Development of a STEP-compliant design and manufacturing framework for discrete sheet-metal bend parts

Zahid Faraz[1], Syed Waheed ul Haq[1], Liaqat Ali[2], Khalid Mahmood[1], Wasim Akram Tarar[1],Aamer Ahmed Baqai[1], Mushtaq Khan[2], Syed Husain Imran[2] and Rizwan Saeed Choudhry[3]

[1]Department of Mechanical Engineering, NUST College of Electrical and Mechanical Engineering, National University of Sciences and Technology, Islamabad, Pakistan.
[2]Department of Design and Manufacturing Engineering, NUST School of Mechanical and Manufacturing Engineering, National University of Sciences and Technology, Islamabad, Pakistan
[3]Department of Mechanical Engineering, Capital University of Science and Technology, Islamabad, Pakistan.

Abstract: Metal sheets have the ability to be formed into nonstandard sizes and sections. Displacement controlled CNC press brakes are used for 3D sheet metal forming. Though the subject of vendor neutral computer aided technologies (CAD, CAPP and CAM etc.) is widely researched for machined parts, research in the field of sheet metal parts is very sparse. Blank development from 3D CAD model depends upon the bending tools geometry and metal sheet properties. Furthermore generation and propagation of bending errors depend upon individual bend sequences. Bend sequence planning is carried out to minimize bending errors, keeping in view the available tooling geometry and the sheet material properties variation.

Research reported in this paper attempts to develop a STEP-compliant, vendor neutral design and manufacturing framework for discrete sheet metal bend parts to provide a capability of bi-directional communication between design and manufacturing cycles. Proposed framework will facilitate the use of design information downstream at the manufacturing stage in the form of bending work plan, bending working steps and a feedback mechanism to the upstage product designer. In order to realize this vendor neutral framework STEP(ISO10303), AP203, AP207, AP219 along with STEP-NC(ISO14649) have been used to provide a basis of vendor neutral data modeling.

Keywords

STEP, STEP-NC, CNC Pressbrake, Sheet metal bending, Material properties variation.

1. Introduction

Discrete sheet metal parts are manufactured in two steps. In the first step 2D flat blanks are cut from sheet metal stock and various features are produced over them by machining and stamping processes. In the second step prepared flat blanks are formed on a CNC pressbrake to achieve the required three dimensional part shapes. Variety of manufacturing equipment is used for both the manufacturing stages. Manufacturing process planning for discrete sheet metal parts require the evaluation of an optimum sequence for both manufacturing stages depending upon the nature of available manufacturing resources.

Variety of software tools are used to automate the activities of design, manufacturing and inspection of discrete sheet metal parts. CNC Pressbrake process control units contain specialized unfolding software modules to unfold sheet metal CAD models to estimate shape and size of the starting 2D flat blanks. CAPP software modules for discrete sheet metal parts are inherently different from discrete machined parts. Manufacturing process planning in the case of discrete sheet metal parts involves: the evaluation of starting 2D flat blank geometry, blank machining strategy and 3D forming and gauging strategy.

Corresponding author:

Syed Hussain Imran Jaffery, Department of Design and Manufacturing Engineering, SMME National University of Sciences and Technology(NUST),H-12 ,NUST HQ, Islamabad 44000, Pakistan.
Email: imran_hj@yahoo.co

Specialized offline CAM software modules are used to generate vendor specific NC code for CNC machine tools to machine sheet-metal blanks. Modern CNC pressbrake process-control units utilize vendor specific specialized unfolding and bend sequencing software modules to program punch displacements and back gauge finger-stop positions. Discrete sheet metal parts CAD models are based on the ideal scenario of circular straight modeling assumptions proposed by Ludwik in 1905[1]. These assumptions are almost impossible to meet in real life manufacturing scenario of material and process variations. Discrete sheet-metal parts design parameters are readjusted depending upon the knowledge generated during bend sequence planning and test part forming. Design parameters readjustment and knowledge retrieval becomes cumbersome in the modern scenario of geographically dispersed design and manufacturing partners using heterogeneous software modules. Vendor specific data formats of heterogeneous software modules make the process of feedback from downstream manufacturing activities to the upstream product designer almost impossible.

Significant research is reported in literature in the area of vendor neutral design and manufacturing data modeling of machined parts to ease the process of knowledge retrieval. Research in the area of vendor neutral data modeling of discrete sheet metal parts is very sparse. With the aim of enabling vendor neutral data modeling across the entire sheet metal design and manufacturing process chain, this paper outlines a design and manufacturing process planning framework for sheet metal bending based on STEP, STEP-NC and combined with additional information requirements.

2. Review of discrete sheet metal parts design and manufacturing processes

Computer-Integrated-Manufacturing (CIM) in the modern scenario of geographically dispersed design and manufacturing partners using heterogeneous software tools make the process of data exchange cumbersome. Knowledge generated during final part manufacturing is seldom retrieved by the upstream product designer. Sheet metal blank machining process planning and execution is similar to conventional material removal machining processes. Sheet metal bending introduces global changes in blank geometry. Process planning related to sheet metal bending involves: Evaluation of an optimum bending sequence, Tooling selection, Individual punch displacements and back gauging strategy. Conventionally bend sequence planning is mostly researched from the managerial perspective of minimizing total manufacturing time and cost. Bend sequencing effect on the overall part accuracy is least researched. Bending sequence and the bending process operating parameters are fine-tuned on the basis of test part bending results. Knowledge generated during manufacturing of test parts can be used to obtain potential time and capital savings if properly utilized in upcoming designs. Last era witnessed a big stride forward in the area of vendor neutral seamless product data flow in the overall computer-aided technologies (CAx) process chain. All these research activities are based on the infrastructure provided by a family of standards cumulatively known as STEP and STEP-NC[2,3]. STEP-NC project (IMS-2003) of IMS (Intelligent manufacturing systems) provided a first true international platform to combine research partners from different regions: Switzerland, European Union, USA and Korea[4]. Most of the research reported centers around developing prototype CAPP, CAM or CAI systems for turned and prismatic parts. Leading examples of these research activities include: ISW Stuttgart ,Germany prototype software platform, "STEPturn"[5,6], STEP tools inc., USA software platform, "ST-Plan"[7], Korean National research laboratory software platform for shop floor programming and management[8,9], Loughborough university, Wolfson school of Mechanical and Manufacturing Engineering software platform ,"AB-CAM"[10] ,University of Auckland, Prototype STEP compliant CAPP system for machined parts[11] and Liaqat et al , STEP enabled computer aided inspection (CAI) framework for prismatic parts[12].

Chryssolouris et al[13] described the history of digital manufacturing evolution and concluded that there is strong need of a vendor neutral product data representation standard to make possible a true seamless and bi-directional computer aided engineering environment. Xianzhi et al[14] proposed a meta-model for CNC part programming by utilizing STEP & STEP-NC. Henry et al[15] explained sustainable machining approach for CAD/CAM/CNC systems by using STEP-NC. Vichare et al[16] described a unified manufacturing resource model for machining by using STEP-NC. Yingguang et al[17] explained recent advances in CNC machining research by utilizing STEP-NC. Shixin et al[18] demonstrated a feature recognition approach for reverse engineering of machined parts by using STEP & STEP-NC. Hardwick et al[19] proposed a roadmap for vendor neural, STEP-NC enabled interoperable machining environment. Hu et al[20] proposed architecture of a STEP-NC controller for closed loop CNC machining.

Vendor neutral manufacturing data models developed for other non conventional manufacturing processes include: STEP-NC data model for wire electro discharge machining[21], Stone machining[22], Rapid prototyping[23], 2D flat sheet metal blank machining[24] and 2D flat sheet metal blank feature recognition and reasoning system[25, 26]. Research reported in the area of vendor neutral manufacturing process planning for sheet metal parts is very sparse as compared to prismatic and turned machined parts. Majority of the research related to vendor neutral manufacturing process planning of discrete sheet metal parts is aimed towards blank machining. Sheet metal blank machining resembles in most respects with material removal machining processes and therefore vendor neutral blank machining research can be thought as an extension of material removal machining processes[27].

Literature review indicates that research in the area of vendor neutral bending process-planning and programming for displacement controlled CNC pressbrakes is very sparse and partial. This paper investigates the area of discreet sheet metal parts design and manufacturing. An IT framework is developed based on contemporary standards STEP (ISO_10303 AP203,224,207), ISO_14649 and additional non-standard manufacturing information. Proposed framework utilizes product information, manufacturing procedure information and manufacturing resources used. Scope of this research is to develop a STEP & STEP-NC enabled design and manufacturing process planning framework for CNC pressbrakes to support knowledge retrieval.

3. STEP enabled manufacturing process planning for discrete sheet metal parts

STEP-NC provides an opportunity of feature based manufacturing process-planning and also facilitate the direct utilization of CAD data as input into the NC process chain. STEP-NC standard provides a vendor neutral bi-directional data model between design and manufacturing cycles. Departure of this vendor neutral bi-directional philosophy from conventional vendor specific unidirectional data philosophy is shown in Fig-1. Contemporary standards STEP&STEP-NC provide the basis of design and manufacturing process chain closure. Based on these standards, a framework is developed for design and manufacturing process-planning of discrete sheet metal parts bending. Significant feature of the proposed framework is the direct utilization of high level design information in the manufacturing cycle in the form of a work-plan, working steps and a mechanism of knowledge retrieval from manufacturing to the upstream design process. This framework is achieved by utilizing STEP (ISO_10303 Parts 203,224,207,219) and STEP-NC (ISO_14649 Part 10, 16) for product and manufacturing data models.

Process of vendor neutral discrete sheet-metal parts design and manufacturing is composed of several steps:

a. Vendor neutral product definition of the part.
b. Identification of individual manufacturing features and the associated tolerance requirements.
c. Identification of manufacturing resources required to manufacture individual features.
d. Manufacturing process-planning and programming for individual manufacturing features by utilizing product and manufacturing data models.
e. Execution of the manufacturing program.
f. Analysis of manufacturing results and feedback to product designer.

Three main aspects of discrete sheet-metal parts design and manufacturing process-planning covered in the proposed framework are: (1)Standardized product definition based on contemporary standards STEP&STEP-NC by encompassing shape definition and the associated tolerances (2)Standardized manufacturing planning by specifying overall strategy, manufacturing procedures, program execution and the required resources (3)Analysis of the manufacturing results and feedback to achieve integrated process control and for overall data utilization across CAx process-chain. Proposed framework produce generalized manufacturing process-plan by utilizing manufacturing data model and design data model. Fig-2 depicts an extract of the authors discrete sheet-metal part information models based on STEP data structure. Output of the framework is a generalized manufacturing process-plan to be executed on a CNC pressbrake. During the course of generalized manufacturing process-planning, part information is extracted from the part model to identify geometry and tolerance detail for the creation of work-plan and individual working steps. Manufacturing information model provides resource information as per required bending sequence. Analysis of the final bending results is used to feedback manufacturing knowledge acquired to the planning and programming phase.
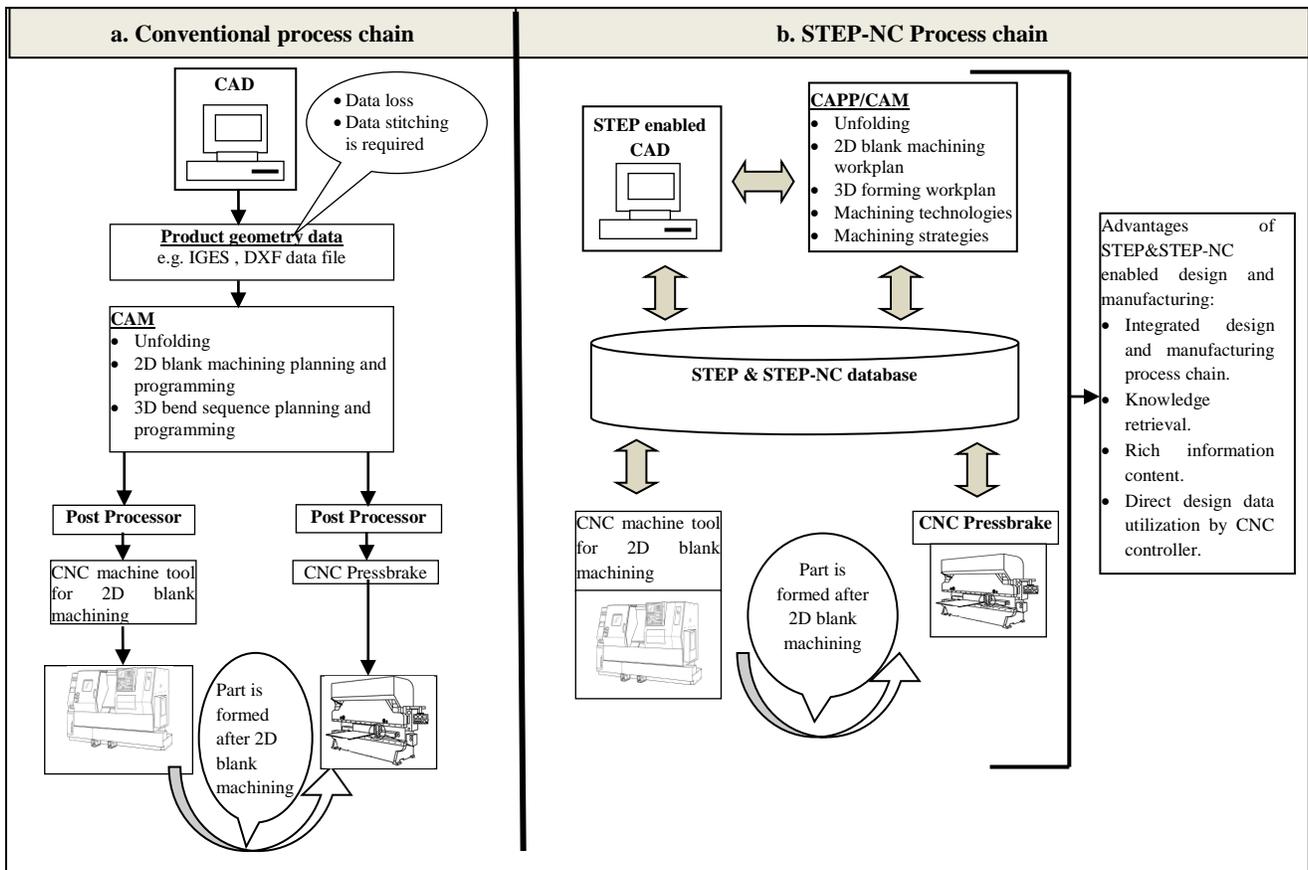

Figure.1 Comparison of conventional and STEP enabled design and manufacturing process chain for sheet-metal parts

3.1 Product information model for discreet sheet-metal component manufacturing

Discrete sheet-metal bent parts are composed of flat plates connected through a series of cylindrical section bends as shown in Fig-3. Overall part shape depends upon the direction and included angle of the individual bends. Individual plates contain two profile defining faces; rest of the faces are thickness defining faces. To evaluate individual bend angles and bend directions, concept of running surface is utilized. Bend angles of individual bends in Fig-3a&b are the same but bend directions are different. Both of the plates have rectangular profile and four thickness defining faces. Individual plates are connected with bends through thickness defining faces.

In order to compute face normal's of profile defining faces, edge loops are constructed in CCW direction[25]. Sheet-metal CAD, modeling starts with

the development of a base plate. Rest of the plates is arranged sequentially with respect to parent base plate[26]. As shown in Fig-3, plate-2 can be connected with plate-1 in two opposite directions. Bend directions are evaluated by taking the cross product of the surface normal vectors of individual plate profile defining faces. For this purpose both of the inner or both of the outer surface normal vectors of respective plates will be selected. This arbitrary selection is for the first plate connected to the base plate, for rest of the plates selection of individual face normal's will be dictated by the running surface generated by the primary bends. For a particular bend if the direction of cross product of face normal vectors is the same as that of the direction of the common edge of the edge loop of the second plate, bend direction will be upside with a concave profile. Accordingly if the directions are opposite, bend direction will be treated downwards with a convex profile.
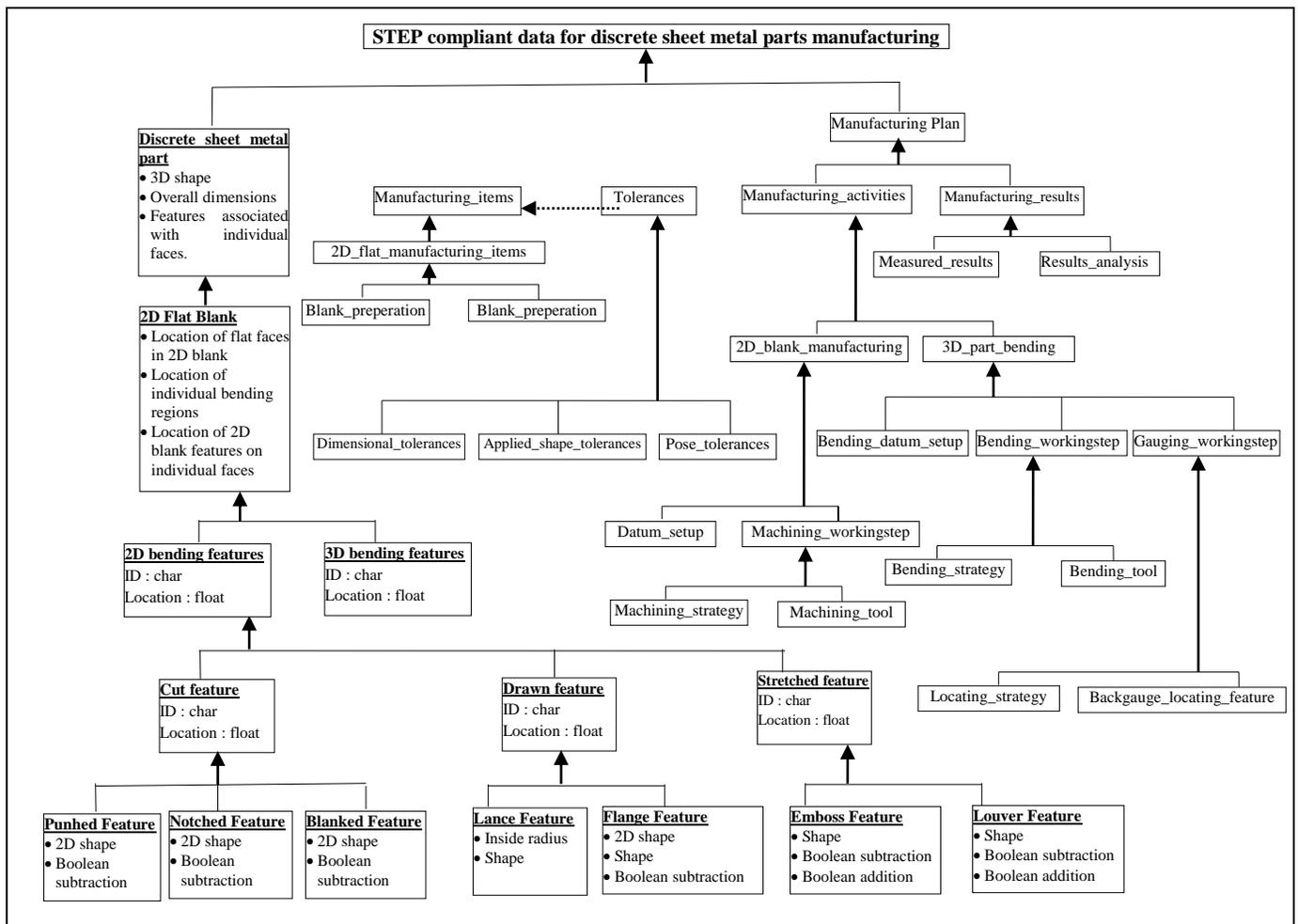
Figure.2 UML representation of STEP & STEP-NC enabled discrete sheet metal parts design and manufacturing

Product information model for discreet sheet metal parts supply necessary information regarding part shape, associated form and features to be manufactured. It also provides tolerance knowledge specified for overall part and individual features. Product information model actually encompass both design and manufacturing phases. Knowledge required to define geometry, features and the associated tolerances is obtained from STEP standards. Discreet sheet metal part information model, depicted in Fig-4(a) serves the purpose of an information centre by providing:

1. Component geometric information as defined in STEP (ISO-10303).
2. Individual locating and bending features.
3. Tolerances associated with overall part and individual features by utilizing STEP, STEP-NC and DMIS.

a. **First plate with respective face normal vectors and edge loops**

b. **Cylindrical bend with an axis to placement vector**

c. **second plate with respective face normal vectors and edge loops**

d. **Concave bend in upward direction**

e. **Convex bend in downward direction**
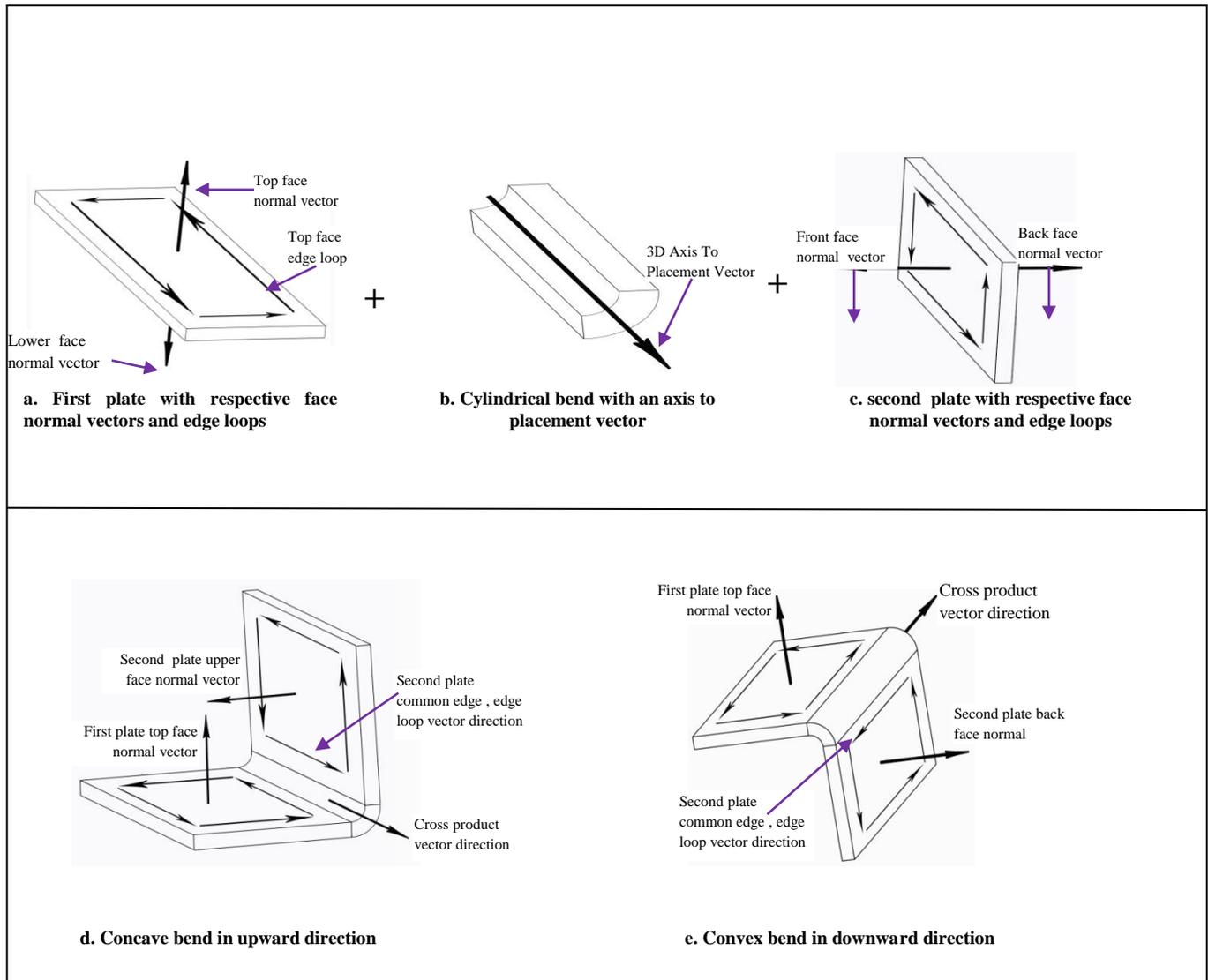
Figure.3 Cylindrical straight bends direction evaluation methodology
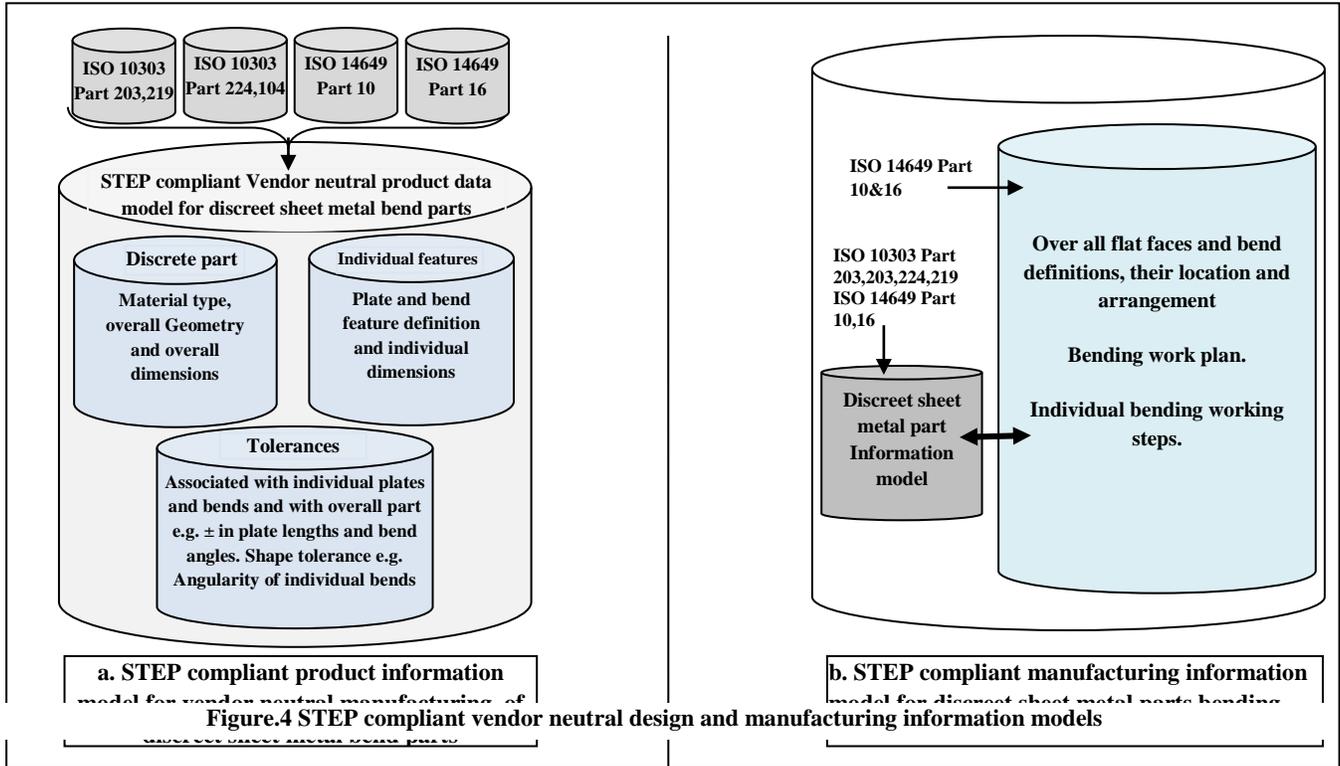
Figure.4 STEP compliant vendor neutral design and manufacturing information models

Some self defined entities are also developed to bridge the information gap found for discreet sheet-metal bend parts. EXPRESS-G diagram of the primary schema for this work is depicted in Fig-5. Discreet sheet-metal parts are composed of individual plates connected through bends. One of the plates in the discreet sheet-metal part will be a base plate to which all other plates will be connected

sequentially. Starting plate in a sheet-metal CAD model is known as base plate which is similar to a parent feature in solid CAD modeling of machined parts[28]. Base plate creation demands same care as is practiced during the creation of a base feature of a regular solid model. Rest of the plates are attributed as secondary plates. Secondary plates are referenced with respect to base plate.
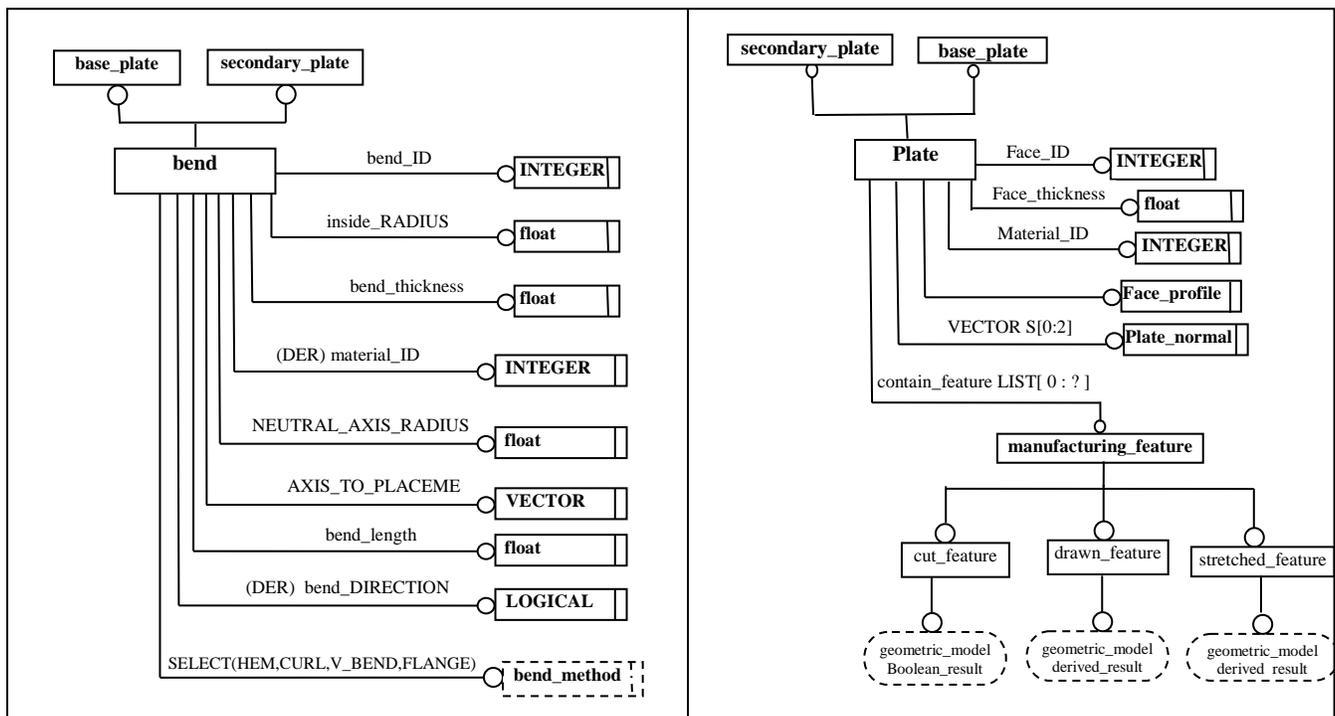
Figure.5 EXPRESS-G definition of cylindrical straight bends

EXPRESS entity definitions are as follows:

```
ENTITY plate
   ABSTRACT SUPERTYPE OF(ONE
     OF(base_face,secondary_face));
   Plate_ID          :INTEGER;
   Plate_thickness  :float;
   Material_ID      :INTEGER;
   Plate_profile_is :plate_profile;
   Contain_feature  : LIST[0:?]OF manufacturing_feature;
   Plate_normal     :VECTOR;
   DERIVE
   SELF\Plate.normal:VECTOR:=normal(plate_profile);
END ENTITY;
```

```
FUNCTION normal (PLANE_CROSS_SECTION):VECTOR;
(* compute normal of a plane*)
END_FUNCTION;
```

```
FUNCTION bend_DIRECTION(vec1,vec2:VECTOR);
(* compute cross product of two vectors"vec1"and"vec2"*)
LOCAL
     Vec1:=plate1.normal;
     Vec2:=plate2.normal;
END_LOCAL;
   IF bend_DIRECTION==1
       RETURN(bend_DIRECTION:=UP);
   ELSE
     RETURN(bend_DIRECTION:=DOWN);
END_FUNCTION;
```

Individual plates of discrete sheet metal part are populated with manufacturing features.

```
ENTITY manufacturing_feature;
   SUPERTYPE OF(ONE OF(cut_feature ,drawn_featue
   ,stretched_feature));
   SUBTYPE OF(geometric_item);
END_ENTITY;
```

3.2 Manufacturing information model for discrete sheet-metal component manufacturing

Manufacturing information model utilize knowledge provided by product information model and at the same time encompass data related to manufacturing process-planning, resources to be used, execution of resource programming, results analysis and final feedback of manufacturing results. Manufacturing process-planning and detailed part programming of the part to be manufactured depends upon the specific attributes of the CNC resource used. Fig-6 depicts the flow diagram of the proposed frame work and the mapping methodology of the final vendor neutral bending program to the CNC pressbrake. Output of the proposed framework is a generalized STEP_enabled feature based manufacturing process-plan for sheet-metal bending. This generalized plan could be a direct input to an intelligent STEP enabled process-control unit of a CNC pressbrake or can be interpreted into a vendor specific code for a conventional CNC pressbrake. Major feature of the proposed framework is the utilization of high level design and manufacturing information in terms of a bending work-plan, working steps and a bi-directional mechanism to feedback final bending results to the product designer. This purpose is achieved by utilizing STEP-NC part 10&16 and STEP part 238&219 for manufacturing data modeling. Sheet-metal part to be formed on a CNC pressbrake is defined in terms of geometry and main dimensions e.g. individual plate dimensions and flat blank geometrical profile etc. In the next step geometric and dimensional tolerances are added to the 3D part as well as 2D flat blank. The entity "work-piece" i.e. 2D flat blank, according to STEP-NC standard specifies material, surface condition and geometry in the form of a geometric model which is actually the state of some previous manufacturing operation e.g. sheet-metal shearing. Proposed framework has the object oriented data structure of STEP-NC standard for generating a bending process-plan file
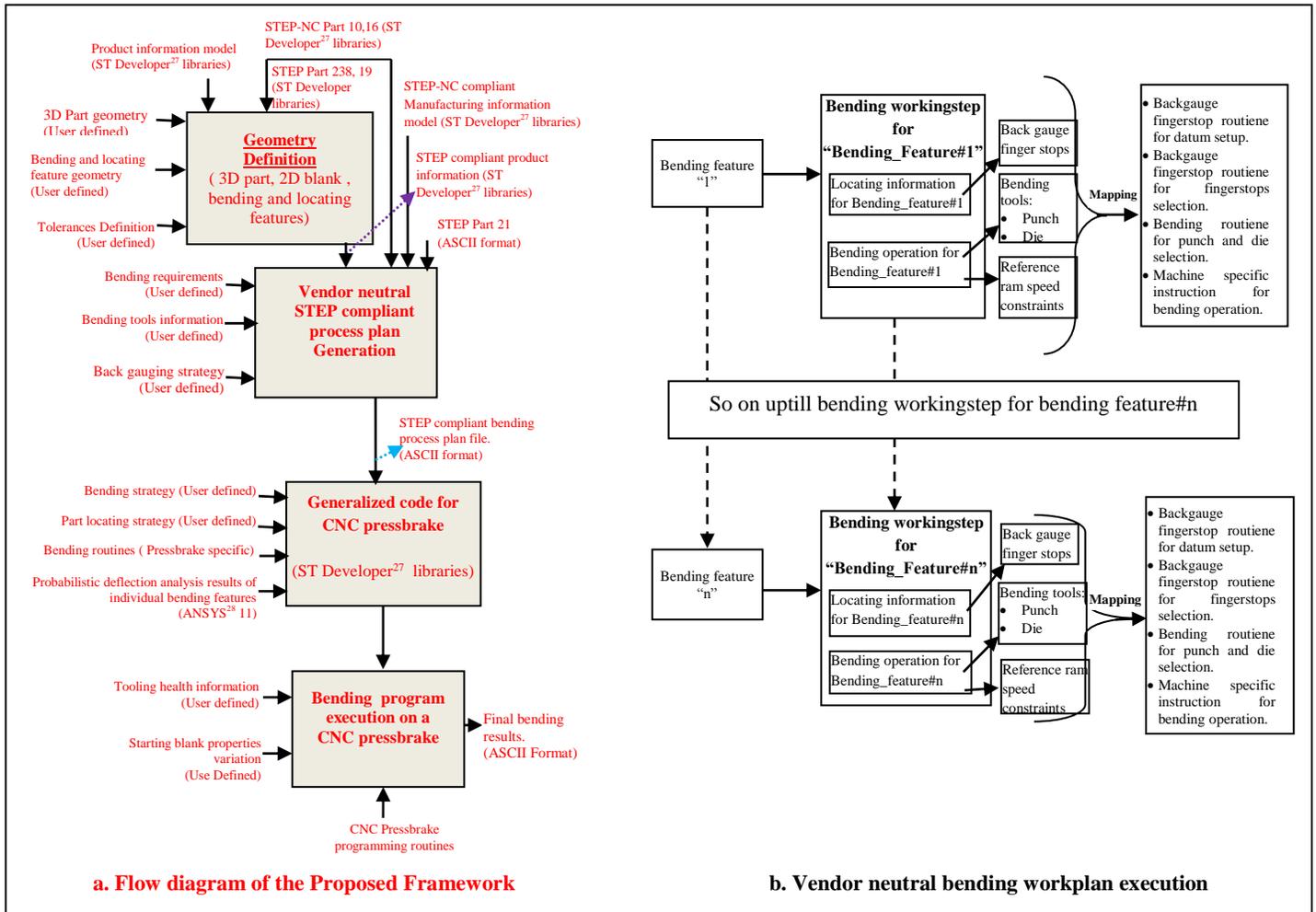
Figure.6 Working structure of the proposed vendor neutral design and manufacturing framework of discreet sheet-metal bend parts

Bending and locating features are defined by using 2½D manufacturing and transition features of ISO 14649-10. Geometric and dimensional tolerances are added to the main part as per ISO 14649 part 16 and ISO 10303 part 219. Geometric and dimensional tolerances are also added to each bending feature e.g."±" tolerance added to the inside bend radius as a dimensional tolerance and parallelism tolerances added to the individual plates of the part. Based on the geometrical information provided by product information model, individual bending features and bending requirements are defined. Currently insufficient information is available in STEP-NC standard for feature based sheet metal manufacturing. Manufacturing information model

generates a bending work-plan which contains executables i.e. bending working steps for each bending feature present in the part. Bending working step includes bending operation, punch and die information and the gauging strategy. Each bending working step refers to a result statement where actual measured results are stored. Bending work-plan for a discrete sheet metal part having "**n**" number of bending features is shown in Fig-6b. Information about the work-piece and bending features geometry and the bending and locating activities (work-plan, bending working steps etc.) is combined in a STEP-NC compliant bending file for a.CNC-pressbrake.

This file contains "Header" and "DATA" sections. Header section is composed of the project statement. Statements specifying information regarding part&feature geometry, bending items, associated tolerances ,work-plan, bending working step, bending and locating tools used etc ,are the part of the "Data section".

These statements are updated with actual results obtained after bending part on a CNC pressbrake. This file can be interpreted for a specific CNC pressbrake. Bending results obtained from bent part inspection are fed back to update the bending file. STEP-NC bending file is composed of a number of bending workingsteps. Ideally there is a single bending workingstep for each individual bending operation corresponding to individual bending features. Bending workingstep in the proposed STEP-NC file contains a set of bending items which can be combined into a single bending operation depending upon the availability of tooling and pressbrake capability. Individual bending working steps can be directly mapped for CNC pressrake specific bending instructions as shown in Fig-6b.

```
ENTITY sheet_metal_bending
    ABSTRACT        SUPERTYPE        OF        (ONE
    OF(air_bending,bottom_bending              ,coin_bending
    ,bottoming_with_springback));
    SUBTYPE OF(sheet_metal_forming);
    Punch_depth:            length_measure;
    Punch_speed:            time_measure;
    Its_forming_strategy:    bending_strategy;
END ENTITY;
```

Where "punch depth" is the total distance punch has to travel to form the required angle. Initial punch displacements are estimated for individual bends by Ludwik[1] circular straight model assumptions. Actual punch displacements are estimated by Montecarlo probabilistic deflection simulations and are fine tuned by forming test parts. Punch displacement result statements are updated after final part bending and can be utilized for future parts design and manufacturing process planning. "Punch_speed" is

the optional speed required for certain strain rate sensitive materials.

3.3 Bend sequence planning based on knowledge provided by product and manufacturing data models

Bending time and the dimensional accuracy depends upon the bending sequence. In sheet-metal bending shape of the part is achieved by plastic deformation. Metal sheets are subjected to both thickness and material properties variation. DIN 1541[29] allows 15-20% thickness variation for cold rolled steel sheets and 20% yield strength variation is allowed by DIN 1623[30].3D shape of the discreet sheet-metal part is achieved by bending 2D flat blank, dimensions and shape of whom are provided by product information model. 2D flat blank geometry is obtained by unfolding 3D sheet-metal part model, which is based on ideal conditions of constant blank thickness and material property conditions. In actual practice both of them vary within certain permissible level. Furthermore for the case of air bending, developed bend lengths also depend upon the geometry of bending tools[31]. Nominal Punch and die sets are used by manufacturers for discreet sheet metal parts bending. Due to this reason required 2D sheet metal blank differ in size from one manufacturing setup to other. Due to all these variations required blank size differ than that provided by the product information model. Blank size and geometry is fine-tuned after bending test parts and by utilizing empirical equations for bending region developed length calculation. In V-bending developed blank length and the inside radius depend upon the die opening length. Accuracy of the final bent part depends upon the accuracy in size of the starting 2D flat blank. In displacement controlled CNC pressbrakes angle bent on the part depends upon the punch displacement. Punch displacements are calculated to overcome the spring back. Sheet-metal bending is subjected to both material and process variations.

Inability of analytical models to tackle material and process variations arose the need of empirical equations to calculate blank sizes and ram displacements. Empirical equations utilize the most expected values of the material and process variations. In addition to all these blank size calculation errors, further error is caused during the blank shearing process. Bending errors generated during individual bending setups propagate during the execution of a bending sequence[32].

Propagation of bending errors depends upon the particular bending sequence adopted. That bending sequence is feasible from accuracy point of view which yields lowest cumulative error. Generation and propagation of bending errors is mostly studied by taking constant deterministic process and material variations[32]. In real life industrial practice material and process variations are probabilistic in nature. Therefore expected error for each bending setup "$E(e_i)$" is computed which is the probability weighted average error value of all possible errors of a particular bending setup. Total expected error for a discreet sheet-metal part composed of "n" bends is the summation of expected errors of individual bending setups i.e.

$$E(e) \quad = \quad \sum_{i=1}^{i=n} E(e_i) .... (1)$$

Montecarlo probabilistic deflection simulations are utilized in this work to compute expected error associated with each bending setup. Potential material and process variations used in the deflection simulations are :2D blank thickness variation ,blank size variation caused by the blank shearing process , Punch and die set alignment variation ,blank positioning error variation caused by back gauge finger stops, blank material yield strength variation ,punch displacement variation and the expected spring back variation .Analytical circular straight models compute spring back and developed blank lengths based on constant deterministic variables. Assumption of constant deterministic material and process variations cause an error of 0.3°-1° in spring back calculation and 5-10% error in developed bend length calculation[32]. Fig-7a shows a 2D flat sheet metal blank located from left side. Part after bending is shown in Fig-7b. As can be seen actual position of the bent leg deviates from the nominal. Expected error in the position of the bent leg is the cumulative sum of the expected errors: locating error, blank length error, punch and die misalignment and the spring back. For an individual bending event, "X" a random bending error,"η" is generated. Then "η_1 ,η_2 ,η_3,...... η_n" are the bending errors associated with ,"n" individual bending events with a standard deviation "σ".Total error generated by "n" individual bending trials is:

$$\Phi_n = \sum_{i=1}^{i=n} \eta_i \quad .... (2)$$

Expected error of the sum of "n" individual bending events is:

$$E(\Phi_n) = E(\sum_{i=1}^{i=n} \eta_i) = n\mu \quad .... (3)$$

a. Initial bending setup

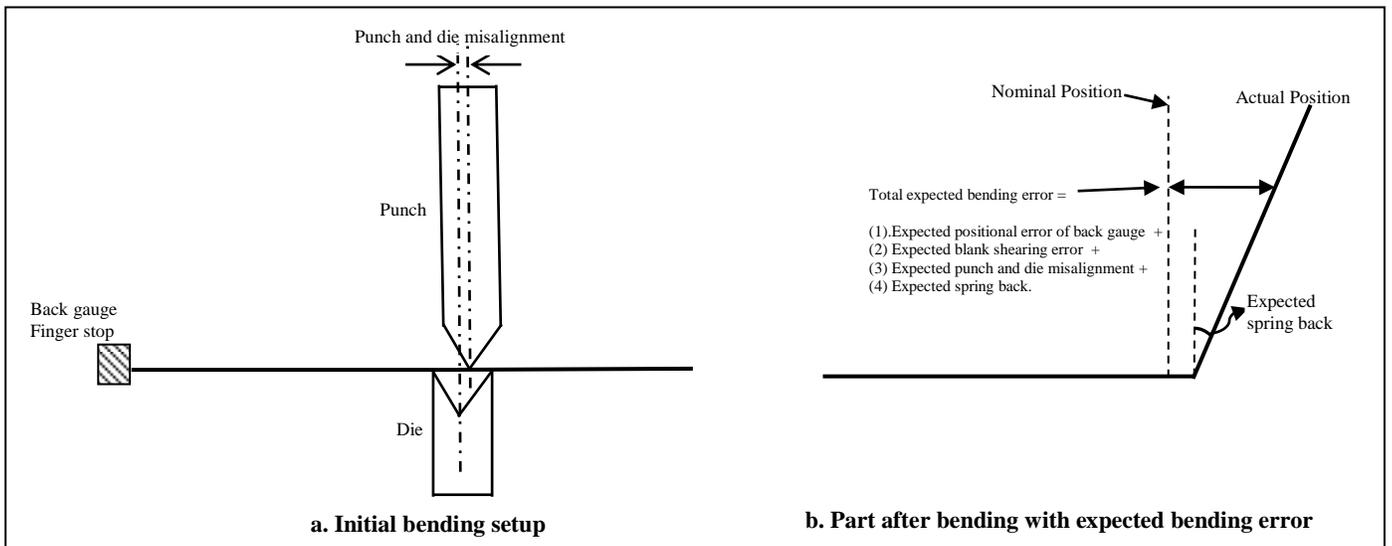**b. Part after bending with expected bending error**

Figure.7 Expected bending error caused due to process and material variations

Where "**μ**" is the population mean. "Central Limit Theorem" states that for any arbitrary interval (X1,X2), distribution of sum of "n" number of independent random trials greater than or equal to 30 will obey normal distribution[33]. According to the "rule of three sigma", probability for the sum "Φ_n" to lie within "**±3σ**" of the population mean is as follows:

$$\mathbf{Pr}\left\{\left|\frac{1}{n}\sum_{i=1}^{n}\boldsymbol{\eta}_i - \boldsymbol{\mu}\right| < \frac{3\sigma}{\sqrt{n}}\right\} \approx 99.8\%$$

(4)

From accuracy point of view that bending sequence will be optimum whose total bending error will be the lowest. Thus, for a bending sequence of "**n**" number of bends, cost function to be minimized is the cumulative expected bending error. Theoretically for, "**n**" number of bends, total of "**n!**" number of bend sequences are possible. Exhaustive search techniques therefore lend themselves infeasible for finding an optimum solution in such a huge solution space. Branch and bound, traveling sales man problem (TSP) algorithm proposed by Little et al[34] is utilized for evaluating potential feasible solution with lowest possible cumulative error.

4. Framework implementation for generation of manufacturing files for bending discreet sheet metal parts with straight line bends on CNC pressbrakes.

STEP compliant design and manufacturing framework for discreet sheet-metal parts bending is utilized in this case study for an industrial bracket.

Process of designing bracket in terms of flat sheet plates and individual bending objects is illustrated. Overall configuration of the bracket used in this work is the same used by Duflou et al[32] in their work. Material properties data and accuracy specifications were absent in their work. Material selected for this case study is 2mm Mild steel sheets. Young's modulus of the selected material is, "210 GPa" and Poisson's ratio "0.3". Fig-8a shows required final 3D shape of the bracket. Critical bracket dimensions to be maintained during bending are: leg lengths, distance between legs and base length. Fig-8b shows exploded view of the bracket, showing how this bracket is designed according to the proposed framework. Bracket is composed of 11 plates interconnected through a network of 10 individual bends. Inside radius of individual bends is taken equal to sheet thickness i.e. 2mm. Developed blank of 3D bracket is shown in Fig-8c. Developed blank dimensions are obtained by combining the lengths of flat sheet plates and the circumferential developed lengths of the individual bend features. In air bending included angle depends upon the punch displacement. Developed length and the bend inside radius depends upon the V-die opening width. Pressbrake tooling manufacturers devise empirical equations for the selection of tooling for various metal sheet grades. Punch and die tooling used in this case study for individual bends are from Cincinnati incorporated[31]. Tooling manufacturer recommends V-die opening width to be eight times blank thickness. For the case study part it is 16 mm. Now a V-die will be selected whose opening width will be closest to 16mm. Nearest available die in the available range has a die opening width of 19mm and the accompanying punch has a radius of 1.6mm. According to the empirical equations provided by manufacturer for mild steel, inside bend radius will be.2.9mm.

a. Required part 3D geometry

b. Exploded view , representing individual bends and plates of 3D part

c. Flat blank required for the part

d. Modified flat blank required for bending

Figure8.Case study part design and manufacturing scheme
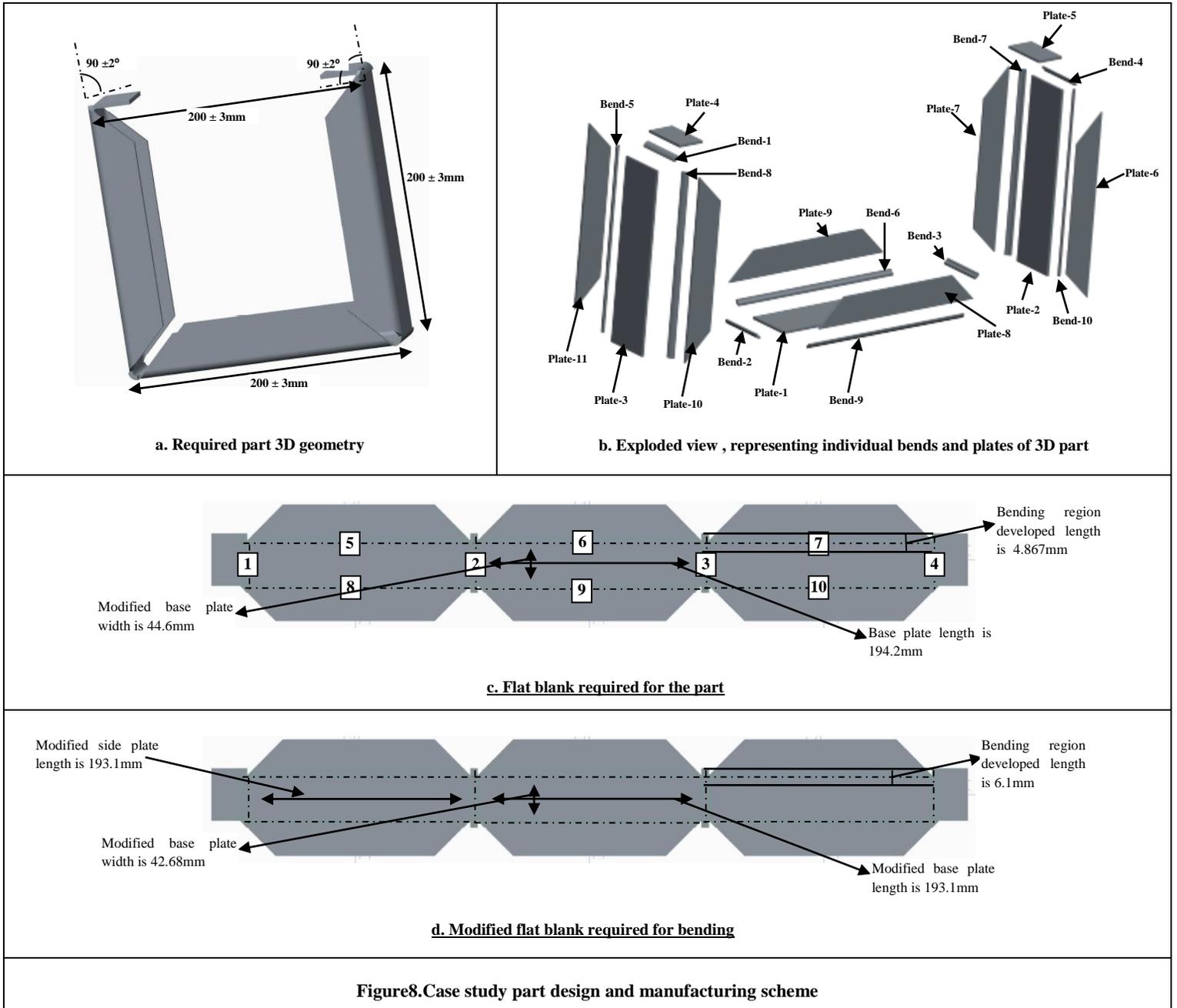
Standard deviations selected for material and process variations are:Ram reversal=0.2mm, punch and die centerline misalignment=0.3mm, back gauge positioning error=0.2mm, Blank thickness variation=0.1mm, Yield strength variation=50Pa and Blank length shearing error = 0.5mm. Monte Carlo probabilistic deflection simulations are run by utilizing ANSYS[36] programming capabilities. Fig-9 depicts relative frequency distributions of spring back and bends centerline deviation of bend-5. Expected cumulative bending errors evaluated from the respective frequency distributions and arranged in a FROM-TO error matrix shown in table 1 below.

a. Spring back frequency distribution for bend-1   b. Bend center line frequency distribution for bend-1
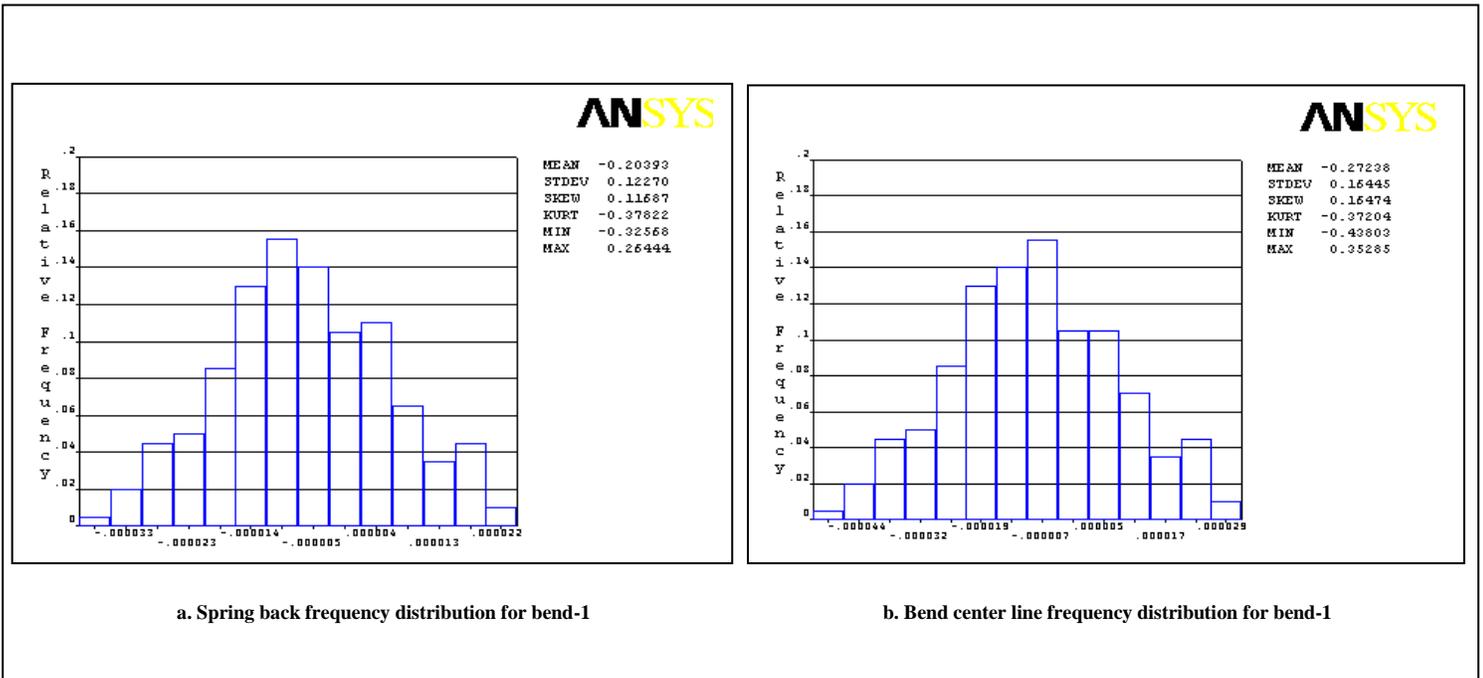
Figure9. Montecarlo probabilistic deflection simulation results for bend-5

Table 1.From_To error matrix

		1	2	3	4	5	6	7	8	9	10
Individual bends →											
Individual bend directions	1	∞	0.42	0.35	0.30	0.68	0.7	0.41	0.65	0.45	0.50
	2	0.6	∞	0.30	0.47	0.9	1.2	0.90	0.85	0.65	0.55
	3	0.43	0.8	∞	1.2	0.4	0.75	0.65	0.75	0.80	0.45
	4	0.80	0.25	0.9	∞	0.85	0.45	0.50	0.60	0.65	0.55
	5	1.3	0.6	0.45	0.95	∞	0.28	0.45	0.60	0.55	0.45
	6	0.95	0.68	1	0.85	0.5	∞	0.30	0.55	0.60	0.40
	7	0.70	0.75	0.60	0.90	0.85	0.55	∞	0.25	0.90	0.35
	8	0.90	0.60	0.45	0.40	0.85	0.75	0.75	∞	0.25	0.65
	9	0.65	0.85	0.55	0.60	0.60	0.60	0.40	0.45	∞	0.28
	10	0.20	0.80	0.85	0.55	0.55	0.50	0.40	0.40	0.40	∞

Work plan
Set of "10" Bending workingsteps

Bending workingstep-5
Bending workingstep-6
Bending workingstep-7
Bending workingstep-8
Bending workingstep-9
Bending workingstep-10
Bending workingstep-1
Bending workingstep-4
Bending workingstep-2
Bending workingstep-3

ASCII STEP File

#1=PROJECT('sheet_metal_project1',#14,(#2),$,$,$);
#2=WORKPIECE('bracket',,,$,$,#3);
#3=2D_FLAT_BLANK('upper_blank_plane',$,#159);
#4=BEND_1('circular_straight_bend',$,$,(#110,$,$));
#5=BEND_2('circular_straight_bend',$,$,(#123,$,$));

Bracket

2.28   2.46
5,6   **5,6**

2.31   2.52
6,7   **6,7**

2.32   2.58
7,8   **7,8**

2.32   2.7
8,9   **8,9**

2.32   2.91
9,10   **9,10**

2.32   2.91
10,1   **10,1**

2.32   2.91
1,4   **1,4**

2.32   2.91
4,2   **4,2**

2.32   2.91
2,3   **2,3**

a. Branch and bound error tree of test part

b.STEP-NC enabled bending process plan

STEP enabled CAD file is generated for all the plate and bend features entered.

STEP-NC enabled bending process plan file for CNC pressbrake is generated for the part.

c. Prototype IT platform for framework validation

Figure 10.Generation of vendor neutral bending process plan file for case study part

Branch and bound traveling sales man problem (TSP) algorithm proposed by little et al[34] in 1963 is used to solve this error matrix. Branch and bound tree generated by the algorithm is shown in Fig-10a. Maximum and minimum possible bending errors associated with each bend pair is written over bend pairs in dotted rectangles. Optimum bend sequence evaluated from the tree is [5,6,7,8,9,10,1,4,2,3] with a total expected bending error of 2.41mm.

A prototype IT system is developed by using ST-Developer Visual C++ programming libraries of STEP Tools Inc[35] to demonstrate the working of proposed framework. As shown in Fig-10c configuration of individual plate and bend features is entered in the prototype IT system. Software platform require tolerances for both plate and bend features. Once the configuration of all the plate and bend features is entered, software generates two files i.e. a STEP enabled CAD design file and a bending process plan file for CNC pressbrake process control unit. Both of these files are in character based physical file formats.

Individual bending working steps are arranged to conform to the optimum bending sequence evaluated. Optimum arrangement of bending workingsteps is shown in Fig-10b. Complete STEP-NC enabled bending process plan file generated by the prototype IT platform for the part is given at the end in APPENDIX. STEP enabled bending process plan file contains a bending work-plan which is 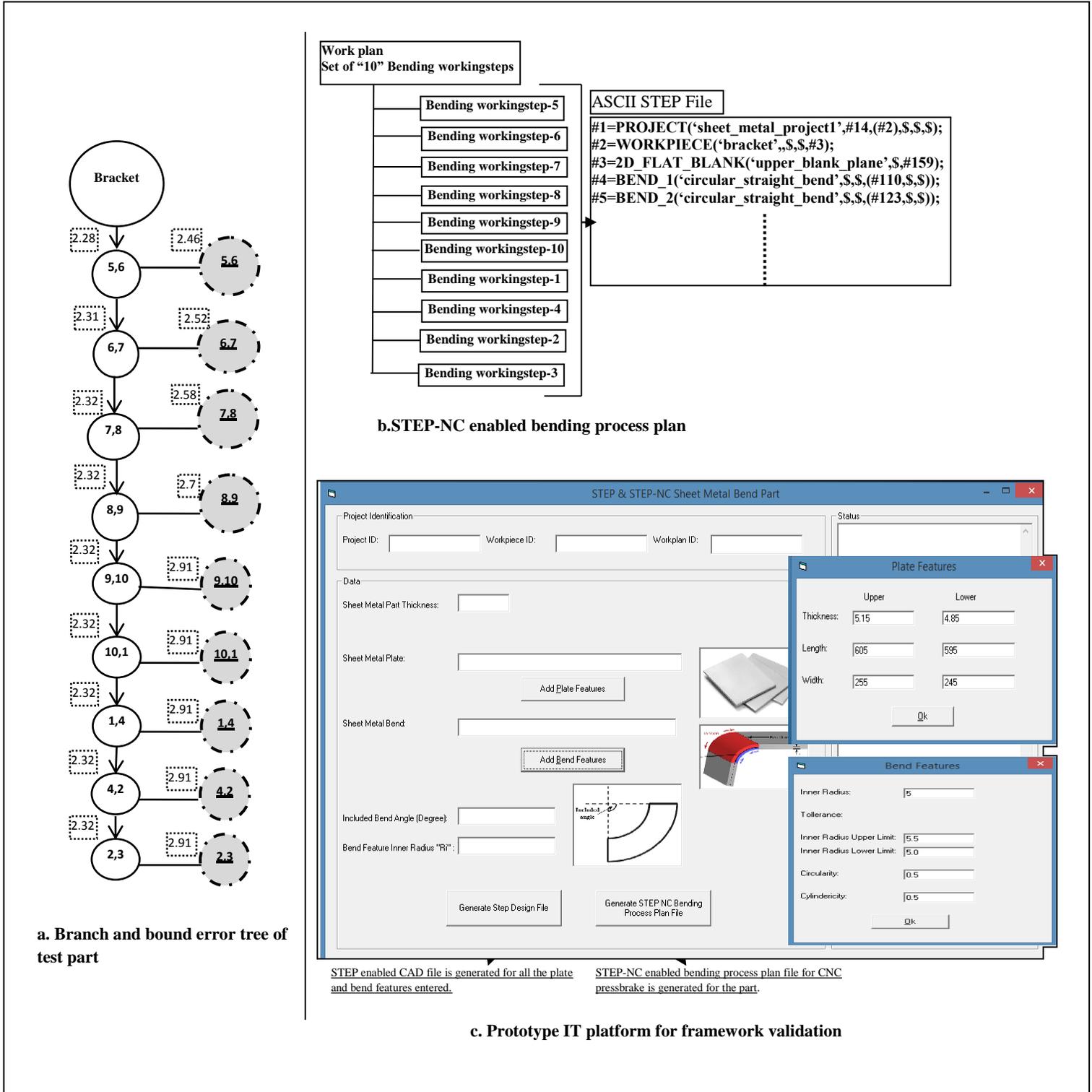composed of a total ten bending working steps. Individual bending working steps refer to corresponding result statements which can be updated at the end of the bending setups.

Work in this paper, propose a vendor neutral design and manufacturing process planning framework for discreet sheet-metal bend parts. Bend sequence planning depends upon process and material variations which vary from one manufacturing setup to other. Potential design parameters are readjusted at the manufacturing level. Proposed vendor neutral framework will help knowledge retrieval and is most suitable for the modern low quantity high variety manufacturing scenario.

Conclusion

Knowledge retrieval from the manufacturing stage is the most critical requirement of modern low quantity high variety sheet metal manufacturing scenario. Starting sheet metal blank is subjected to both thickness and properties variation. Design parameters of discreet sheet metal parts are almost always readjusted at the manufacturing stage to achieve the critical dimensional parameters. Potential knowledge is lost by the vendor specific design and manufacturing methodology used by the industry. Proposed framework is based on vendor neutral family of standards cumulatively known as STEP and STEP-NC. Missing information gaps are filled by self defined entities. This novel framework helps to bridge the gap between design and manufacturing cycles for discreet sheet-metal bend parts and facilitate knowledge retrieval from manufacturing stage to the upstream product designer

References

[1]..Ludwik, Technologische Studie i~ber Blechbiegung (Sonderabdruck aus den Technischen Bliittern), Deutschen Polytechnischen Vereins, BShmen, Prag, 1905.

[2] ISO10303-1,1994,"Industrial.automation.systems.and.integration_Product.data.representation.and.exchange – Part.1:.Overview.and.fundamental.principles",.(International.Organization.for.Standardization,.Geneva, Switzerland)

[3] ISO14649-1,2001,"Industrial.automation.systems.and.integration_Physical.device.control-Data.model.for computerized.numerical.controllers– Part.1:.Overview.and.fundamental.principles",(International.Organization.for

Standardization,Geneva,Switzerland),.TC184/SC1/ WG7,ISO14649/FDIS

[4] IMS.STEP-NC.Consortium.Technical.Report.3.of.IMS.Project.(97006).STEP-Compliant.Data.Interface.for Numerical.Controls.(STEP-NC),.(Report.Period:.Jan.01.–.June.31,.2003.

[5] Weck,M.and.Wolf,.J..ISO.14649.provides.information.for.sophisticated.and.flexible.numerically.controlled production,.2002.

[6] Wolf,.J.STEP-NC-integrating.shop.floor.into.industrial.data.flow.for.the.enabling.of.intelligent.near.to process.function,.2001

[7] Hardwick, M.,.On.STEP-NC.and.the.complexities.of.product.data.integration. .Transactions.of.the.ASME..J. Comp..Inform..Sci..Engg.,2004,.4,.60–67

[8] Suh,S.H.,Cho,J.H..and.Hong,.H.D.,.On.the.architecture.of.intelligent.STEP-compliant.CNC..Int.J.Comp. Integ..Manufac.,.2002a,.15,168–177.

[9] Suh,S.H.,Lee,B.E,Chung,D.H and why Cheon,.S.U.,.Architecture.and.implementation.of..shop-floor programming.system.for.STEP-compliant.CNC..Comp-Aid.Des.,2002b,35,1069–1083.

[10] Allen,R.D.,Harding,J.A.and.Newman,.S.T.,.The.application.of.STEP-NC.using.agent.based.process planning..Int..J..Prod..Res.,2004,43,655–670.

[11] Xu,X., and Realisation.of. andSTEP-NC.enabled.machining,.robotics.and.computer-integrated.manufacturing.Int.J. Prod.Res.,2005,22,144–153.

[12] L.Ali,S.T.Newman.and.J.Petzing,Proceedings.of.the. Institution.of.Mechanical.Engineers,PartB:Journal.of Engineering.Manufacture.2005.219:557,DOI:10.1243/095440505X32364

[13]Digital manufacturing: History, perspectives, and outlook. 2009. G Chryssolouris, D Mavrikios, N Papakostas, D Mourtzis, G Michalos and K Georgoulias.Proc IMechE Part B: J Engineering Manufacture 2009 223: 451. DOI: 10.1243/09544054JEM1241

[14] A meta-model of computer numerical controlled part programming languages .2015. Xianzhi Zhang, Aydin Nassehi and Stephen T Newman .Proc IMechE Part B: J Engineering Manufacture. DOI:10.1177/0954405415585084

[15]Sustainable machining approach for CAD/CAM/CNC systems based on a dynamic environmental assessment. 2016. Hery Andriankaja, Julien Le Duigou, Christophe Danjou and Benoıˆt Eynard. Proc IMechE Part B: J Engineering Manufacture. DOI: 10.1177/0954405416629104

[16] A unified manufacturing resource model for representation of computerized numerically controlled machine tools. 2009. P Vichare, A Nassehi, and S Newman. Proc IMechE Part B: J Engineering Manufacture. DOI: 10.1243/09544054JEM1363

[17] From computer-aided to intelligent machining: Recent advances in computer numerical control machining research.2015. Yingguang Li, Chen-Han Lee and James Gao. Proc IMechE Part B: J Engineering Manufacture. DOI: 10.1177/0954405414560622

[18] STEP-NC based reverse engineering of in-process model of NC simulation. 2016. Shixin Xú , Nabil Anwer , Charyar Mehdi-Souzani , Ramy Harik & Lihong Qiao. Int J Adv Manuf Technol.DOI 10.1007/s00170-016-8434-6

[19] A roadmap for STEP-NC-enabled interoperable manufacturing. 2013. M. Hardwick , Y. F. Zhao , F. M. Proctor , A. Nassehi , Xun Xu & Sid Venkatesh. Int J Adv Manuf Technol,DOI 10.1007/s00170-013-4894-0.

[20] Architecture and implementation of closed-loop machining system based on open STEP-NC controller. 2015.Po Hu , Zhenyu Han , Hongya Fu1 & Dedong Han. Int J Adv Manuf Technol. DOI 10.1007/s00170-015-7631-z.

[21] Sokolov,A.,Richard,J.Nguyen,V.K.,Stroud,I.,Maeder,W..and.Xirouchakis,P.,Algorithms.and.an.extended STEP-NC-compliant.data.model.for.wire.electro.discharge.mac

hining.based.on.3D.representations..Int.J.Comp. Integ.Manufac,2006,19,593–602.

[22] Stroud,I..and.Xirouchakis,P.,Strategy.features.for.communicating.aesthetic.shapes.for.manufacturing.Int. J. Comp.Integ..Manufac.,2006,19,639–649.

[23] Ryou,M.S.,Jee,H.S.,Kwon,W.H..and..Bang,Y.B.,Development.of.a.data.interface.for.rapid.prototyping.in STEP-NC.Int.J..Comp.Integ.Manufac.,2006,19,603–613.

[24] S.Q.Xie.&.X.Xu(2008)STEP-compliant.process.planning.system.for.compound.sheet.metal.machining, International.Journal.of.Production.Research,46:1,25-50,DOI:10.1080/00207540600818963

[25] T.R.Kanna.n&.M..S..Shunmugam(2009)Processing. of.3D.sheet.metal.components.in.STEP.AP-203.format. Part-I:.feature.recognition.system,.International.Journal.of.Production.Research,47:4, 941-964, DOI: 10.1080/00207540701510055

[26] T.R..Kannan.&.M.S..Shunmugam(2009).Processing. of.3D.sheet.metal.components.in.STEP.AP-203.format. Part-II:feature.reasoning.system,.International.Journal.of. Production.Research,47:5,1287.1308, DOI: 10.1080/00207540701510063

[27] Jagirdar,R.,Jain,V.K..and.Batra,.J.L.,.Charecterization.and.identification.of.forming.features.for.3D.sheet

metal.components.Int.J..Mach.Tools.Manufact.,2001 ,41,1295–1322.

[28] PTC,In.c(http://www.ptc.com/)..(URL.visit.date:23. May.2015)

[29] DIN.1541,Kaltgewaltzes.Breitband.und.Blech.aus.unlegierten.andStahlen,.Masse,.andzulaissige.Massun d Formabweichungen,and 1975

[30] DIN.1623,and Kaltgewaltzes.Band.und.Blech.aus.weichen.unlegierten.Stahlen,Gutevorschriften,1972.

[31] Cincinnati.incorporated,(URL.visit.date:23.May.2015) http://static1.1.sqspcdn.com/static/f/1520155/23188182/1374861578797/Bend+Allowance+low+res.pdf?token=HIiRAjuMKfSbKrwONBi2T9FGFvE%3D

[32] Duflou.J.R,Vancza.J.and.Aerens.R.Computer.aided. process.planning.andfor.sheet-metal.bending.Computers.in industry.56(2005)747-771

[33] Bluman_AG_Elementary.statisticsand:step.by.step.approach.3rd.ed.andNewYork:andMcGraw.Hill,2003, pp300–420.

[34] Little,J.D.C.,Murty,K.G.,Sweeney,D.W.and.Karel,C. 1963,An.algorithm.for.the.Traveling Salesman. Problem.Operations.Research,11,972-989

[35] ST-Developer-v-14.-CAD/CAM/BIM--"http://www.steptools.com/products/stdev

[36] ANSYS Inc. http://www.ansys.com/

Appendix

STEP enabled bending process plan for the case study part

#1=PROJECT('sheet_metal_project_casestudy',#14,(#2),$,$,$);
#2=WORKPIECE('bracket',,$,$,#3);
#3=2D_FLAT_BLANK('upper_blank_plane',$,#159);
#4=BEND_1('circular._straight bend',$,$,(#110.,$,$));
#5=BEND_2('circular_.straight_bend',$,$,(#123.,$,$));
#6=BEND_3('circular_straight._bend',$,$,(#121.,$,$));
#7=BEND_4('circular_straight_.bend',$,$,(#119.,$,$));
#8=BEND_5('circular_straight_bend',$,$,(#130.,$,$));
#9=BEND_6('circular_straight_bend',$,$,(#128.,$,$));
#10=BEND_7('circular_straight_bend',$,$,(#126.,$,$));
#11=BEND_8('circular_straight_bend',$,$,(#113.,$,$));
#12=BEND_9('circular_straight_bend',$,$,(#115.,$,$));
#13=BEND_10('circular_straight_bend',$,$,(#117.,$,$));
#14=WORKPLAN('bending_workplan1',(#15,#16,#17,#18,#19,#20,#21.,#22,#23,#24),#35.,$,$,$);
#15=BENDING_WORKINGSTEP('BEND_1',#4,#25,(#36,#37,#42,.#44,#45));
#16=BENDING_WORKINGSTEP('BEND_2',#5,#26,(#36,#37,#42,#44,#45));
#17=BENDING_WORKINGSTEP('BEND_3',#6,#27,(#36,#37,#42,.#44,.#45));
#18=BENDING_WORKINGSTEP('BEND_4',#7,#28,(#36,#37,#42,.#44,.#45));
#19=BENDING_WORKINGSTEP('BEND_5',#8,#29,(#36,#37,#42,#44,#45));
#20=BENDING_WORKINGSTEP('BEND_6',.#9,#30,(.#36.,#37.,.#42,.#44,.#45));
#21=BENDING_WORKINGSTEP('BEND_7',.#10,.#31,(.#36.,#37.,.#42,.#44,.#45));
#22=BENDING_WORKINGSTEP('BEND_8',.#11,.#32,(.#36,.#37.,.#42,.#44,.#45));
#23=BENDING_WORKINGSTEP('BEND_9',.#12,.#33,(.#36,.#37.,.#42,.#44,.#45));
#24=BENDING_WORKINGSTEP('BEND_10',.#13,.#34,(.#36,.#37.,.#42,.#44,.#45));
#25=BENDING_OPERATION(form BEND_1,$,(.#110,.#50),.#35.);
#26=BENDING_OPERATION(form BEND_2,$,(.#111,.#50),.#35.);
#27=BENDING_OPERATION(form BEND_3,$,(.#112,.#50),.#35.);
#28=BENDING_OPERATION(form BEND_4,$,(.#113,.#50),.#35.);
#29=BENDING_OPERATION(form BEND_5,$,(.#114,.#50),.#35.);
#30=BENDING_OPERATION(form BEND_6,$,(.#115,.#50),.#35.);
#31=BENDING_OPERATION(form BEND_7,$,(.#116,.#50),.#35.);
#32=BENDING_OPERATION(form BEND_8,$,(.#117,.#50),.#35.);
#33=BENDING_OPERATION(form BEND_9,$,(.#118,.#50),.#35.);
#34=BENDING_OPERATION(form BEND_10,$,(.#119,.#50),.#35.);
#35=BENDING_STRATEGY('USER_DEFINED',(.$,.$,.$,.$,.$,.$,.$,.$,.$,.$.), (.$,.$,.$,.$,.$,.$,.$,.$,.$,.$.),.$,.$);
#36=TOLERANCED_DIMENSION_ITEM(inside radius of bend,.#38.,$,(.#40.,#44.));
#37=TOLERANCED_DIMENSION_ITEM(bend angle,.#39,.$,(.#41.,#42.));
#38=TOLERANCED_LENGTH_MEASURE(.2.0,.#40.);
#39=TOLERANCED_ANGLE_MEASURE(.90,.#41.);

#40=PLUS_MINUS_VALUE(.2.50,.1.50.);
#41=PLUS_MINUS_VALUE(.92,.88.);
#42=TOLERANCED_POSE_ITEM(parallelism z,$,(.#35,.#43));
#43=PARALLELISM_TOLERANCE(.1.55,(.#35,$.));
#44=TOLERANCED_SHAPE_ITEM(.'.circularity .of bend',.$,(.#35,.#46.));
#45=TOLERANCED_SHAPE_ITEM(.'.cylindricity .of bend',.$,(.#35,.#47.));
#46=CIRCULARITY(.0.5,$);
#47=CYLINDRICITY(.0.5,$);
#48=CARTESIAN_POINT('null',(0.0,0.0,0.0));
#49=REFERENCE_DATUM_SETUP(#48);
#50=BENDING_TOOL('V die and punch set',$,$,$,$,$,$,$);
#51=DIRECTION('',(0.7071,-0.7071,0));
#52=DIRECTION('',(1,1,0));
#53=DIRECTION('',(0,1,0));
#54=DIRECTION('',(-0.7071,0.7071,0));
#55=DIRECTION('',(-0.7071,-0.7071,0));
#56=VECTOR('',#51,56.35);
#57=CARTESIAN_POINT('',(0.0,0.0,0.0));
#58=LINE('',#57,#56);
#59=VECTOR('',#52,143.35);
#60=LINE('',#58,#59);
#61=DIRECTION('',(0.7071,0.7071,0));
#62=VECTOR('',#61,56.35);
#63=LINE('',#59,#62);
#64=VECTOR('',#51,56.35);
#65=LINE('',#63,#64);
#66=VECTOR('',#52,143.35.35);
#67=LINE('',#65,#66);
#68=VECTOR('',#61,56.35);
#69=LINE('',#67,#68);
#70=VECTOR('',#51,56.35);
#71=LINE('',#69,#70);
#72=VECTOR('',#52,145.35);
#73=LINE('',#71,#72);
#74=VECTOR('',#61,56.35);
#75=LINE('',#73,#74);
#76=VECTOR('',#52,48.65);
#77=LINE('',#75,#76);
#78=VECTOR('',#53,48.65);
#79=LINE('',#77,#78);
#80=DIRECTION('',(-1,0,0));
#81=VECTOR('',#80,48.65);
#82=LINE('',#79,#81);
#83=VECTOR('',#55,56.35);
#84=LINE('',#82,#83);
#85=VECTOR('',#80,143.35);
#86=LINE('',#84,#85);
#87=VECTOR('',#55,56.35);
#88=LINE('',#86,#87);
#89=VECTOR('',#54,56.35);
#90=LINE('',#88,#89);
#91=DIRECTION('',(-1,0,0));
#92=VECTOR('',#91,145.35);
#93=LINE('',#90,#93);
#94=VECTOR('',#55,56.35);
#95=LINE('',#93,#94);
#96=VECTOR('',#54,56.35);
#97=LINE('',#95,#96);
#98=VECTOR('',#80,143.35);
#99=LINE('',#97,#98);
#100=VECTOR('',#55,56.35);

```
#101=LINE('',#99,#100);
#102=VECTOR('',#80,48.65);
#103=LINE('',#101,#102);
#104=DIRECTION('',(0,-1,0));
#105=VECTOR('',#104,48.65);
#106=LINE('',#103,#104);
#107=VECTOR('',#52,48.65);
#108=LINE('',#106,#107);
#109=VECTOR(0,1,0),48.65);
#110=LINE('',(0,0,0),#109);
#111=ORIENTED_EDGE('',$,#110);
#112=VECTOR('',#52,199.5);
#113=LINE('',#110,#112);
#114=ORIENTED_EDGE('',$,#110);
#115=LINE('',#113,#112);
#116=ORIENTED_EDGE('',$,#115);
#117=LINE('',#115,#112);
#118=ORIENTED_EDGE('',$,#117);
#119=LINE('',#117,#109);
#120=ORIENTED_EDGE('',$,#118);
#121=LINE('',#115,#109);
#122=ORIENTED_EDGE('',$,#121);
#123=LINE('',#113,#109);
#124=ORIENTED_EDGE('',$,#123);
#125=VECTOR('',#77,199.5);
#126=LINE('',#119,#125);
#127=ORIENTED_EDGE('',$,#126);
#128=LINE('',#126,#125);
#129=ORIENTED_EDGE('',$,#128);
#130=LINE('',#128,#125);
#131=ORIENTED_EDGE.('',.$.,.#.130);
#132=ORIENTED_EDGE.('',$.,.#.58);
#133=ORIENTED_EDGE.('',.$.,.#.60);
#134=ORIENTED_EDGE.('',$,.#.63);
#135=ORIENTED_EDGE.('',$,.#.65);
#136=ORIENTED_EDGE.('',$,.#.67);
#137=ORIENTED_EDGE.('',$,.#.69);
#138=ORIENTED_EDGE.('',$,.#.71);
#139=ORIENTED_EDGE.('',$,.#.73);
#140=ORIENTED_EDGE.('',$,.#.75);
#141=ORIENTED_EDGE.('',$,.#.77);
#142=ORIENTED_EDGE.('',$,.#.80);

#143=ORIENTED_EDGE.('',$,.#.82);
#144=ORIENTED_EDGE.('',$,.#.84);
#145=ORIENTED_EDGE.('',$,.#.86);
#146=ORIENTED_EDGE.('',$,.#.88);
#147=ORIENTED_EDGE.('',$,.#.90);
#148=ORIENTED_EDGE.('',$,.#.93);
#149=ORIENTED_EDGE.('',$,.#.95);
#150=ORIENTED_EDGE.('',$,.#.97);
#151=ORIENTED_EDGE.('',$,.#.99);
#152=ORIENTED_EDGE.('',$,.#.101);
#153=ORIENTED_EDGE.('',$,.#.103);
#154=ORIENTED_EDGE.('',$,.#.106);
#155=ORIENTED_EDGE.('',$,.#.108);
#156=EDGE_LOOP('',.$.,(.#.132, #.133, #.134, #.135., #.136,
#.137, #.138, #.139, #.140, #.141, #.142, #.143, .#.144, #.145,
#.146, #.147, #.148,. #.149, #.150, .#.151, #.152, #.153, #.154,
#.155));
#157=FACE_OUTER_BOUND('',$,156);
#158=AXIS2_PLACEMENT_3D('',(0.0,0.0,0.0),.#52,.#53);
#159=PLANE('',#158);
#160=ADVANCED_FACE('',#158,.#159);
#161=BENDING_RESULT(.#15,#35,$,$);
#162=BENDING_RESULT(.#16,#35,$,$);
#163=BENDING_RESULT(.#17,#35,$,$);
#164=BENDING_RESULT(.#18,#35,$,$);
#165=.BENDING._RESULT.(#19,#35,$,$);
#166=BENDING._.RESULT.(.#20,#35,$,$);
#167=BENDING._.RESULT.(.#21,#35,$,$);
#168=BENDING_RESULT.(.#22,#35,$,$);
#169=BENDING_.RESULT.(#23,#35,$,$);
#170=BENDING._RESULT.(#24,#35,$,$);
#171= GLOBAL._.K.-
.FACTOR._.OF._.SHEET._.METAL._.PART(0.5.)
#172=(.LENGTH._.UNIT(.)NAMED_UNIT(*)SI_UNIT(.MILLI.,
METRE.).);
#173=(.NAMED._.UNIT(*)PLANE_ANGLE_UNIT(.)SI_UNIT($
,.RADIAN.));
#174=PLANE._.ANGLE._.MEASURE._.WITH._.UNIT(.PLANE
._.ANGLE._.MEASURE.(1.7453E-2),#173);..
#175=.CONVERSION._.BASED_UNIT.('DEGREE',#174.)NAM
ED._.UNIT(*)PLANE._.ANGLE_UNIT(.).);
```