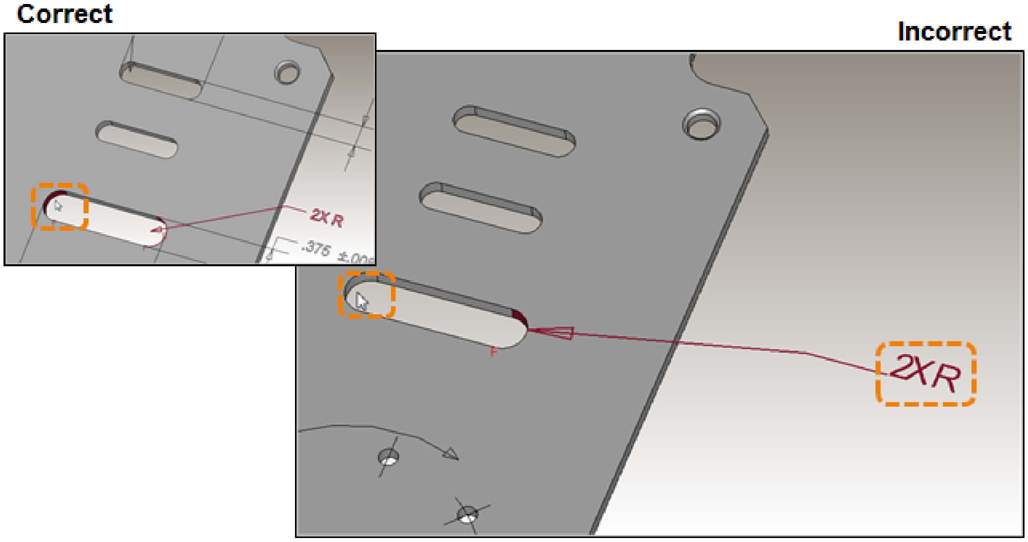
This dimension is not associated with the specified edge.

Annotation Geometry: DIM not associated with face

Representation Limitation

Correct

Incorrect



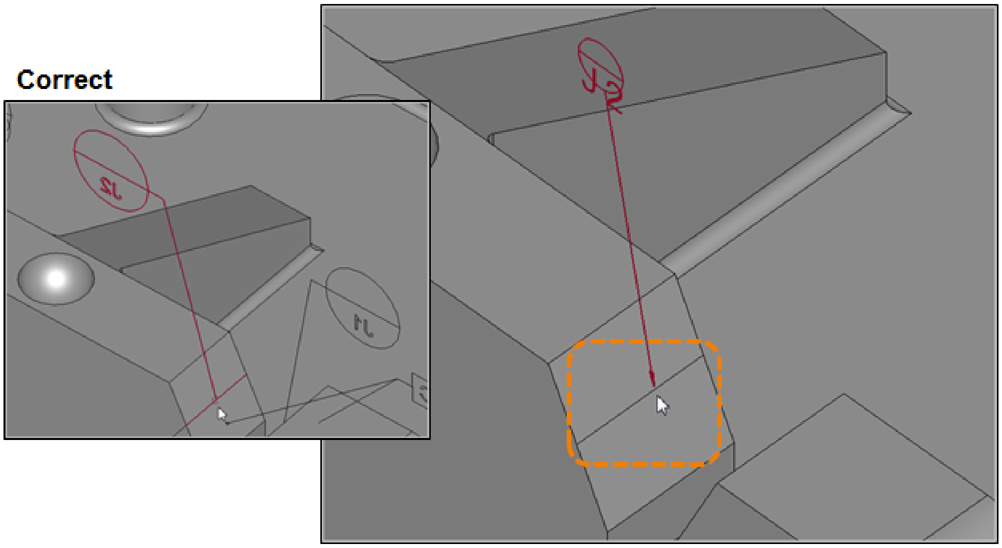
This dimension is not associated with both specified faces.

Annotation Geometry: DTS not associated with SG curve

Representation Limitation

Correct

Incorrect



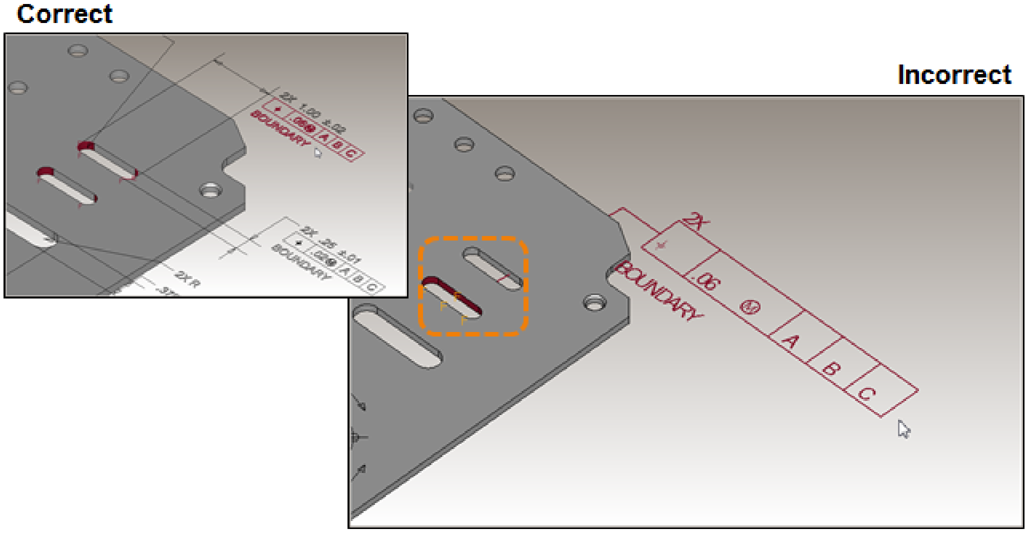
This datum target symbol is not associated with the specified curve.

Annotation Geometry: FCF associated with incorrect face

Representation Limitation

Correct

Incorrect

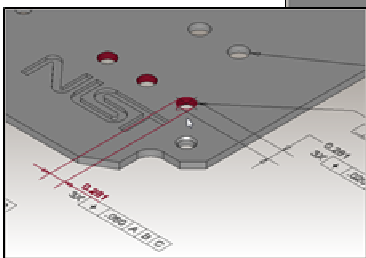


This feature control frame is not associated with the correct faces.

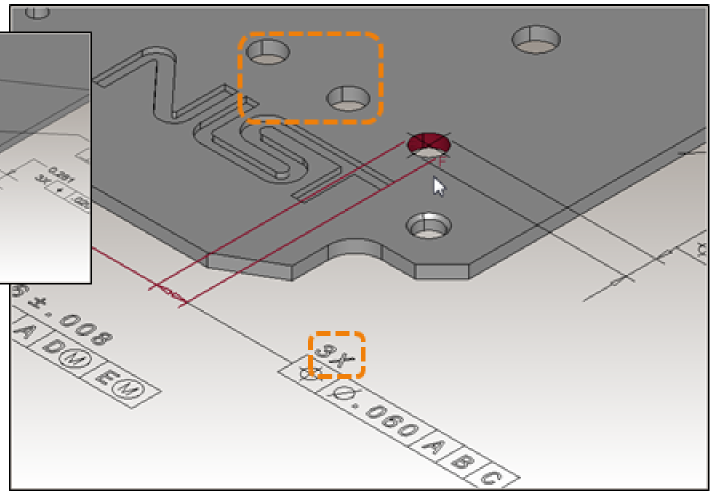
Representation Limitation

Annotation Geometry:
FCF extension line DIM not associated with correct face

Complete



Incomplete

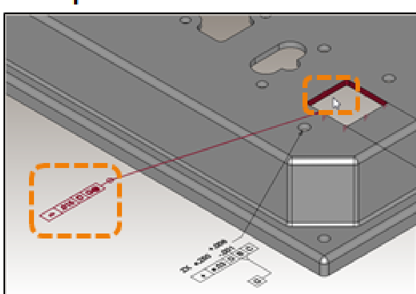


The extension lines for this dimension are not associated with all of the specified faces.

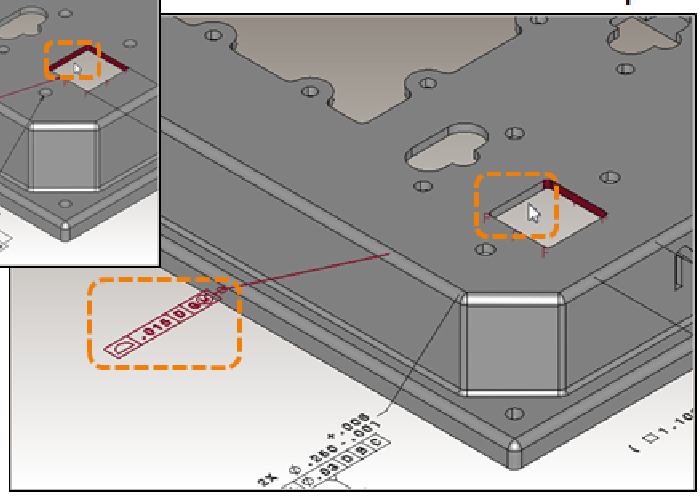
Representation Limitation

Annotation Geometry:
FCF not associated with complete set of faces

Complete



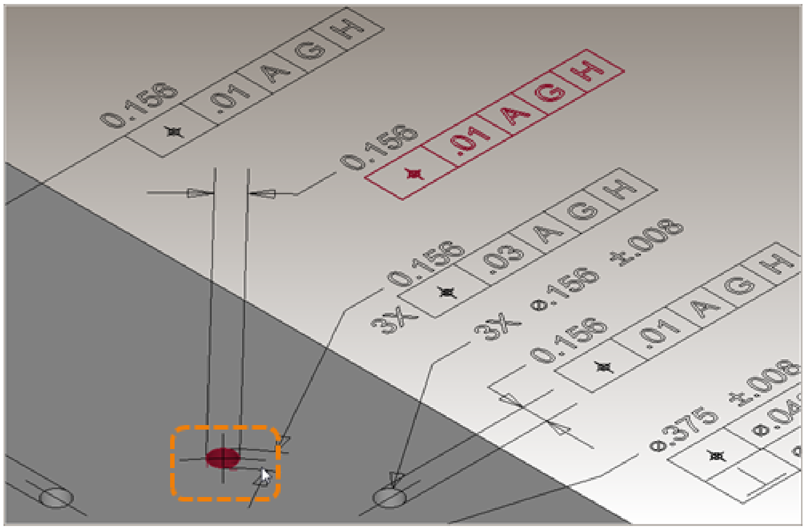
Incomplete



This feature control frame is not associated with all of the specified faces.

Annotation Geometry:
FCF not associated with SG curve

Representation Limitation

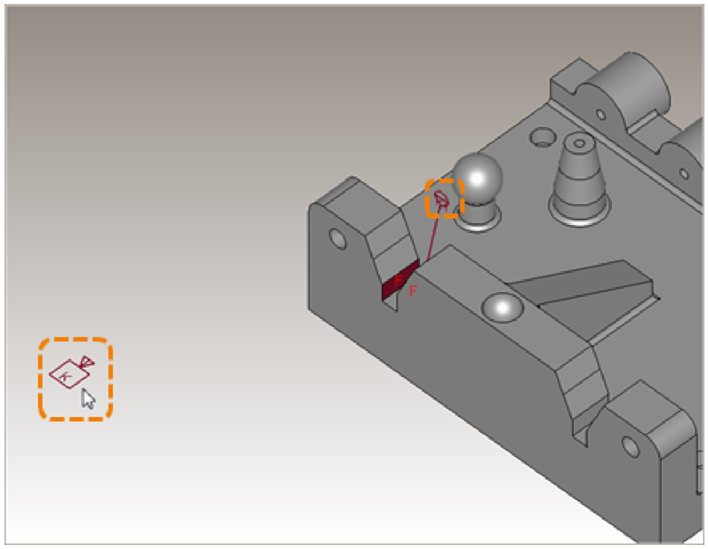


This feature control frame is not associated with the supplemental geometry curve that defines its tolerance direction on this face.

Appendix E: Presentation Limitation Examples

Presentation Limitation

Annotation Visibility:
DFS is extraneous when DTS is defined

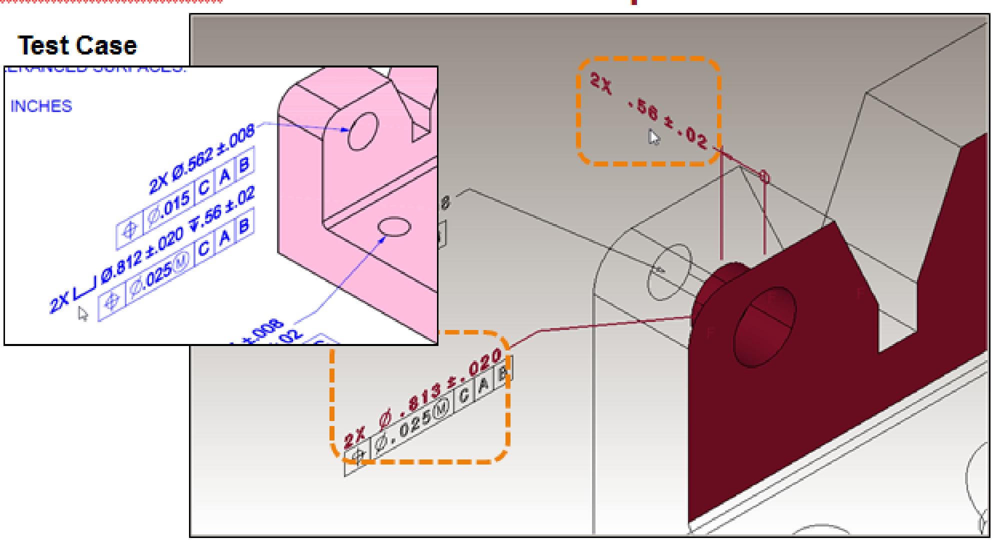


This datum feature symbol is unnecessary when a datum target symbol is defined.

Presentation Limitation

Annotation Layout:
Counterbore DIM defined as two separate DIM's

Test Case

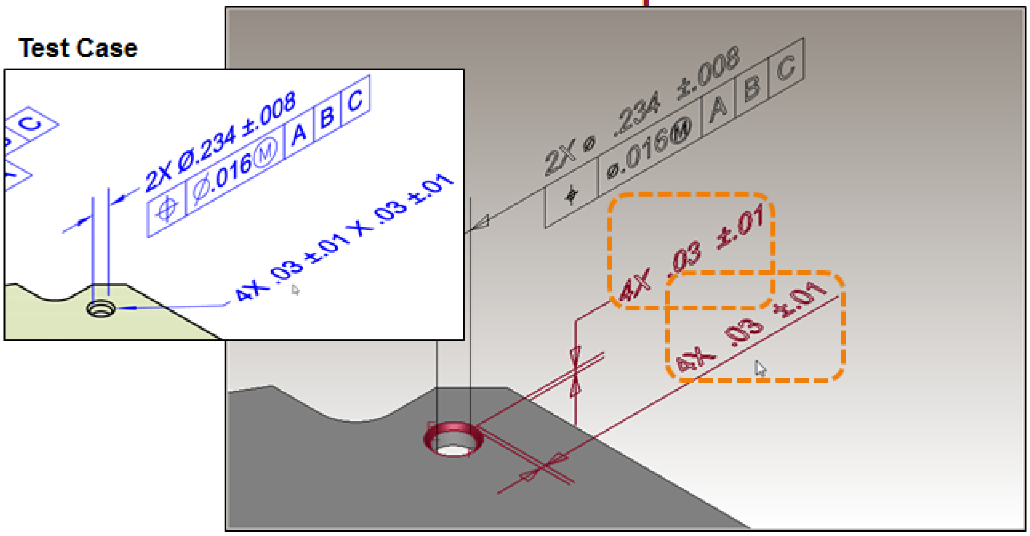


This counterbore dimension cannot be defined as a single annotation with named parameters that each have correct face associations. It must be defined as two separate dimensions.

Presentation Limitation

Annotation Layout:
Countersink DIM defined as two separate DIM's

Test Case



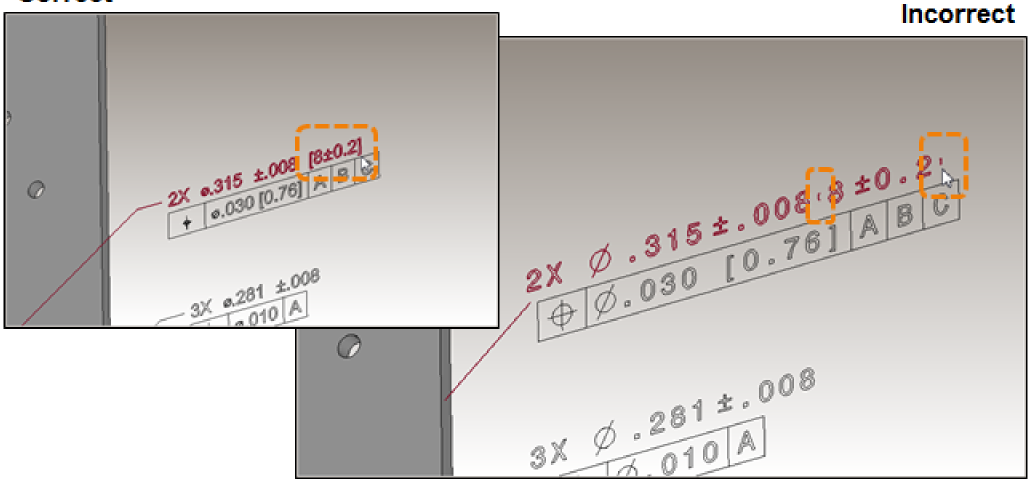
This countersink dimension cannot be defined as a single annotation with named parameters that each have correct face associations. It must be defined as two separate dimensions.

Presentation Limitation

Annotation Layout:
DIM dual dimension bracket size very small

Correct

Incorrect



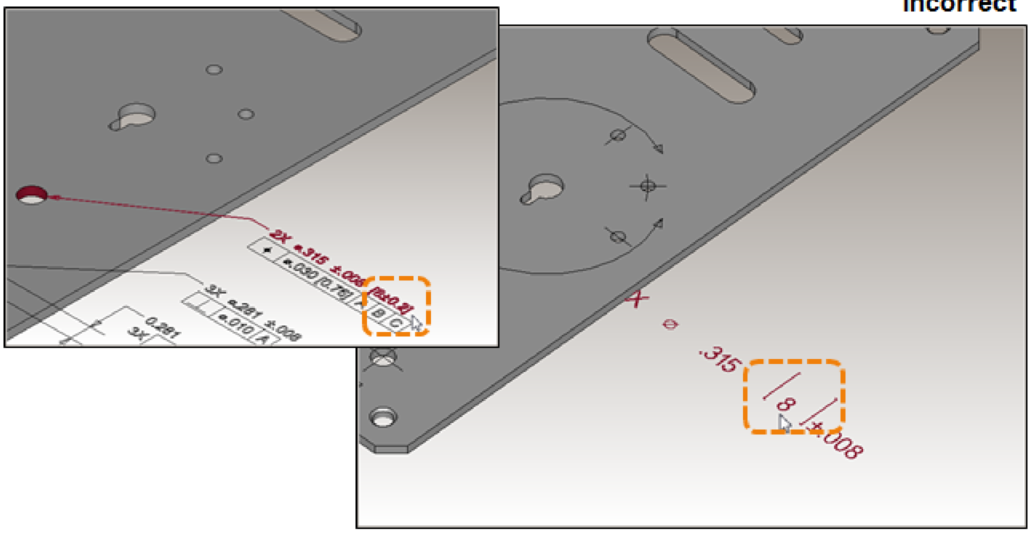
The brackets on this dimension are very small relative to the text height.

Annotation Layout: DIM dual dimension position is incorrect

Presentation Limitation

Correct

Incorrect

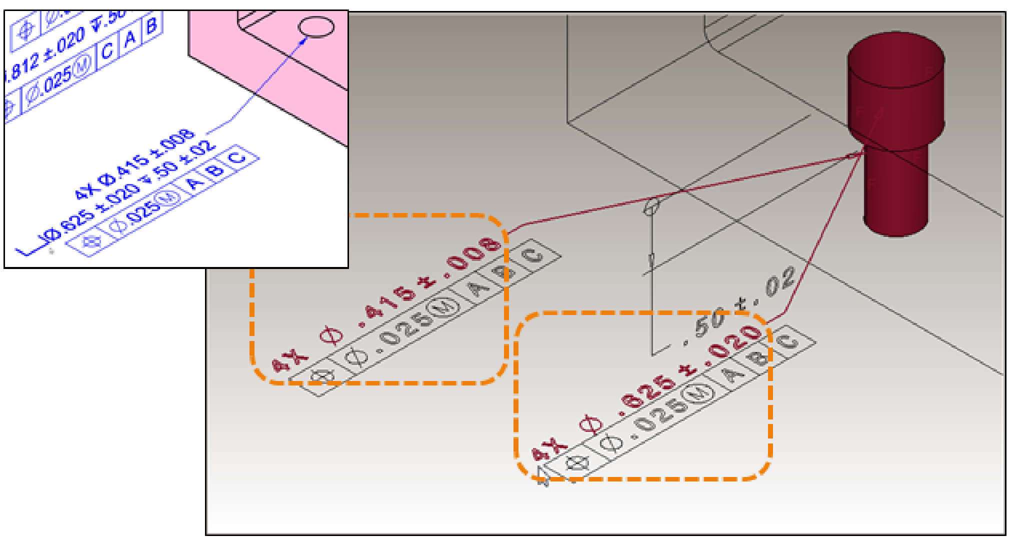


This dual dimension is inserted between the primary nominal dimension and its tolerance.

Annotation Layout: DIM not stacked correctly

Presentation Limitation

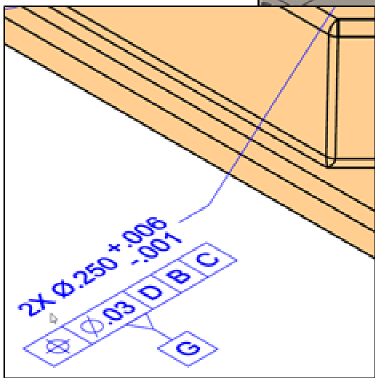
Test Case

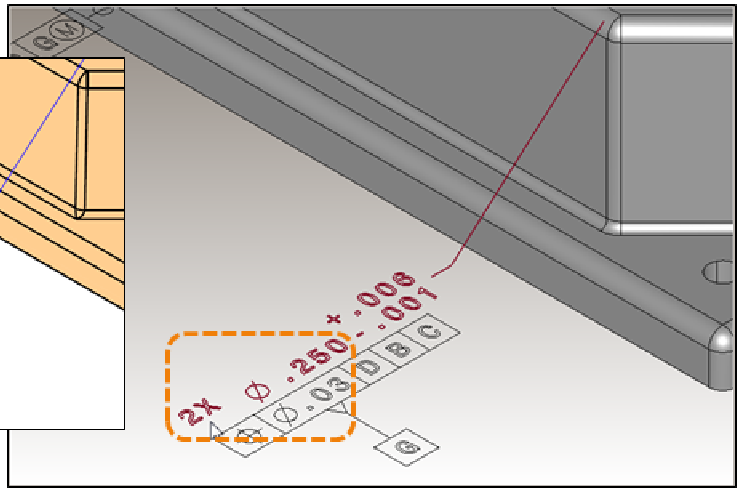


These hole and counterbore dimensions are not combined as specified.

Annotation Layout: DIM text misaligned

Test Case

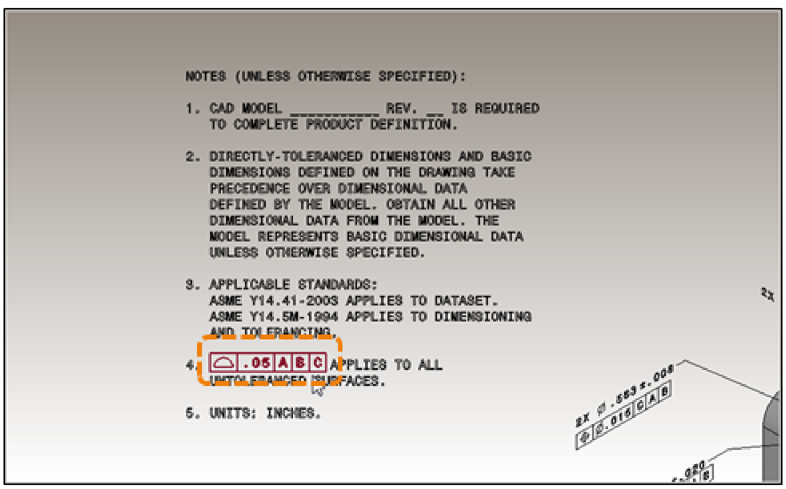




The text for the nominal value of this dimension is not aligned as specified.

Presentation Limitation

Annotation Layout: FCF defined separate from general note text

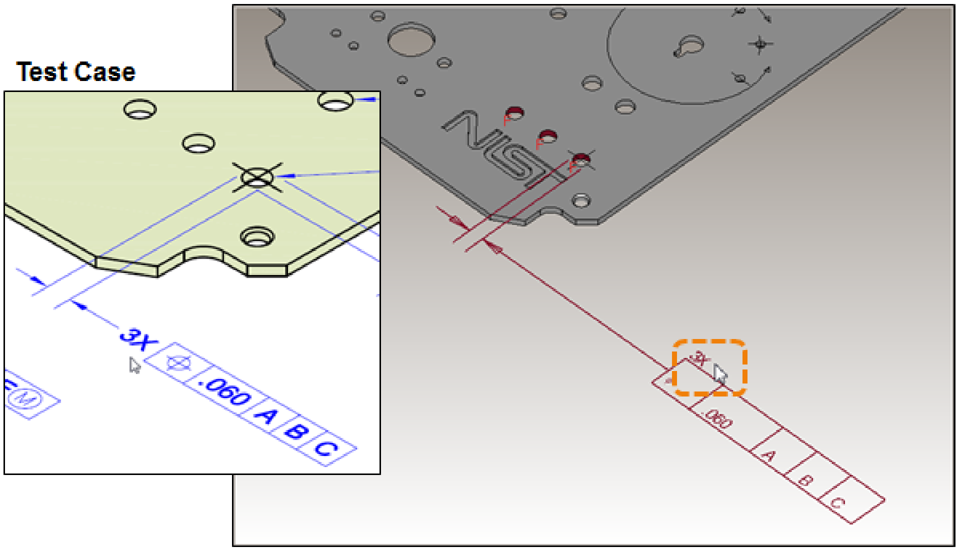


This geometric tolerance is defined as a separate entity from the general notes.

Annotation Layout: FCF instance count not in front

Presentation Limitation

Test Case

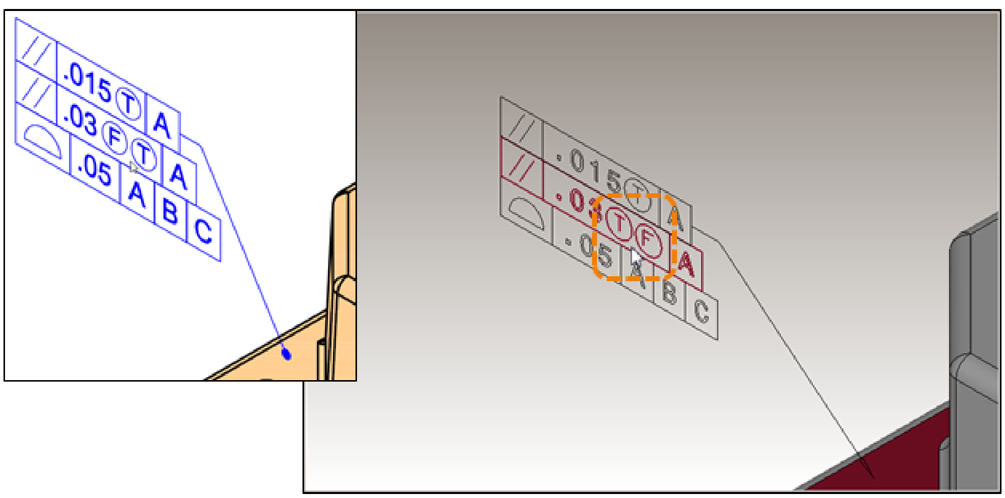


This instance count is not in the specified location.

Annotation Layout: FCF modifiers reversed

Presentation Limitation

Test Case

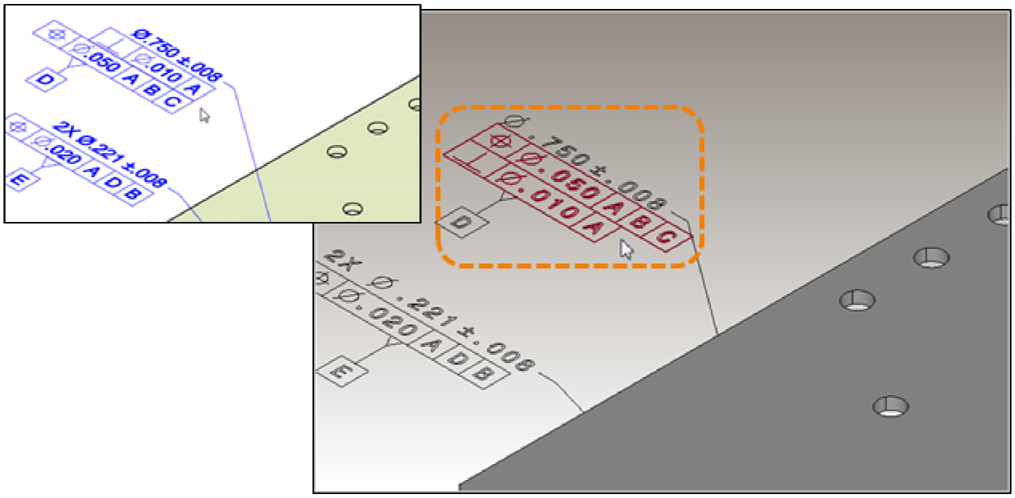


The order of these feature control frame modifiers is reversed from the specification.

Presentation Limitation

Annotation Layout:
FCF stack order reversed

Test Case

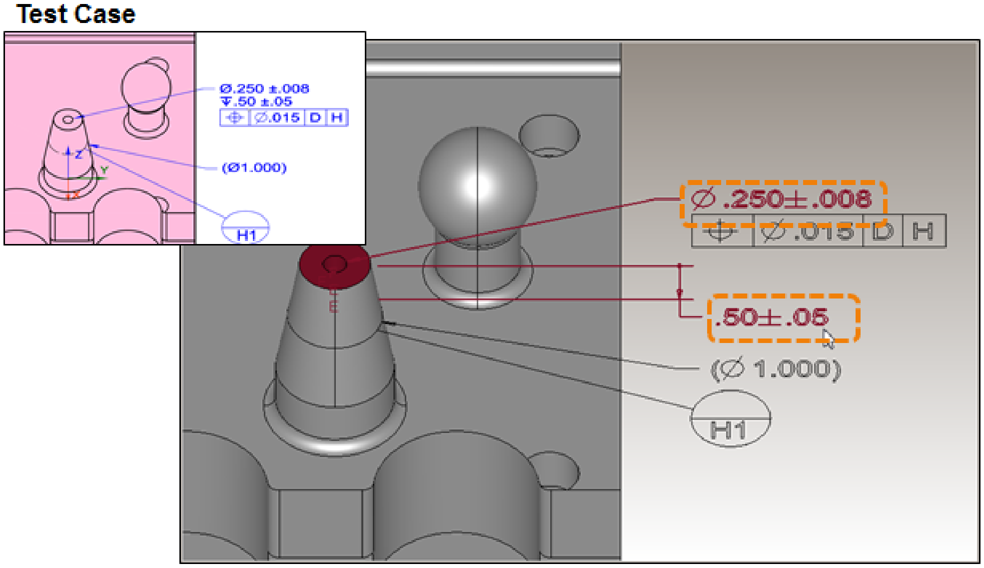


These feature control frames are not stacked as specified.

Presentation Limitation

Annotation Layout:
Hole DIM defined as two separate DIM's

Test Case

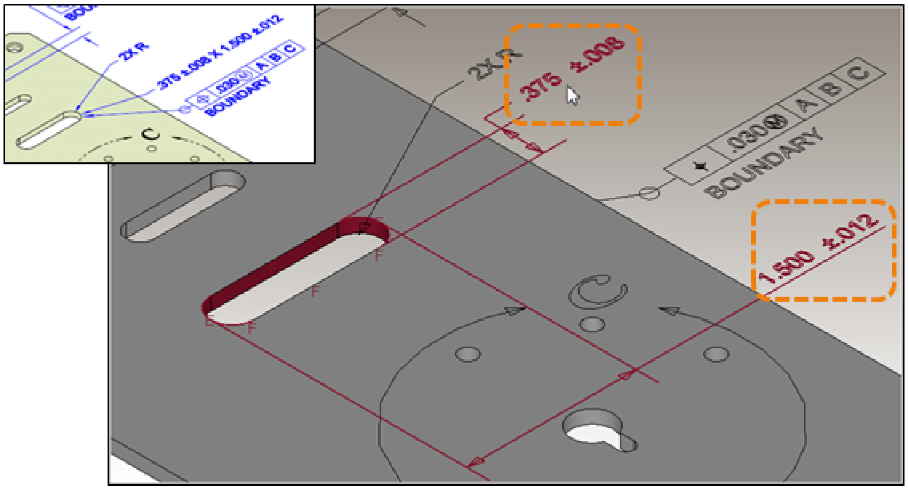


This hole dimension is defined using two separate dimensions.

Presentation Limitation

Annotation Layout:
Slot DIM defined as two separate DIMS

Test Case

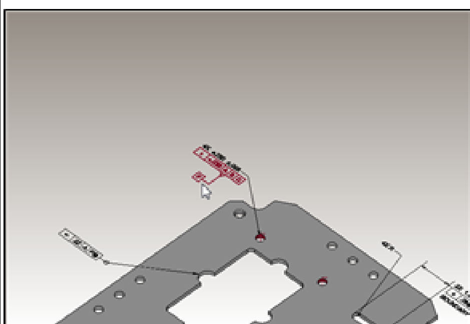


This slot dimension is defined using two separate dimensions.

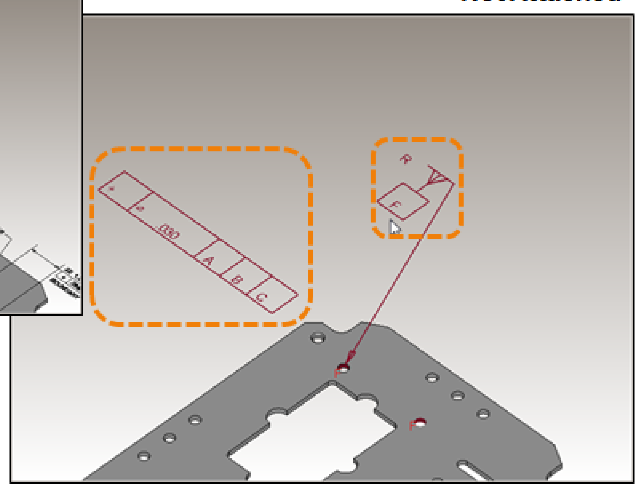
Presentation Limitation

Annotation Location:
DFS not attached to FCF

Attached



Not Attached

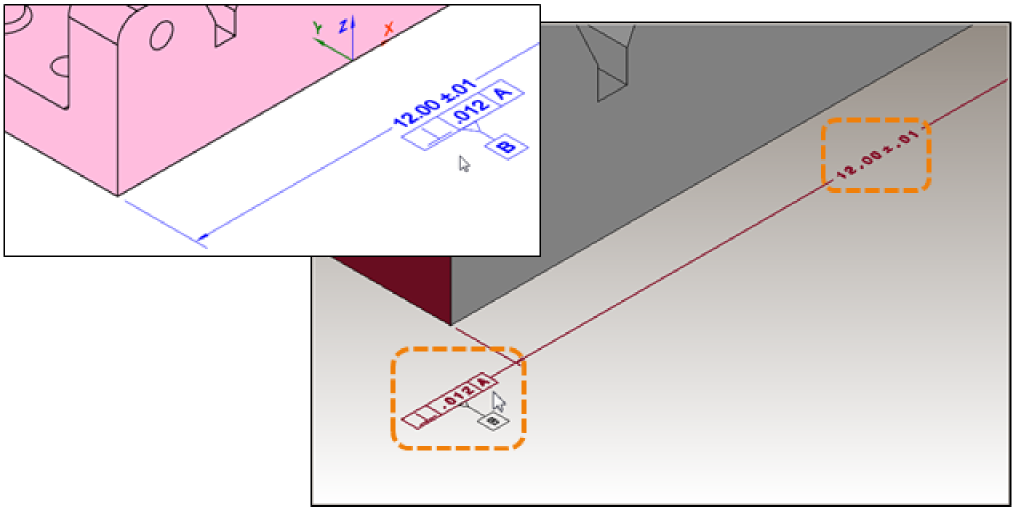


This datum feature symbol is not attached to the associated feature control frame for this hole pattern.

Annotation Location: FCF not attached to DIM

Presentation Limitation

Test Case

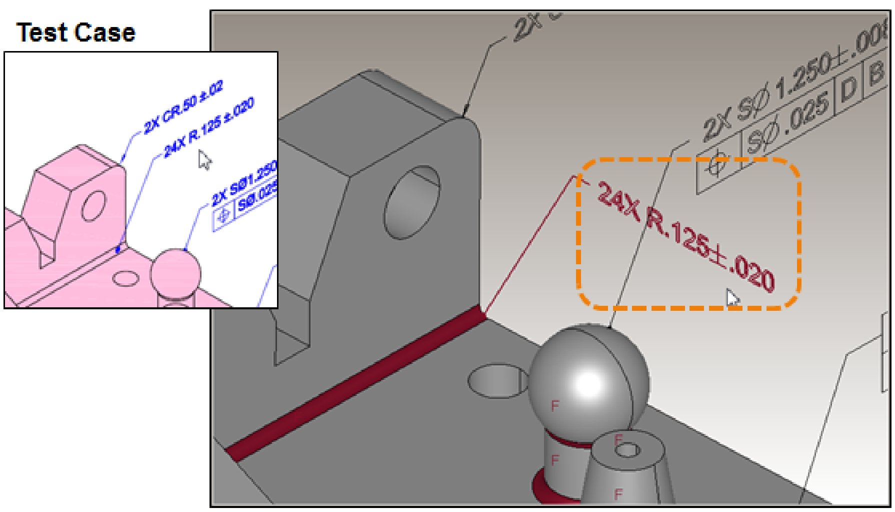


This feature control frame is not attached to it's associated dimension.

Annotation Orientation: DIM view plane rotated

Presentation Limitation

Test Case

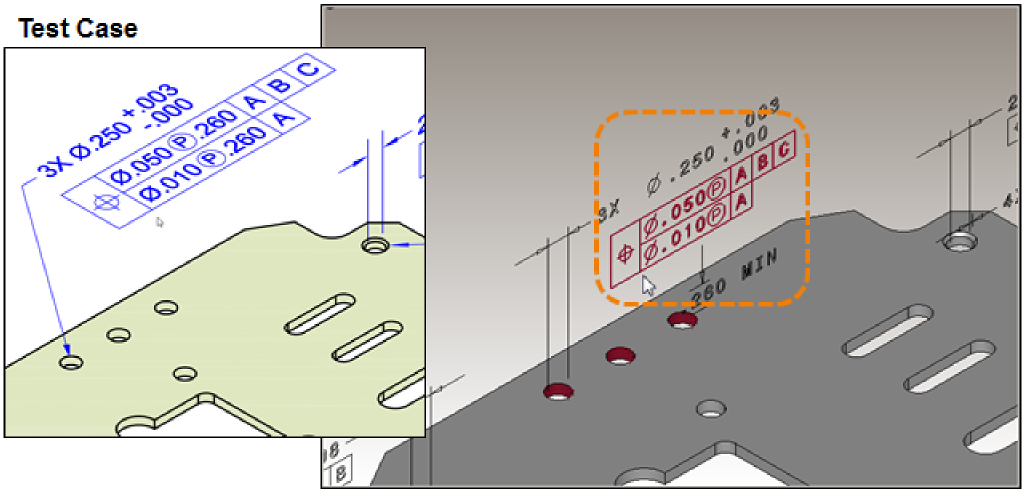


This dimension is not oriented as specified.

Annotation Orientation:
FCF view plane rotated

Presentation Limitation

Test Case

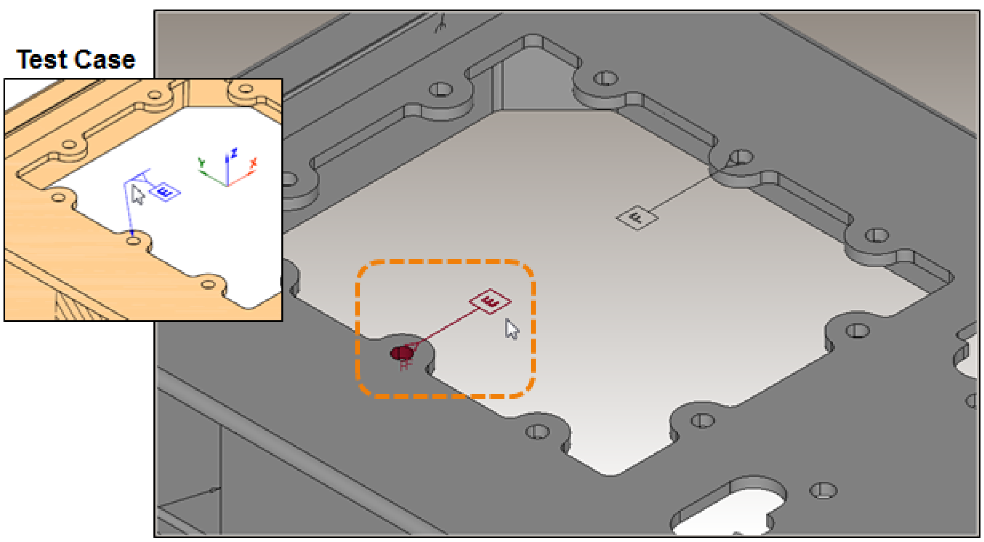


This feature control frame is not oriented as specified.

Annotation Lines:
DFS missing extension line

Presentation Limitation

Test Case

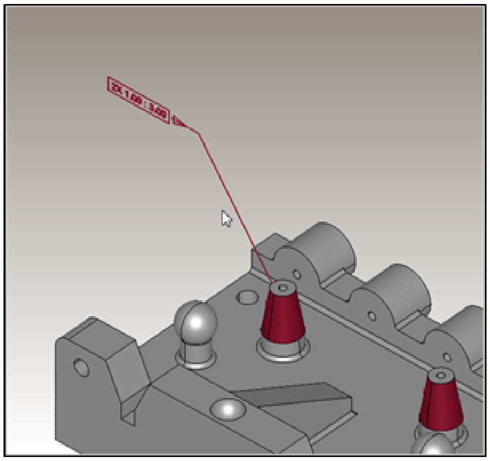


This datum feature symbol does not have the specified extension line.

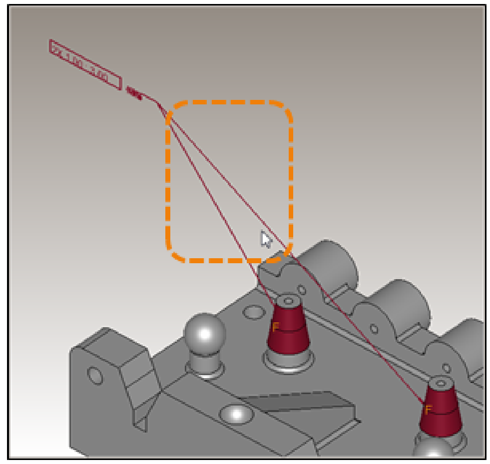
Annotation Lines: DIM leader line is extraneous

Presentation Limitation

Correct



Incorrect

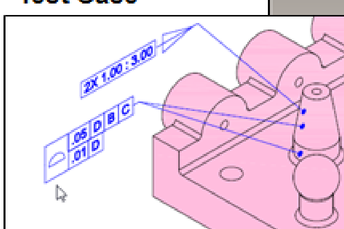


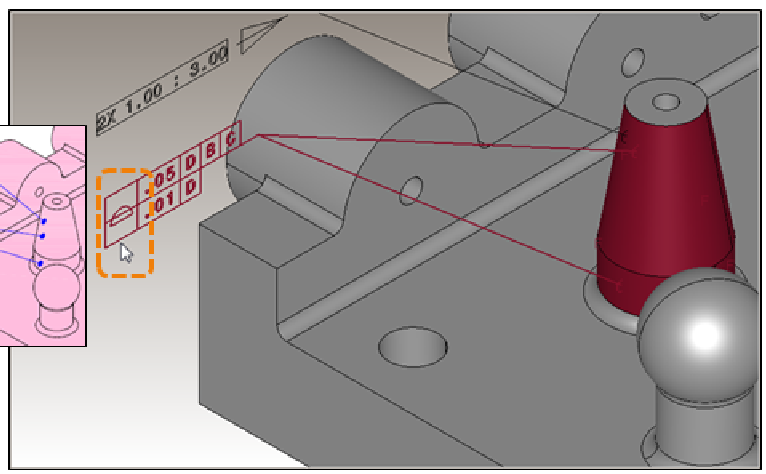
This dimension has an extra leader line that is not specified.

Annotation Lines: FCF divider line cuts through symbol

Presentation Limitation

Test Case

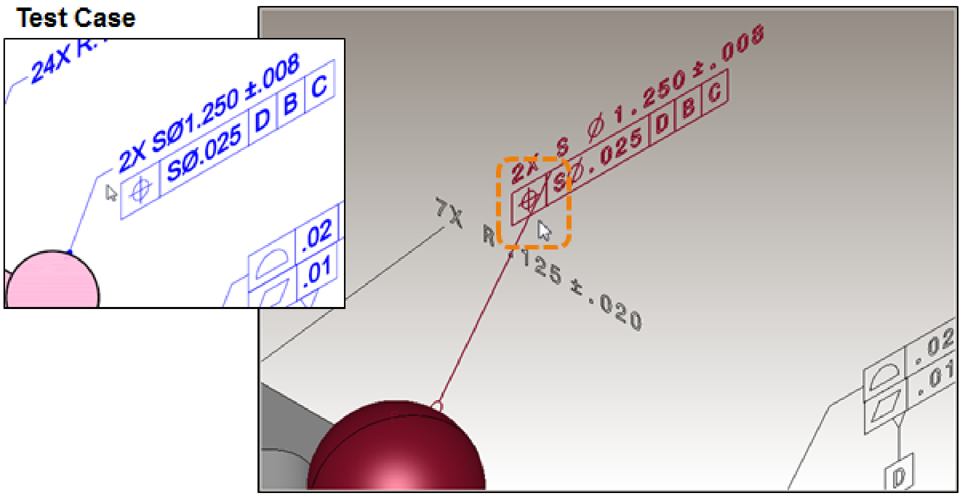




The divider line of this feature control frame runs through the tolerance symbol.

Annotation Lines: FCF leader line passes through FCF

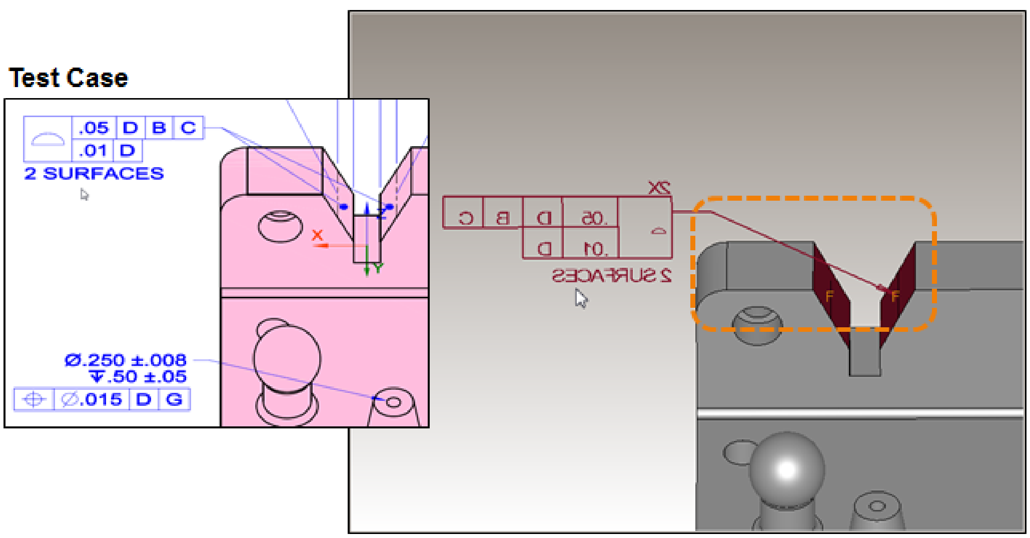
Presentation Limitation



The leader line for this annotation stack passes through the feature control frame.

Annotation Lines: FCF missing dual leader lines

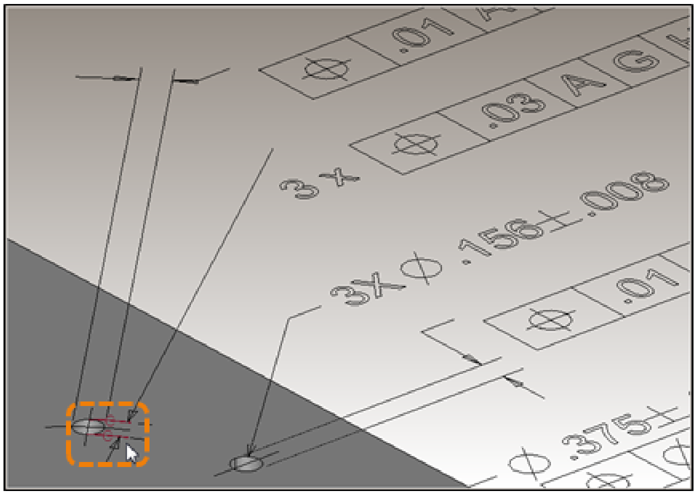
Presentation Limitation



This feature control frame is missing a second leader line.

Annotation Lines:
FCF radial extension lines defined as SG curves

Presentation Limitation

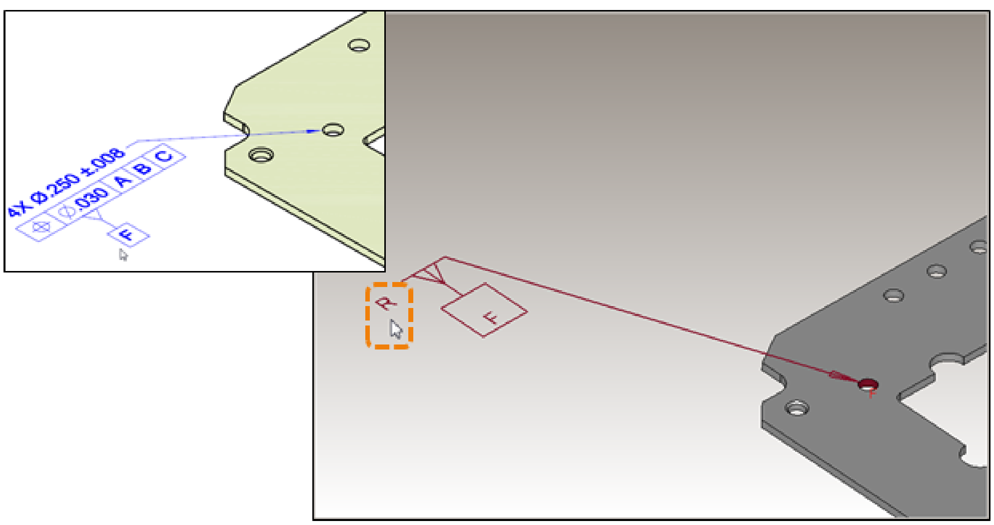


These extension lines have been created as non-solid curves in the model.

Annotation Text:
DFS text is extraneous

Presentation Limitation

Test Case

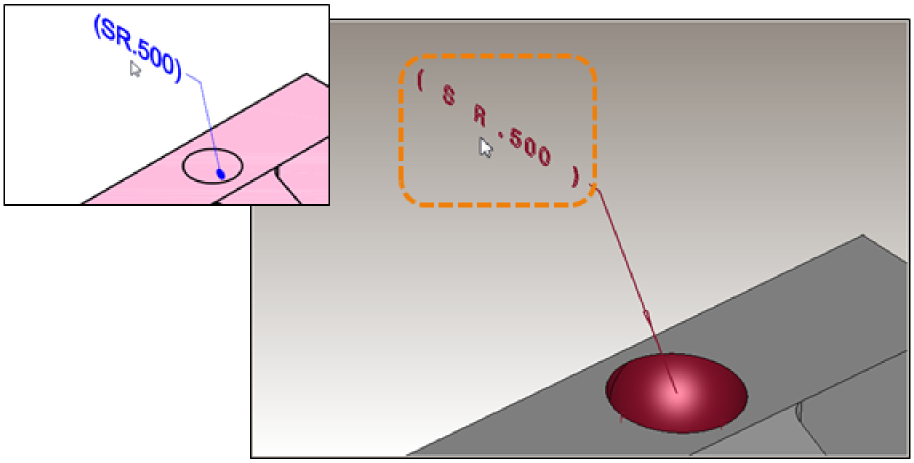


This datum feature symbol has an unspecified “R” symbol.

Annotation Text: DIM has extraneous space

Presentation Limitation

Test Case



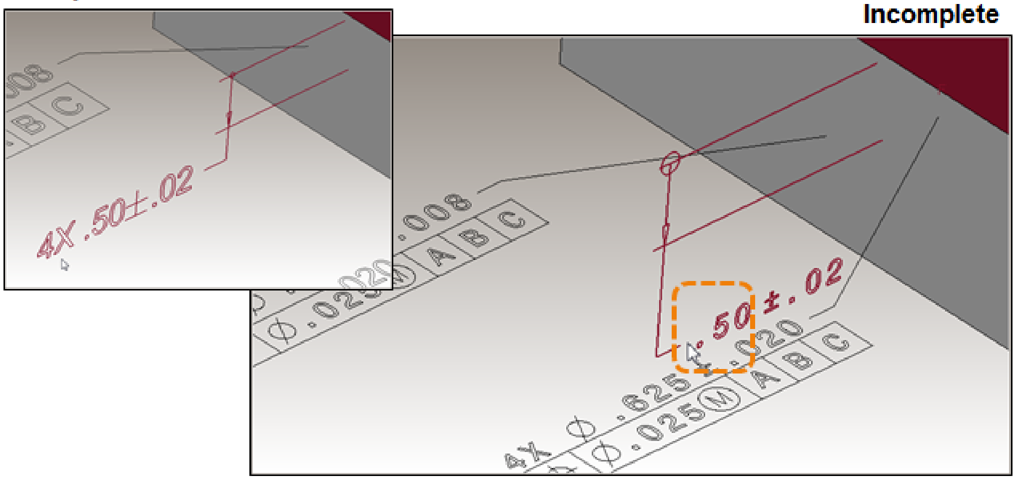
This dimension has extra spaces around the parentheses.

Annotation Text: DIM missing pattern text

Presentation Limitation

Complete

Incomplete

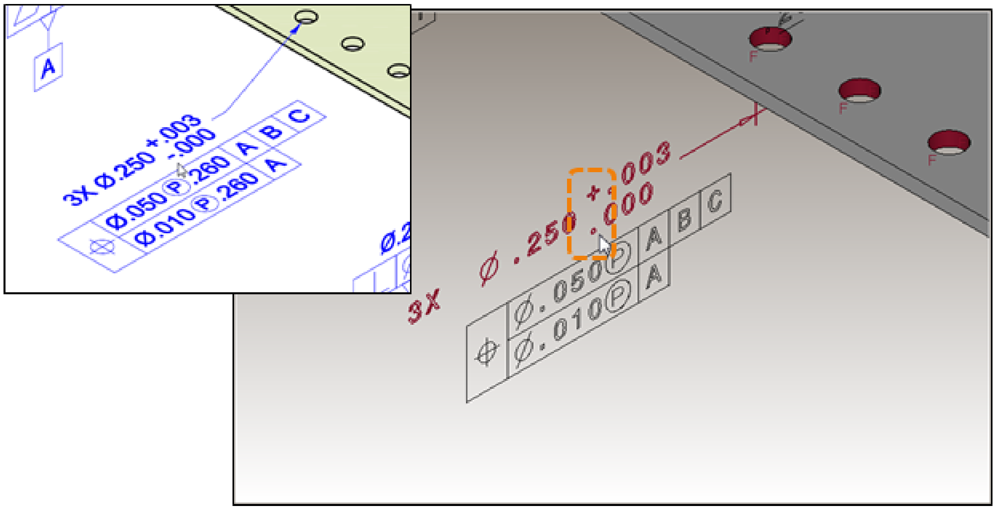


This annotation is missing the pattern instance count.

Presentation Limitation

Annotation Text:
DIM missing zero tolerance limit negative sign

Test Case

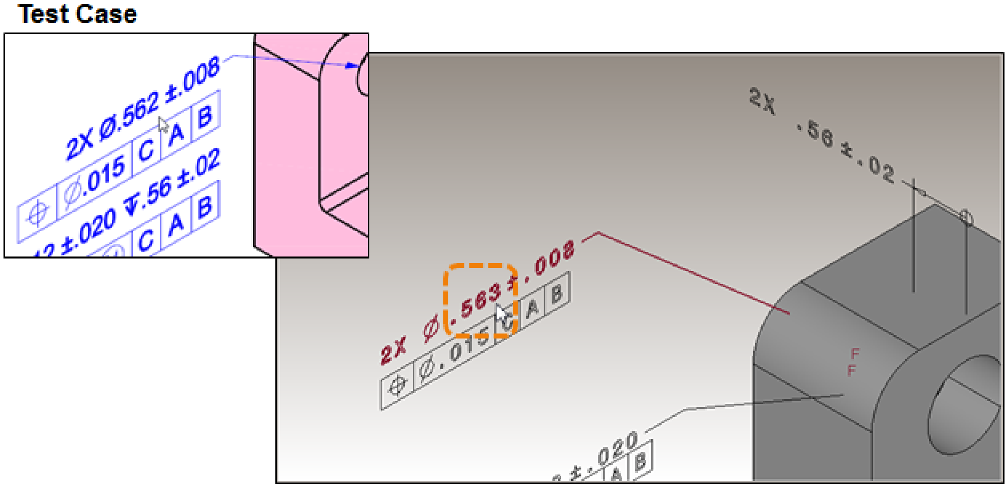


This tolerance is missing the specified negative sign.

Presentation Limitation

Annotation Text:
DIM nominal value rounded incorrectly

Test Case

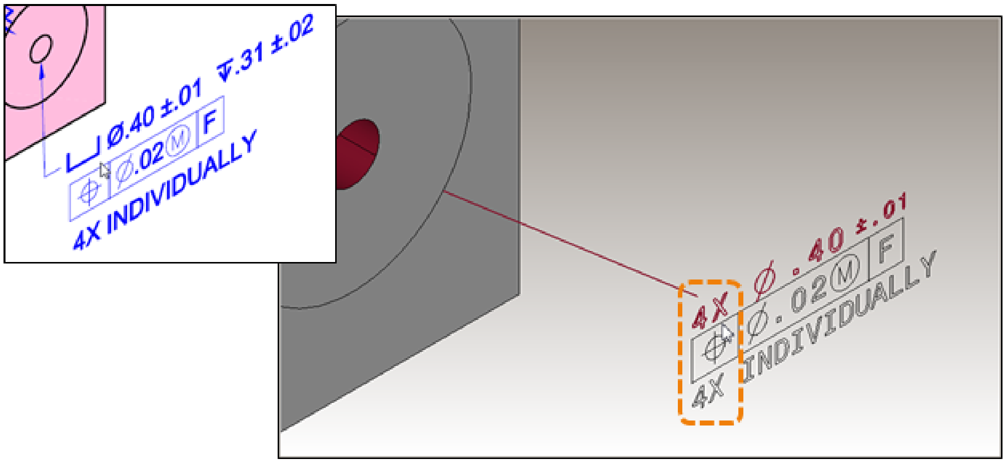


The nominal value of this dimension is rounded incorrectly.

Annotation Text: DIM pattern text is extraneous

Presentation Limitation

Test Case

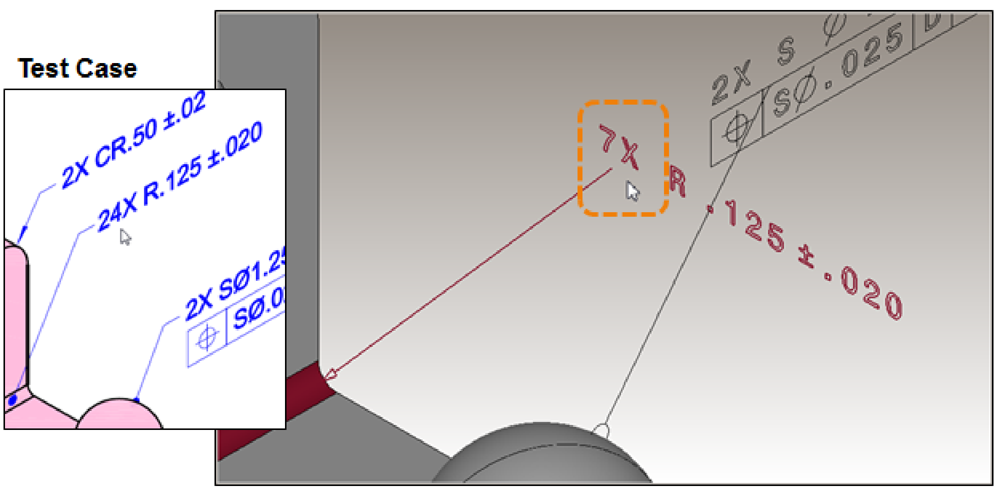


This dimension has extra pattern text.

Annotation Text: DIM pattern text is incorrect

Presentation Limitation

Test Case

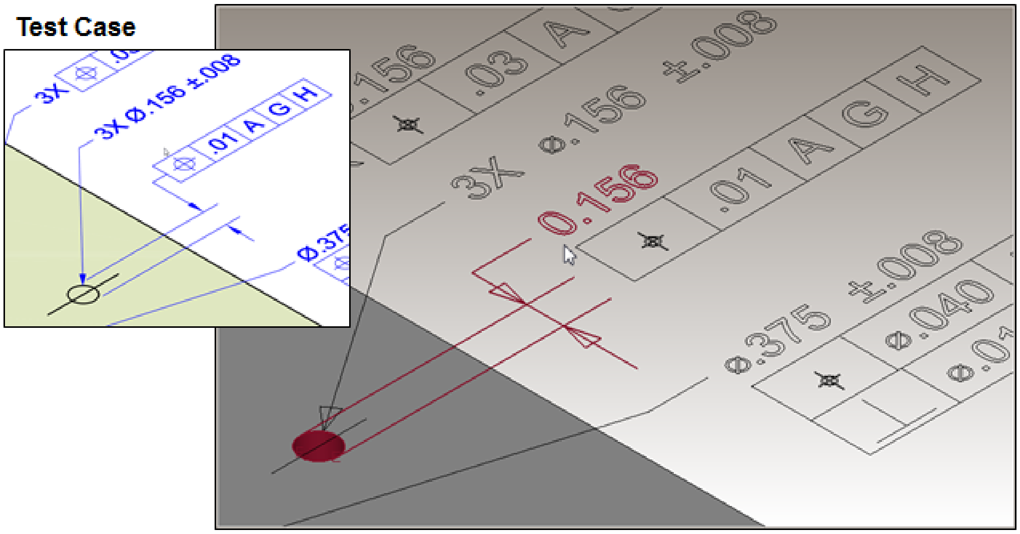


This dimension does not show the specified instance count.

Presentation Limitation

Annotation Text:
FCF extension line DIM text is extraneous

Test Case

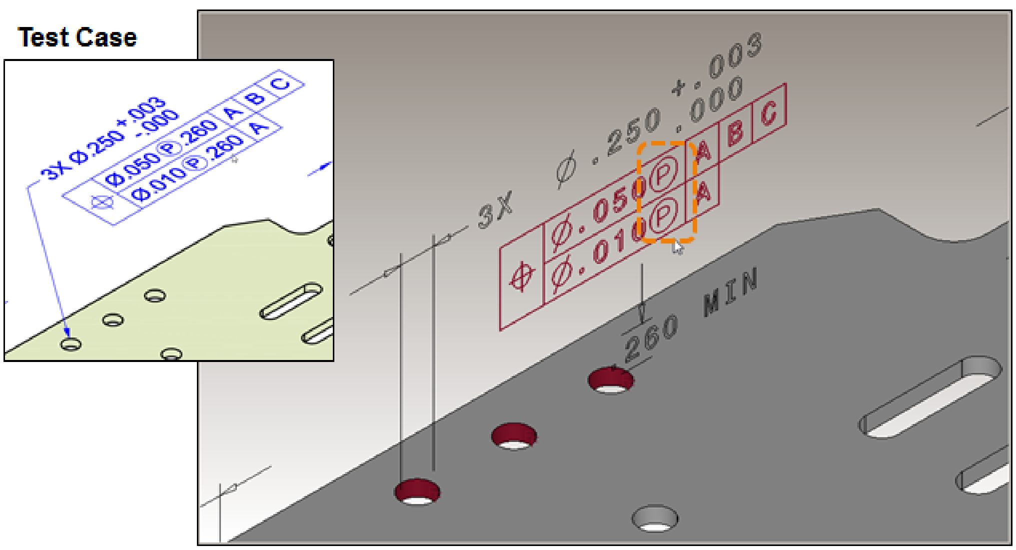


The extension lines for this feature control frame include an unspecified dimension.

Presentation Limitation

Annotation Text:
FCF missing projected tolerance zone length

Test Case

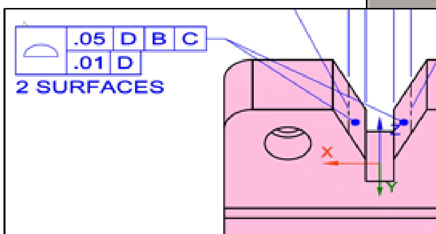


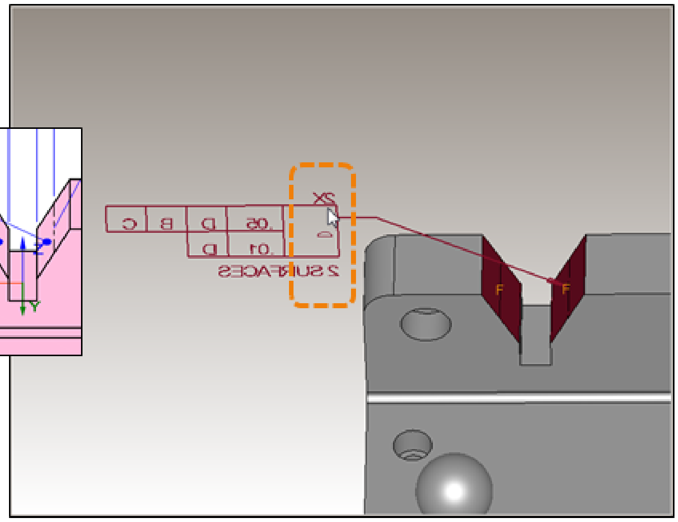
The length of the projected tolerance zone for this feature control frame is not displayed as specified.

Annotation Text: FCF pattern text is extraneous

Presentation Limitation

Test Case



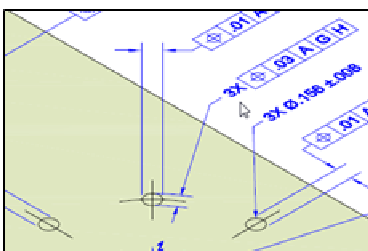


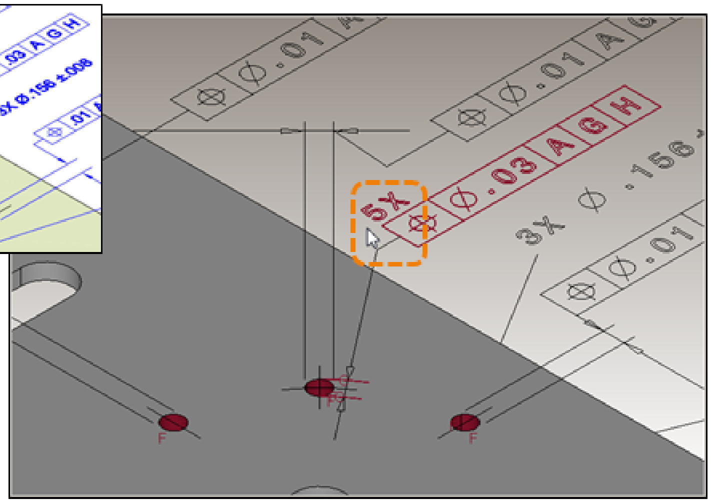
This feature control frame has extra pattern text.

Annotation Text: FCF pattern text is incorrect

Presentation Limitation

Test Case



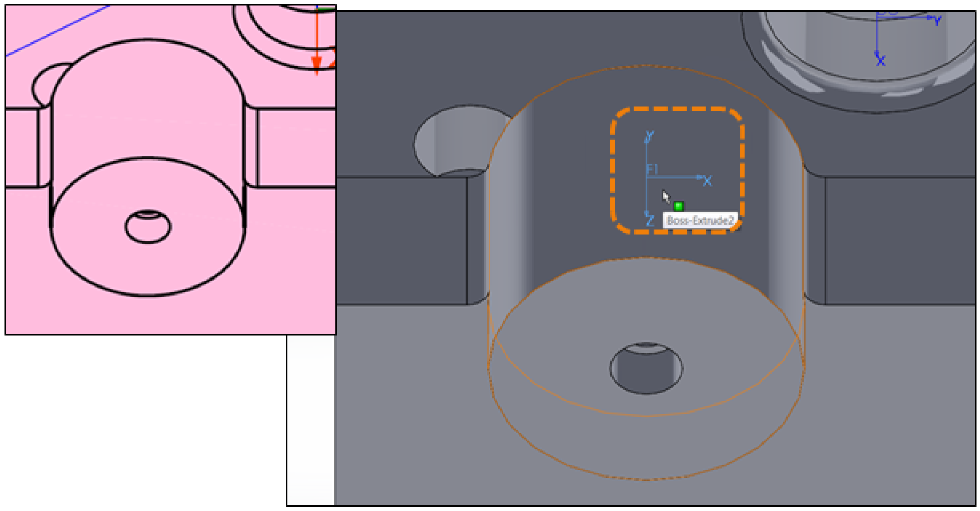


This feature control frame does not show the specified instance count.

Coordinate System Visibility: CS visible in wrong view

Presentation Limitation

Test Case

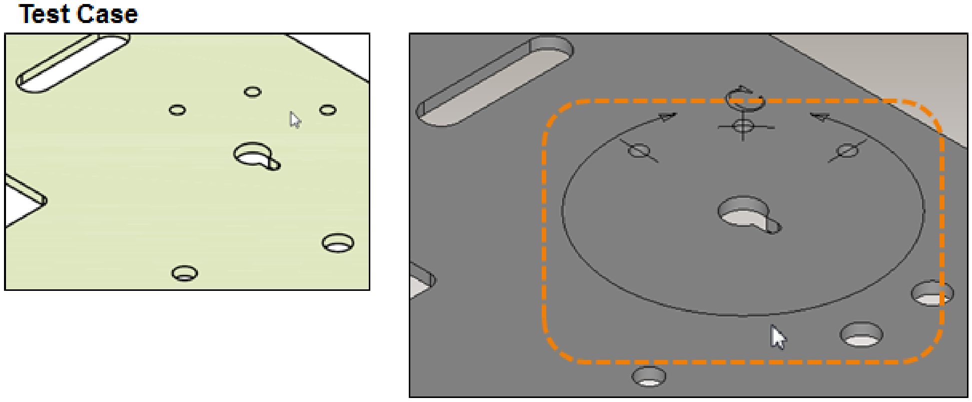


This coordinate system is shown in a view for which it is not specified.

Supplemental Geometry Visibility: SG curve visible in wrong view

Presentation Limitation

Test Case

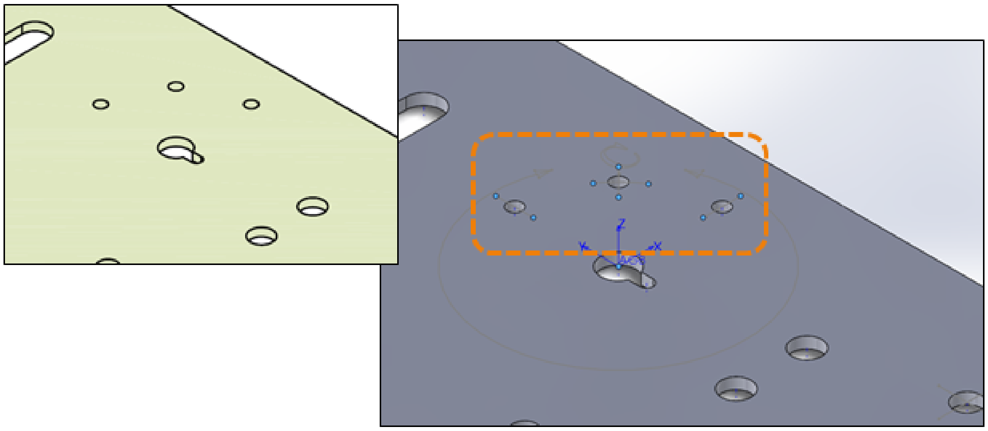


These supplemental curves are visible in a view for which they are not specified.

Supplemental Geometry Visibility: SG point visible in wrong view

Presentation Limitation

Test Case

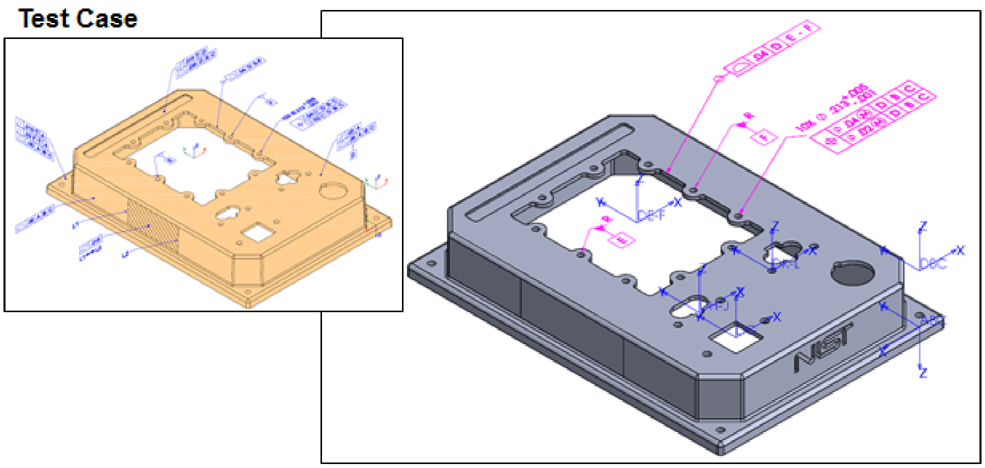


These supplemental points are visible in a view for which they are not specified.

Saved View Structure: View cannot contain annotations on different planes

Presentation Limitation

Test Case

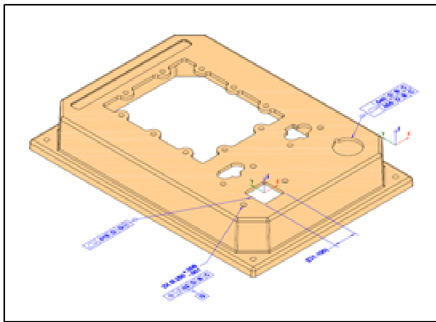


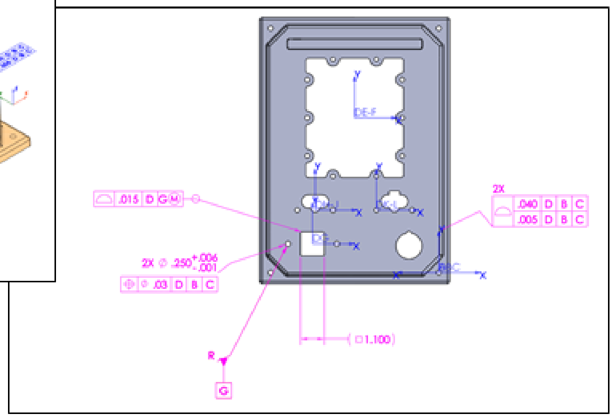
The PMI views in this system are limited to annotations with the same view and reading directions. The specified saved view has annotations with multiple view and reading directions.

Saved View Frustum: View camera position not defined

Presentation Limitation

Test Case



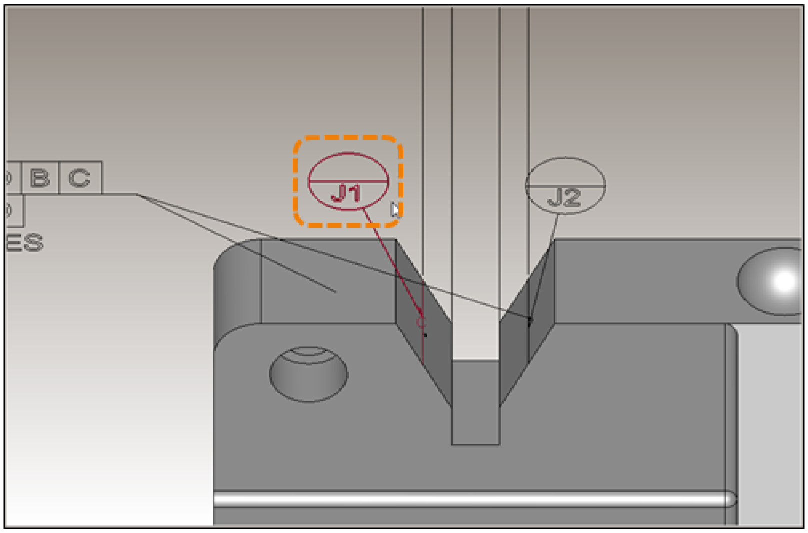


Each saved view in the test case has a specified camera position (view direction and zoom level). This system is unable to store a camera position in its PMI view definition.

Appendix F: Style Difference Examples

Style Difference

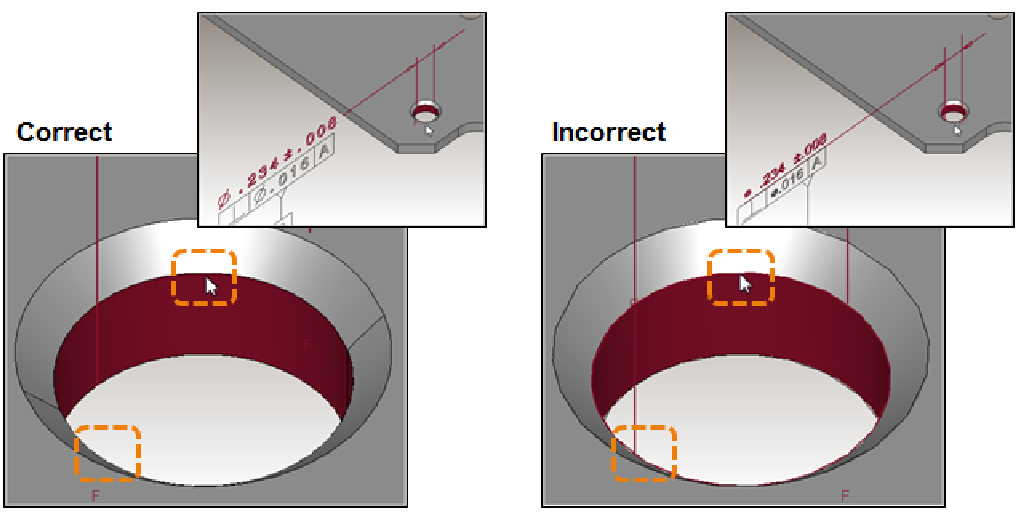
Annotation Structure:
DTS requires DFS to be defined



The system requires a datum feature symbol to be defined when a datum target symbol is defined. It allows the datum feature symbol to be hidden so the view appears as specified in the test case.

Style Difference

Annotation Geometry:
DIM edge association is extraneous

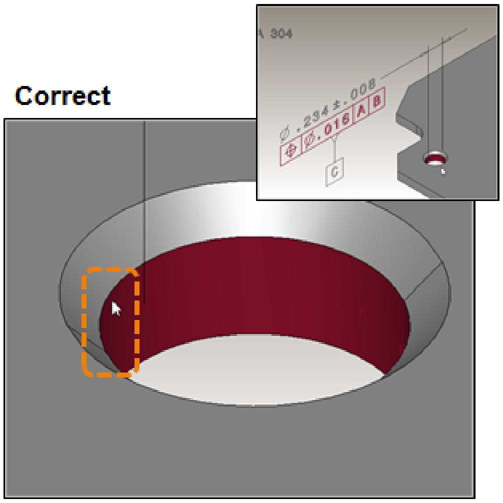


This dimension is unnecessarily associated with the edges of this hole.

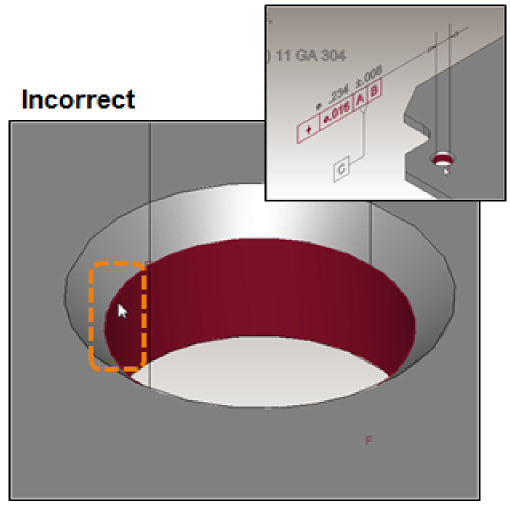
Style Difference

Annotation Geometry: FCF edge association is extraneous

Correct



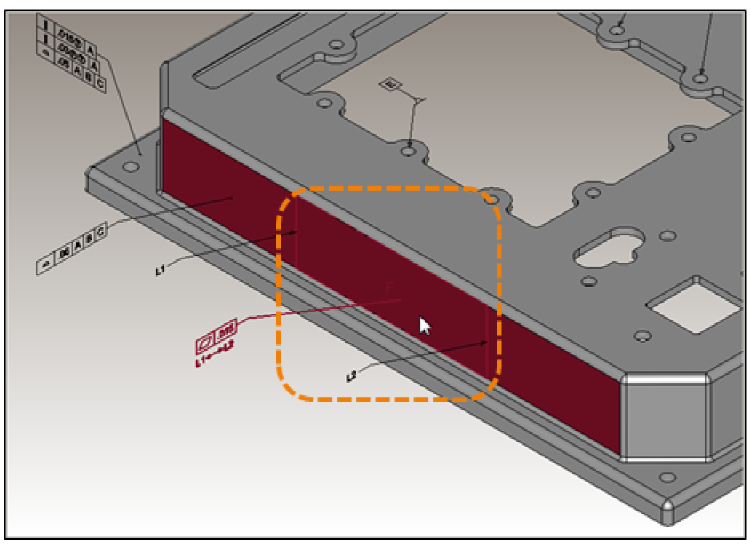
Incorrect



This geometric tolerance is unnecessarily associated with the edges of this hole.

Style Difference

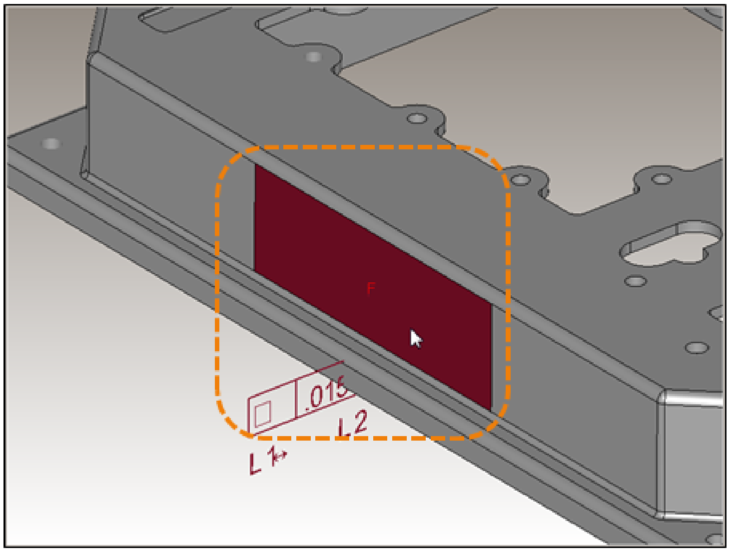
Supplemental Geometry Structure: FCF limited area is non-solid surface on solid face



The limited area for this feature control frame is defined as a non-solid surface placed on the solid face.

Supplemental Geometry Structure: FCF limited area is subdivided solid face

Style Difference



The limited area for this feature control frame is defined as a solid face that has been separated from the adjacent faces in this solid.