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Vključitev numeričnih analiz v zgodnjih fazah konstrukcijskega postopka

Introducing Numerical Analyses in the Early Phases of the Design Process

Tomaž Bučar - Miha Janežič - Primož Pangeršič - Matija Fajdiga

Odločitve, sprejete v razvojnem postopku izdelka, bistveno vplivajo na končno ceno, zmogljivost, zanesljivost, varnost in vpliv izdelka na okolico. Ker je poznavanje konstrukcijskih zahtev in omejitev v zgodnjih fazah proizvodnega postopka izdelka pogosto omejeno, je sprejemanje vsakršnih odločitev za konstrukterja zelo zahtevno. Soočeni s tako zapletenostjo so se posamezni konstrukterji omejili na ozke in dobro opredeljene podnaloge, kar ima za posledico neenotnost napredka na tem področju. V mnogih primerih je bil razvojni postopek izboljšan z računalniško podprtim konstruiranjem (RPK) in tehnikami numeričnih vrednotenj, kakor je metoda končnih elementov (MKE). Združitev obeh postopkov omogoča izračun napetostno-deformacijskih stanj izdelka in njegovo obnašanje pri različnih oblikovnih variantah. Podatke o napetostno-deformacijskih stanjih lahko pridobimo tudi z eksperimentalno analizo fizičnih preizkušancev, toda prednost postopka RPK-MKE je možnost spreminjanja oblikovnih in materialnih parametrov izdelka ter takojšnja numerična vrednotenja pred izdelavo fizičnih prototipov. Ker so računalniški modeli zgrajeni na podlagi mnogih predpostavk in omejitev, tudi rezultati analiz z metodo končnih elementov brez ustrezne razlage nimajo prave vrednosti. V prispevku je zato predlagana metoda za pridobitev referenčne baze podatkov, na podlagi katere poteka vrednotenje rezultatov numeričnih izračunov. Postopek gradnje baze podatkov je prikazan na konkretnem primeru ročne zavore in zavornega pedala osebnega vozila.

(Ključne besede: procesi konstruiranja, CAD, metode končnih elementov, načrtovanje preskusov)

Decisions made during the product development process have a significant influence on factors such as costs, performance, reliability, safety and the environmental impact of a product. However, since the knowledge of all the design requirements and constraints during this early phase of a product's life cycle is usually imprecise, approximate or unknown, the designer's decision-making is a very demanding task. Faced with such complexity, individual designers have restricted themselves to narrow, well-defined sub-tasks and, as a result, progress in this area has been patchy and spasmodic. In many cases, product design has been improved by the help of computer-aided design (CAD) and structural analyses based on the finite-element method (FEM). These two methods, coupled together, allow the calculation of mechanical quantities (such as stresses, deformations and contact pressures) and the investigation of the different behaviour of products with various designs. Such quantities can also be measured by means of in-vitro tests, but the advantage of CAD-FEM is the possibility of changing the geometrical and material properties of the product and evaluating its different behaviour before manufacturing prototypes. However, because the numerical models are based on many suppositions and restrictions, without proper interpretation the finite-element analysis (FEA) results are also of almost no use. Thus, in this article a method of acquiring a reference database, which serves for FEA results validation, is suggested. The procedure of building a suitable reference database is demonstrated by means of two examples, a car's handbrake and brake pedal.

(Keywords: product design, CAD, finite element methods, experiment planning)

0 UVOD

Konstruiranje je zahteven postopek, s katerim se zamisel o zadostitvi nove funkcije v naravi smiselno opredeli do najmanjše podrobnosti in predstavi v nematerialni obliki kot izdelek. Postopek

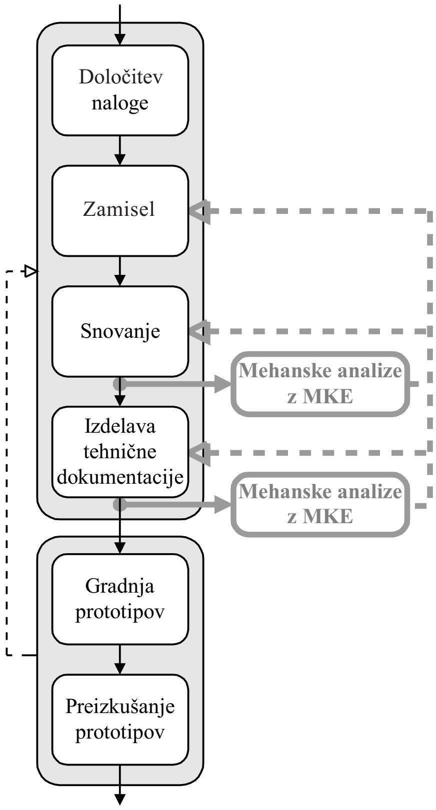
0 INTRODUCTION

Product design is a complex, iterative, decision-making engineering process, the result of which is transforming an abstract principle into a concrete technical solution. It usually starts with the identifikonstruiranja se običajno prične z razpoznavanjem in analizo naloge, ki jima sledi zaporedje dejavnosti, s katerimi iščemo optimalno rešitev problema, in konča s podrobnim opisom izdelka. Posamezne faze konstrukcijskega postopka so pri različnih avtorjih modelov opredeljene različno. Pregled najbolj znanih metod je podan v [1]. V splošnem je konstrukcijski postopek razdeljen na štiri glavne faze [2]. Prva faza je specifikacija naloge, pri kateri se natančno zberejo in določijo informacije o izdelku. Zasnova je druga faza konstrukcijskega postopka, katerega osnovni namen je iskanje idejnih rešitev, ki izpolnijo dano nalogo. Fazi zasnove sledi faza snovanja. V tej fazi se izdela natančen osnutek z določenimi osnovnimi merami in končno obliko. Zadnja faza je dodelava, ki vključuje optimiranje podrobnosti in izdelavo vse potrebne dokumentacije za izdelavo prototipov. S to fazo se konča konstrukcijski postopek v ožjem pomenu, kateremu sledijo še izdelava in preizkusi prototipov. Vse omenjene faze konstruiranja so prikazane na sliki 1. Računalniško podprta orodja so uveljavljena predvsem v končnih fazah konstruiranja, ki obsega določanje oblike in izmer. Razširitev računalniške podpore na zgodnje faze konstruiranja je v zadnjih letih glavni cilj raziskav na tem področju. Nekateri rezultati tovrstnih raziskav so podani v [3] do [5]. Običajno je končna oblika izdelka potrjena šele po intenzivnih in uspešnih eksperimentalnih vrednotenjih dragih fizičnih prototipov. Če testiranja niso uspešna, je treba izdelek na podlagi povratnih informacij večkrat popravljati, kar pomeni dodatne razvojne stroške in je lahko časovno precej zamudno. Da se izognemo nepotrebnemu izdelovanju dragih fizičnih prototipov, se razvoj računalniške podpore konstruiranju vedno bolj usmerja tudi na uporabo numeričnih vrednotenj in računalniških prototipov. Uporaba tehnik numeričnih analiz omogoča sprotno in učinkovito vrednotenje izdelkov brez izdelave fizičnih prototipov. Namen tega prispevka je prikazati trdnostno analizo z metodo končnih elementov kot eno od tehnik numeričnih vrednotenj, ki bo uporabna v zgodnjih fazah konstrukcijskega postopka (sl. 1). Ker tovrstne numerične analize temeljijo na poenostavljenih matematičnih modelih, je treba imeti za vrednotenje rezultatov na voljo primerjalno bazo podatkov. Glavni cilj raziskovalnega dela je zato razviti ustrezno metodo, ki bo ob najmanjšem dodatnem delu in stroških omogočala gradnjo kakovostne baze primerjalnih podatkov. Z uporabo kombinacije numeričnih vrednotenj in tehnik postopka RMS (FMEA, FTA) [6] lahko pridemo v zgodnjih fazah razvoja izdelka bistveno hitreje in z manj porabljenimi sredstvi do kakovostnih rešitev.

V nadaljevanju prispevka je najprej opisana predlagana metoda za gradnjo omenjene primerjalne baze podatkov. Uporaba metode je nato prikazana na dveh dejanskih primerih. Na koncu so podane še nekatere ugotovitve in sklepi.

cation of a need, proceeds through a sequence of activities to seek an optimal solution to the problem, and ends with a detailed description of the product. Researchers define individual phases of the design process in various ways. An overview of the most-known methods can be found in [1]. Generally, a design process consists of four phases [2]. The first phase is product design specification, where information about the product is collected and defined in precise yet neutral terms. Conceptual design represents the second phase of the design process, whose primary concern is the generation of physical solutions to meet the design specification. The conceptual design phase is followed by the embodiment design phase. In this phase, the precise layout and the form of the final product are developed. The final phase is the detailed design, where final decisions on dimensions, arrangement and shapes of individual components and materials are made and production documentation for manufacturing prototypes is completed. With this phase the product design, in a narrow sense, is concluded and followed by prototype manufacturing and testing. Figure 1 summarizes all the mentioned phases of the design process. Computer-aided tools are well established in the later phases of the design process, namely detailing and embodiment with modelling. Extending computer support to the early phases of the design process has been the main research aim in this area in the past few years. Some findings acquired in such researches can be found in [3] to [5]. Usually, the final product form is confirmed after intensive and successful experimental analyses of expensive physical prototypes. Unless experimental testing is successful, the product needs to be redesigned according to feedback information, which leads to further costs and time consumption. In order to avoid expensive and unnecessary prototype manufacturing, computer support for design is aimed at numerical validation and computer prototypes. The use of numerical analysis methods allows a consistent and efficient product evaluation without the need for expensive physical prototypes. The aim of this paper is to demonstrate the structural analysis based on FEM as a numerical analysis method applicable in the early phases of the design process (see Fig. 1). Since such numerical analyses are founded on simplified numerical models, a reliable reference database is required for the validation of FEA results. The main objective of such an approach, and therefore the focus of this paper, is to develop a suitable method that enables us to build a reference database of high quality with minimal additional efforts and costs. Using a combination of numerical analyses and RMS methods (FMEA, FTA) [6] in the early phases of the product design, we can solve the problem in a significantly faster and cheaper fashion.

In the next sections the method for acquiring the reference database is proposed and the procedure is then demonstrated in practice. To end with, some conclusions are given.



Sl. 1. *Faze konstrukcijskega postopka*

1 GRADNJA PRIMERJALNE BAZE PODATKOV

V fazi razvoja izdelka se za numerične analize z metodo končnih elementov uporabljajo bolj ali manj zahtevni matematični modeli, ki temeljijo na različnih omejitvah in predpostavkah. Tako ustvarjeni matematični modeli so nenatančni in dejanski izdelek opišejo le približno. Ker so zaradi tega približni tudi rezultati numeričnih analiz, morajo za njihovo vrednotenje obstajati primerne primerjalne vrednosti. Primerjavo za vrednotenje rezultatov pomeni primerjalna baza podatkov, ki jo pridobimo s predhodnimi numeričnimi izračuni in preizkusi. Predlagana metoda gradnje baze primerjalnih podatkov je prikazana na sliki 2. Predstavljeni postopek se opravi le enkrat, bodisi na že znanem izdelku ali na izdelku v razvoju. Izdelano primerjalno bazo podatkov je mogoče uporabiti tudi pri razvoju sorodnih izdelkov. Konstrukcijski postopek izdelkov se tako pospeši, saj ovrednoteni rezultati numeričnih analiz v veliki meri nadomestijo izdelavo in eksperimentalno analizo dejanskih prototipov. Uvajanje sprotnega in učinkovitega vrednotenja ter preizkušanja izdelkov na tako imenovanih računalniških prototipih je torej naš glavni namen.

Kakor smo že omenili, je na sliki 2 prikazan postopek za gradnjo kakovostne baze podatkov, na podlagi katere se v zgodnjih fazah razvoja izdelka vrednotijo rezultati numeričnih izračunov. V pretočnem diagramu je nazorno prikazano zaporedje posameznih

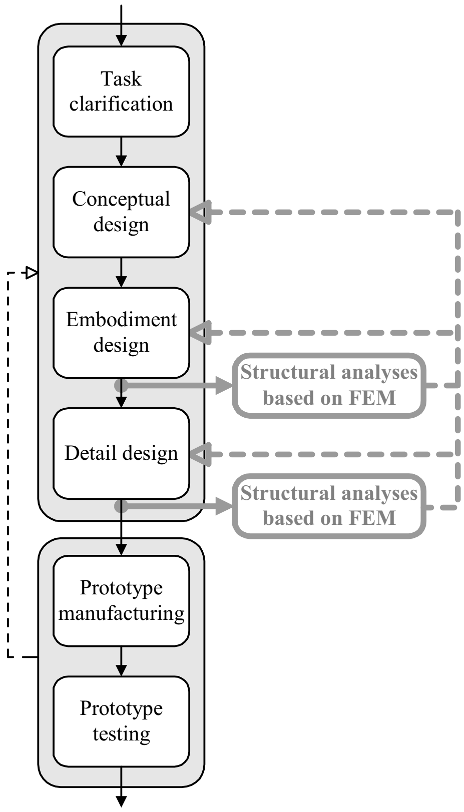
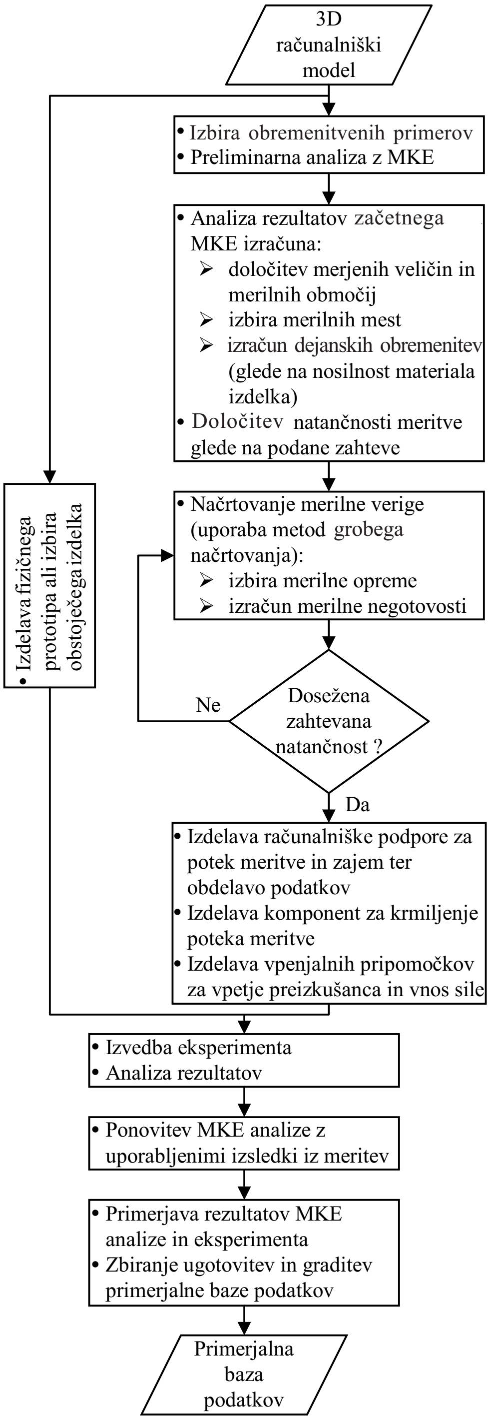


Fig. 1. *The phases of product design*

1 REFERENCE DATABASE ACQUISITION

During product design, various numerical models based on many suppositions and restrictions are used for finite-element analyses. Thus, such models are inaccurate and describe the physical product only approximately. Consequently, FEA results are also approximate, which is why comparative examples are required for their validation. These comparative examples are a reliable reference database that is acquired through preceding numerical calculations and experimental analyses. The suggested method for building a reference database is shown in Figure 2. The shown procedure is performed only once on the existing product or on the product in the development process. The elaborated reference database can also be used in the development of similar products. This way the product development process is accelerated, for the evaluated FEA results largely substitute for expensive prototype manufacturing and experimental analyses. The introduction of a consistent and efficient product evaluation using so-called computer prototypes is therefore our main purpose.

As mentioned, Figure 2 presents the procedure for reference database elaboration on which the evaluation of numerical calculations in the early phases of product design are based. The block diagram shows the sequence of tasks clearly. It is worth



Sl. 2. *Metoda za gradnjo primerjalne baze podatkov*

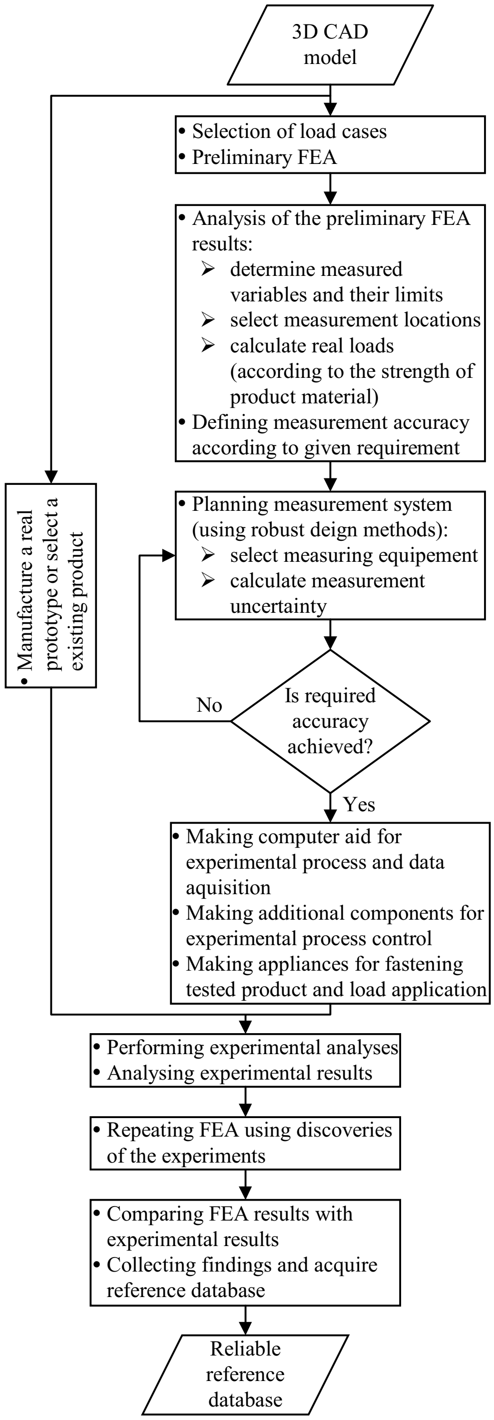


Fig. 2. *The method for reference database acquisition*

opravil, podrobnejša razlaga pa sledi na stvarnih primerih. Omeniti je treba le to, da je eksperimentalno preverjanje numeričnih rezultatov mogoče le z zelo kakovostnimi in premišljeno načrtovanimi preizkusi ([7] in [8]). Ker ima pri tem primeren in pravilno zasnovan merilni sistem pomembno vlogo, si pri izdelavi zamisli meritve pomagamo tudi z metodami grobega načrtovanja ([9] in [10]). Glavno načelo omenjene metode je izboljšanje kakovosti eksperimentalne analize z zmanjšanjem občutljivosti

mentioning that experimental verification of the FEA results is only possible by means of perfected and well-planned tests ([7] and [8]). Since a suitable and properly conceptualised measurement system plays an important role here, the method of robust design ([9] and [10]) can be of great help when preparing the experiment concept. The key principle of this method is to improve the quality of the experimental analysis through reducing the measurement system's sensitivity to disturbing factors. Our task is merilnega sistema na motilne dejavnike. Naša naloga je torej, da izberemo komponente merilnega sistema tako, da bo na izhodu iz sistema vpliv motilnih signalov na želenega čim manjši. Postopek izgradnje primerjalne baze podatkov bo v nadaljevanju prikazan na dveh realnih primerih.

to select the components of the measurement system in such a way that the influence of the disturbing signals on the chosen one is minimised. In the rest of the paper the procedure of reference database acquisition is demonstrated by means of two practical examples.

2 ZGLEDI

2 EXAMPLES

2.1 Ročna zavora

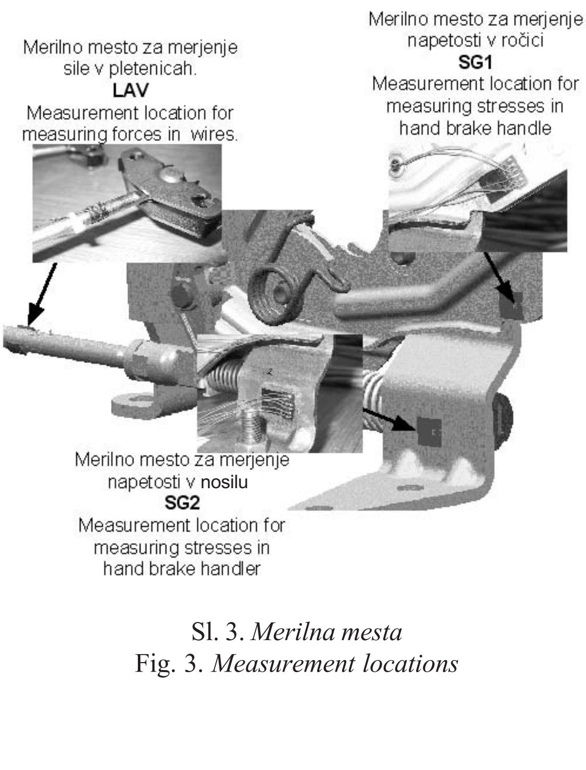
V tem poglavju je predstavljen sistem eksperimentalnega preverjanja numerične analize ([12] in [13]), s kakršnim na izdelkih določenega tipa gradimo bazo znanja. S tako pridobljeno bazo podatkov si v konstrukcijskem postopku podobnih izdelkov pomagamo pri gradnji modelov končnih elementov in pri vrednotenju rezultatov.

Da bi pred meritvami bolje spoznali napetostno in deformacijsko stanje pri izbranih obremenitvah, je bila izdelana začetna analiza z metodo končnih elementov. Z začetno analizo napetostnega stanja smo določili najprimernejša mesta na konstrukciji za merjenje napetosti. Ker smo za merjenje mehanskih napetosti izbrali merilne lističe, morajo imeti merilna mesta pri vseh obremenitvenih primerih razmeroma veliko napetost, njen gradient po površini pa naj bi bil čim manjši. Merilno mesto mora biti tudi geometrijsko primerno za namestitev merilnega lističa. Na podlagi rezultatov začetne analize sta se za najugodnejši mesti za merjenje napetosti izkazali mesti SG1 in SG2 (sl. 3). Na teh mestih se pojavijo razmeroma velike napetosti pri vseh obremenitvenih primerih. Izbrani mesti sta geometrijsko ustrezni za namestitev merilnih lističev in sta eno na ročici drugo pa na nosilu ročne zavore.

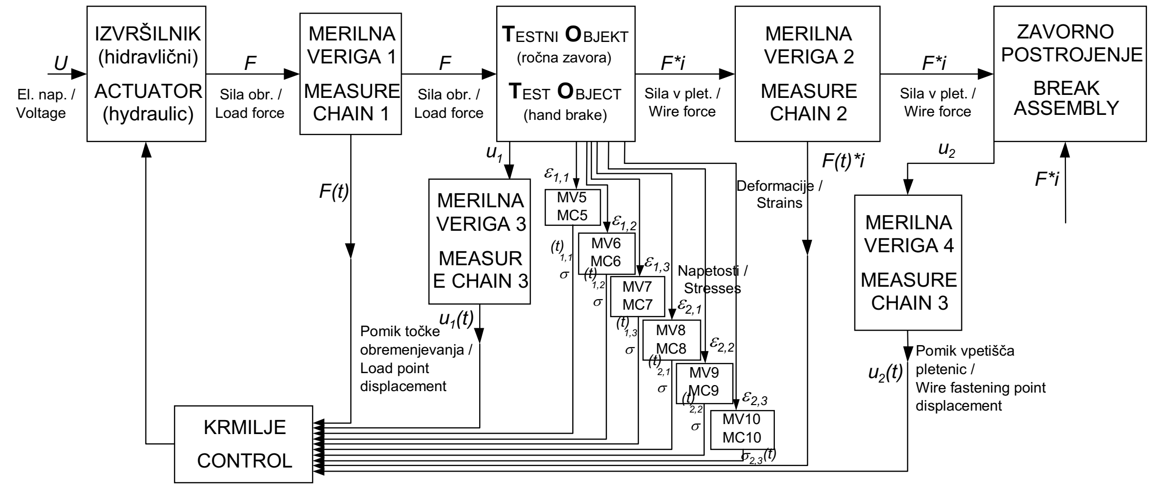
2.1 Handbrake

In this section we present a system for the experimental validation of numerical analysis ([12] and [13]) with which we can build a reference database that would help us when designing and validating similar structures. Such a database can, in the design processes of similar structures, help us to build finite-element models and validate numerical simulation results.

A preliminary analysis using the finite-element method was made in order to get to know better the stress and strain states in the chosen load cases. This preliminary stress-state analysis helped us define the most suitable locations to measure the stresses on the structure. Since we chose strain gauges to measure the mechanical stresses, all the measurement locations need to have a relatively high stress in all load cases, and the stress gradient on the surface needs to be as low as possible. Measurement locations also have to be geometrically suitable for placing strain gauges. On the basis of a preliminary analysis we found that the best locations for stress measurement were locations SG1 and SG2 (see Fig. 3). On these locations stresses are relatively high in all the load cases. They are also geometrically suitable for placing strain gauges: one is on the handbrake handle and the other on its holder.



Sl. 3. *Merilna mesta*
Fig. 3. *Measurement locations*



Sl. 4. *Sistemska slika preizkuševališča*
Fig. 4. *Experimental system scheme*

Celotno merilno verigo, uporabljeno pri eksperimentalnem delu, prikazuje slika 4. Poleg mehanskih napetosti so bile merjene tudi naslednje veličine: sila obremenjevanja ročne zavore, pomik točke vnosa obremenitev, sila v pletenicah in pomik vpetišča pletenic.

Napetosti na predhodno izbranih mestih so bile določene na podlagi deformacij, ki so bile merjene z merilnimi lističi s tremi mrežami HBM-RY91. Enako načelo je bilo uporabljeno tudi za merjenje sile v pletenicah, le da so bili pri tem uporabljeni merilni lističi z dvema mrežama HBM-XY11. Za merjenje sile obremenjevanja ročne zavore je bila uporabljena tlačno/natezna sonda proizvajalca HBM z znanimi karakteristikami. Merjenje pomika točke vnosa sile je bilo izvedeno z vrtljivo merilno letvijo (PMS-RML), ki deluje na načelu prirastkovnega dajalnika sunkov. Pomik vpetišča pletenic je bil merjen z linearnim variabilnim diferencialnim transformatorjem (LVDT). Karakteristike obeh zaznaval za merjenje pomikov so bile podane od izdelovalca. Za celoten merilni sistem je bila izdelana tudi analiza merilne negotovosti [11].

Obremenitveni primeri so bili prilagojeni za preračun z metodo končnih elementov. Za osnovo je rabil prevod tehničnih določil naročnika. V tem dokumentu bo obravnavan le najznačilnejši obremenitveni primer, tj. obremenitev ročice navzgor (sl. 5). Poleg tega sta bila obravnavana še obremenitvena primera z bočno obremenitvijo, in sicer prvi v sproščenem in drugi v napetem stanju.

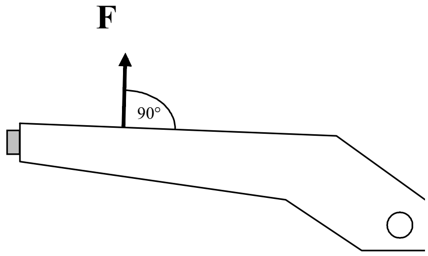
Slika 6 prikazuje z metodo končnih elementov dobljeno porazdelitev napetosti na mestih, kjer sta pri meritvi nameščena merilna lističa, pri obremenitvi 248 N. Na podlagi takšnih slik pri različnih obremenitvah dobimo sliko spreminjanja povprečne napetosti na merilnem mestu v odvisnosti od obremenitve. Primerjavo tako dobljenih rezultatov analize z MKE in

The complete measurement chain in the experiment is shown in Figure 4. Besides mechanical stresses the following quantities were also measured: handbrake loading force, displacement of the load-applying point, force in the wire and displacement of the wire-fastening point.

Stresses on the preliminarily chosen locations were defined on the basis of deformations that were measured by 3-grid strain gauges HBM-RY91. The same method was used for measuring the force in the wire, but 2-grid strain gauges HBM-XY11 were applied. To measure the handbrake loading force we used an HBM load cell RSCA 1t with known characteristics. The displacement of the load-applying point was measured by means of a linear incremental encoder (PMS-RML), which functions on the incremental rotary encoder principle, and the displacement of the wire-fastening point was measured by means of a linear variable differential transformer (LVDT). The characteristics of both sensors used were defined by the producers. For the entire measurement system an analysis of the measurement uncertainty was also performed [11].

All load cases were adapted for the finite-element method calculation, and based on the customer's technical specifications. This paper deals only with the most typical load case, that is, when the handle is loaded upwards (see Fig. 5). In addition to this, however, we also studied two load cases with the load directed sideways, one with the handbrake in loose state and the other in pretense state.

Figure 6 describes the stress distribution on the strain-gauge locations at maximum load 248 N as obtained with the finite-element analysis. On the basis of such figures at different loads, we can get a chart representing the dependence of the average stresses at measuring locations on the applied load. Figure 7 shows the comparison of the results obtained with the finite-element analysis with the results obtained from meas-



Sl. 5. *Vnos obremenitve*
Fig. 5. *Load application*

eksperimentalne analize prikazuje slika 7. Na ta način pridemo do spoznanja o velikosti odstopanja rezultatov simulacij od rezultatov meritev. Ker se rezultati simulacij nikdar ne ujemajo popolnoma z rezultati meritev, takšne primerjave ponovimo večkrat na podobnih konstrukcijah. Ob večkratnem ponavljanju meritev na podobnih konstrukcijah najdemo povezavo med rezultati simulacij in rezultati meritev. Takšni izsledki so že pomemben del baze znanja, ki bo pri prihodnjih konstrukcijah namenjena za to, da bomo lahko s simulacijo kar se da natančno ugotovili napetostno deformacijsko stanje ročne zavore.

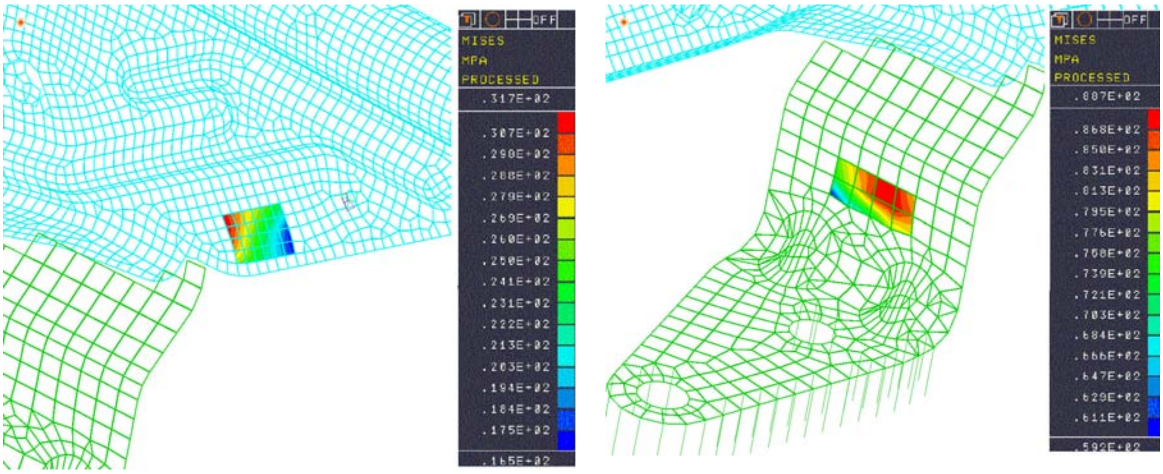
Krivulji na sliki 8 prikazujeta drugo vrsto rezultatov, ki prav tako sodijo v bazo znanja. Omenjeni potek predstavlja odvisnost sile v vpetišču pletenic od pomika le-tega, torej predstavlja togost celotnega zavornega sistema. V obravnavanem primeru se je izkazalo, da je izmerjena karakteristika bilinearna. To je sicer bolj ali manj splošno znano dejstvo, pa vendar značilen primer ugotovitve meritev, ki skupaj z numeričnima vrednostma obeh togosti sodi v bazo znanja. Značilna ugotovitev, ki sledi iz takšnega spoznanja je, da za natančno analizo podobnih konstrukcij z MKE uporaba linearnih reševanj zaradi nelinearnosti robnih pogojev ni zadostna. Za nadaljnje numerične simulacije podobnih konstrukcij je torej pomembno, da poprej pridobimo ali izmerimo podatek o togosti zavornega sistema ter nato izdelamo nelinearno analizo z MKE. Vsa zgoraj našteta spoznanja pa nenazadnje pripomorejo k znatnemu skrajšanju časa, potrebnega za izvedbo podobnih simulacij ob hkratnem izboljšanju zanesljivosti rezultatov.

Matematični model ročne zavore je bil v konkretnem primeru zgrajen z uporabo končnih elementov, izračunane vrednosti so nato primerjane z izmerjenimi vrednostmi. Po pričakovanju se je izkazalo, da se med dobljenimi rezultati pojavi določeno razhajanje, kar je v veliki meri posledica poenostavitev in predpostavk, uporabljenih pri analizi z MKE, ki dejanski model idealizirajo, npr. zveza med napetostjo in deformacijo je v celotnem območju obremenjevanja linearna (Hookeov zakon), vrednost elastičnega modula E je stalna, material je izotropen, debelina pločevine je po končnem elementu nespremenljiva.

urements. From this we can find the difference between the simulation results and the measurement results. Since the simulation results always vary from the measurement results, the comparison between the simulation and the measurement should be repeated and statistically treated on similar structures. With this method, the general rules of dependency between the measured and the simulated results that apply well to other similar structures can be acquired. Such general rules are an important part of a reference database, which would help us with an accurate stress-state estimation with simulations on similar structures in the future.

The diagram in Figure 8 shows other kinds of results, which can also play a significant role in building a quality reference database. This diagram represents the measured results of the dependency of the force in the wire on the displacement of the wire-fastening point, which represents the stiffness of the whole breaking system. In the discussed case, we can see that the stiffness has a bilinear characteristic. Although this is more or less a commonly known fact, it is still a characteristic example of a measurement result, which, together with both values of stiffness, belongs to a reference database. A characteristic finding, which follows from such a result, is that because of the nonlinearities (bilinear) included in restraints of this and similar structures, a simple, linear finite-element analysis for estimating stress states of this type of structure cannot be used. For further finite-elements analyses it is very important to measure or somehow provide a breaking system's stiffness characteristics and to use appropriate non-linear finite-element solvers. Finally, all the findings mentioned above contribute to a considerable shortening of the time needed for a realization of a finite-element analysis of similar structures and a simultaneous improvement of the results' reliability.

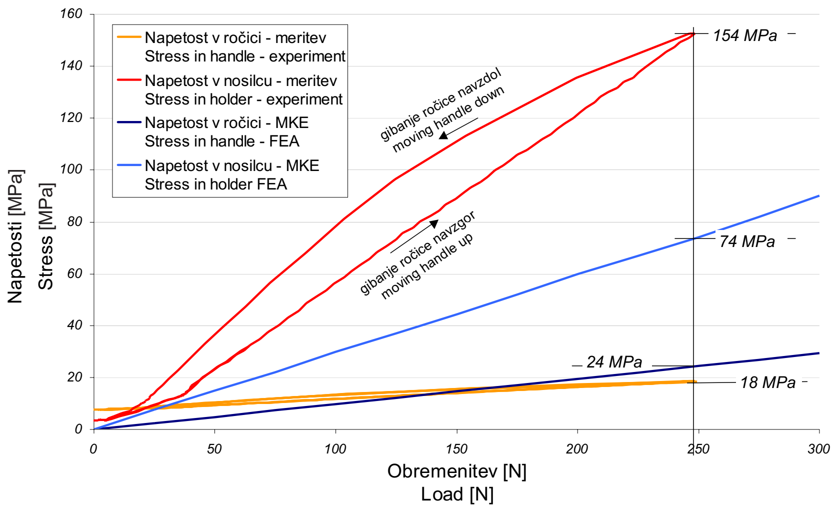
The mathematical handbrake model in this case was constructed with the help of finite elements. The calculated values are compared to the measured values. As we anticipated, it turned out that there was a considerable difference between the results obtained with each method, particularly with respect to the stresses. The finite-element analysis is based on a set of simplifications and suppositions that idealize the real model, e.g., the relationship between stress and strain is linear everywhere (Hooke's law), the value of Young's modulus (E) is constant, the material is isotropic, the thickness of the sheet is constant according to the finite element, etc.



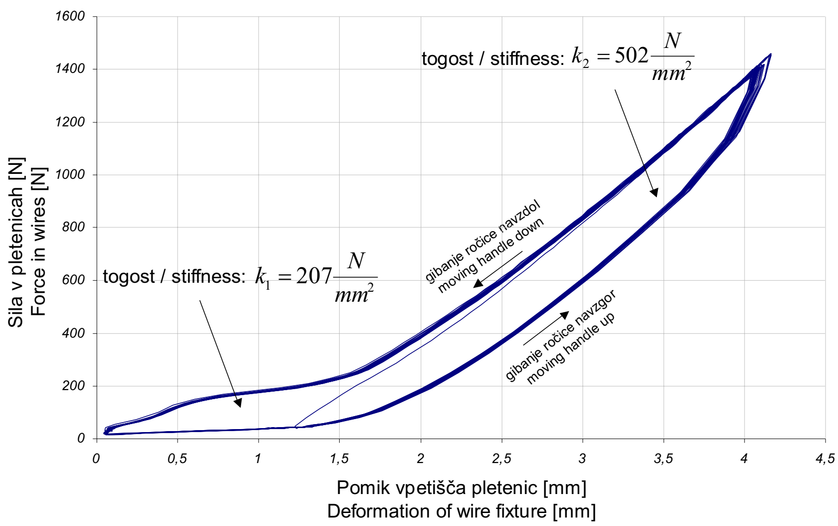
a) Ročica σ≈25MPa
a) Handle σ≈25MPa

b) Nosilec σ≈75MPa
b) Holder σ≈75MPa

Sl. 6. *Napetosti, dobljene z MKE na mestih merilnih lističev pri največji obremenitvi*
Fig. 6. *Stress distribution at strain-gauge locations during maximum load, obtained by FEA*



Sl. 7. *Napetosti kot funkcije obremenitve*
Fig. 7. *Stresses in the handbrake*



Sl. 8. *Togost zavornega sistema*
Fig. 8. *Stiffness of the whole braking system*

Pri izdelavi matematičnega modela se pojavlja tudi vprašanje modeliranja zračnosti in naleganja posameznih sestavnih delov. V primeru, da je naleganje dveh elementov v matematičnem modelu napačno, dobimo močno spremenjen fizikalni sistem, ki obravnavani dejanski sistem opiše napačno. Za izboljšanje zanesljivosti rezultatov simulacij in nenazadnje tudi baze znanja, bi bilo treba natančno raziskati tudi vpliv zgoraj navedenih parametrov na rezultate numeričnih simulacij in predvsem na njihovo odstopanje od rezultatov meritev.

2.2 Zavorna stopalka

Drugi zgled ustvarjanja baze podatkov in izpopolnjevanja postopka konstruiranja je predstavljen na primeru zavorne stopalke [14]. Na sedanji konstrukciji je bilo treba odpraviti problem prevelike bočne deformacije, ki se je pojavila v primeru testiranja ene od konstrukcijskih zahtev. Problem se je pokazal v primeru simulacije izstopanja voznika iz vozila, pri čemer si pomaga z odrivanjem desne noge od stopalke zavore. Za izboljšanje togosti konstrukcije je bilo treba to spremeniti, vendar s poudarkom na najmanjših stroških, ki bi spremljali to spremembo. Poglavitni namen je bil poiskati najšibkejši del konstrukcije in ga ustrezno izboljšati, tako da bi konstrukcija ustrezala predpisani zahtevi, tj. dovoljena bočna deformacija sredine stopalke zavore, kar je prikazano na sliki 9.

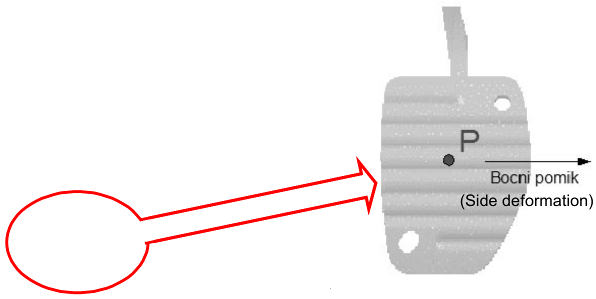
Za sedanjo konstrukcijo je bila najprej izdelana linearna napetostno-deformacijska analiza z MKE. Dobljeni rezultati vedno pomenijo določeno odstopanje od dejanskega stanja, zato je nujno potrebno določiti velikostni razred odstopanja. Tega določimo z ustrezno izvedenim preizkusom oziroma meritvijo, ustreznost rezultatov meritev pa je mogoča le z natančno izdelanim merilnim sistemom. Do razlik pride zaradi poenostavitev pri analitičnem delu in merilne negotovosti pri eksperimentalnem delu. Ob poznavanju obeh pa lahko določimo usmeritev oz. neko bazo znanja, ki omogoči cenejše in hitrejše

When making the mathematical model, we face two problems: how to model looseness and how to model contacts between component parts. If the contact between two elements in the mathematical model is not correct, we get a totally different physical system, which describes the discussed real model incorrectly. To improve the reliability of the simulation results and the reliability of the reference database, we should make an exact investigation of the influence of the mentioned parameters on the results of the numerical simulations and on their deviation from the measurement results.

2.2 Brake Pedal

The second example of database acquisition and the imperfection of the design procedure is shown for the case of a pedal assembly [14]. The existing design needed to be improved because its lateral deformation, when testing one of the structural demands, was too large. This boundary condition simulates a driver leaving the vehicle, while using the brake pedal as a support for his/her right leg. The design had to be modified to improve the stiffness, but with minimum costs. The weakest part of the structure was identified and improved so that the new structure will fulfil all the structural demands, in particular the allowed size of the lateral deformation (the centre of stepping area of a brake pedal - point P), shown in Fig.9.

A linear stress-strain analysis was made for the existing structure with a finite-element method (FEM). The results always deviate from reality, so the magnitude of the deviation had to be established. This was done with an appropriately performed experiment together with an exact measurement system. The differences are a result of simplifications in the analytical work and the measurement uncertainty of the experiment. When both of them are known, a database can be created, and this can be helpful when cheaper and faster modifications to similar structures have to be produced. The results of the strength analysis can be



Sl. 9. *Predmet testiranja*
Fig. 9. *Testing object*

spreminjanje sorodnih konstrukcij s podobnimi poenostavitvami. Pri načrtovanju merilnega sistema torej bistveno pomagajo rezultati analitičnega dela, tj. trdnostnih analiz, s katerimi določimo npr. velikost merilnih območij in ustrezno izberemo merilno opremo.

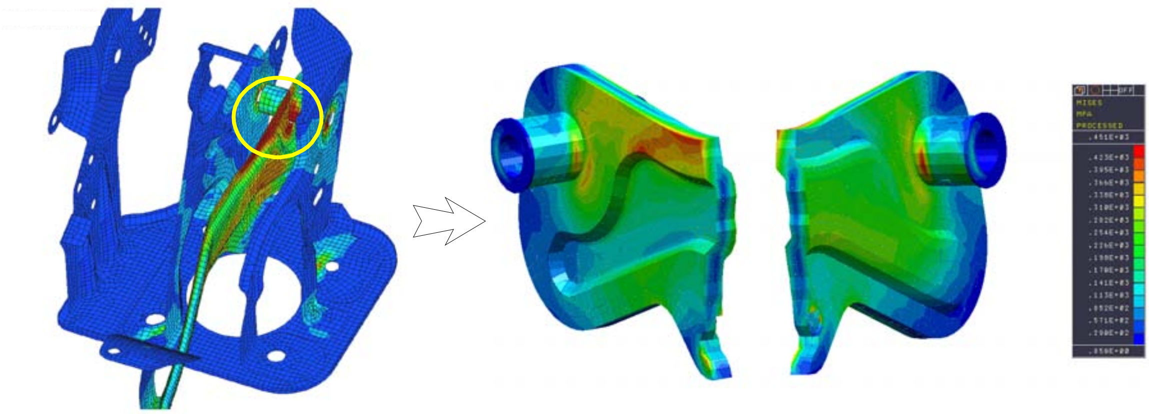
Trdnostna analiza je potekala v dveh delih. Prvi del analize je potekal na celotnem sestavu zavore in rezultat je pokazal, da se večinoma deformira stopalko zavore, nosilo pa precej manj. Posebej veliko področje velike napetosti v materialu naj bi bilo na zgornjem delu stopalke zavore in okoli spoja med stopalko in jekleno cevjo (=vrtišče). Omenjeni spoj na sedanji konstrukciji je bil izveden kot krčni nased in rezultat prvega dela trdnostne analize je nakazoval, da ta spoj lahko bistveno prispeva k velikosti bočne deformacije. S preoblikovanjem tega spoja bi torej lahko zmanjšali nastali problem. Drugi del trdnostne analize je bil narejen na bolj natančnem modelu stopalke zavore, s tem, da so bile upoštevane tudi plastične puše, ki so montirane v vrtišču stopalke. Ker stanja v krčnem nasedu med stopalko in cevjo ne moremo zadovoljivo modelirati, je bila uporabljena srednja možnost med krčnim nasedom in varjenjem pedala in cevi. Torej smo že uporabili zamisel, kako bi preoblikovali sedanjo stopalko zavore. Tudi natančnejša analiza je potrdila velike napetosti v okolici spoja cevi in stopalke (sl. 10).

Glede na dobljene rezultate drugega dela trdnostne analize smo povzeli, da ta del konstrukcije bistveno prispeva k velikosti bočnih deformacij, predvsem zaostalih bočnih deformacij v primeru preobremenitev. To predpostavko je bilo treba potrditi ali ovreči z izvedbo meritve na stopalki zavore. Dobljeni rezultati so pomagali pri nadaljnji izbiri merilne opreme in načrtovanju merilnega mesta. Zaradi prej omenjenega dogovora pri modeliranju stopalke zavore smo načrtovali izvajanje meritev na sedanji in spremenjeni izvedbi stopalke zavore. Pri varjeni izvedbi smo pričakovali boljše ujemanje rezultatov.

very helpful when planning the measurement system because it is easier to define a measurement range and choose the appropriate equipment.

The strength analysis was made in two steps. First, the whole structure was analyzed. The results showed that the most deformable part of the structure is the brake pedal and not the support. The areas with stresses higher than the yield stress are on the top of the brake pedal and around the joint of the pedal and the steel tube (= revolution point). The joint on the existing structure was made with a compressive forming technology, and because the results of the stress analysis imply that this joint could have a large influence on the magnitude of lateral deformations and its modifications could result in resolving the problem. The second step of the strength analysis was done on a more exact model of the brake pedal, where the plastic sliding elements in the revolution joint were also considered. Because the stress-strain state in the compression joint cannot be modelled satisfactorily, a compromise between the compression-forged joint and welded joint of the pedal and tube was used. Basically, the idea of how to modify the existing brake pedal had been already used. The results of the second step of the strength analysis confirmed that areas of high stress appear around the joint of the pedal and tube (see Fig.10).

According to the results of the second part of the strength analysis we concluded that this structural part contributes significantly to the size of the lateral deformations, mostly to the residual deformations in the case of overloading. This assumption should be confirmed or refuted with an experiment. The results of the strength analysis were helpful when we planned the measurement system and choose equipment for it. Because the model used for the FEA was a compromise between a compressed and a welded joint, measurements were planned for both the existing and the modified brake pedal. The results for the welded brake pedal were expected to be closer to the results of the FEA.



Sl. 10. *Rezultati napetostno deformacijske analize – primerjalna napetost*
Fig. 10. *Results of stress-strain analysis – comparative stress*

Predpisani pogoji preizkušanja zahtevajo, da je merilni sistem sestavljen tako, da je mogoče nadzorovati dejanske vhodne signale glede na zahtevane vhodne signale (dejanska sila F_D proti zahtevani obremenitvi F_R). Med testiranjem je treba zbirati podatke v točki P (pomik).

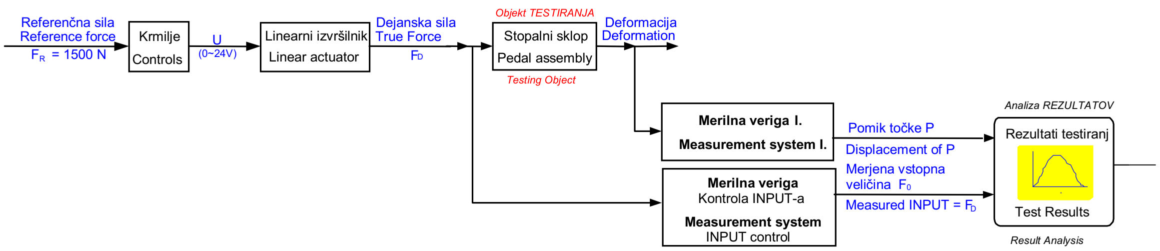
Na izbiro elementov merilnega sistema so bistveno vplivali rezultati trdnostne analize, saj smo tako lahko določili zahtevano merilno območje opreme in zaznaval ter preverili merilno negotovost obeh merilnih verig, ki naj bi bila nižja od 0,5%. Negotovost je bila določena za vsako merilno verigo posebej, in sicer z metodo najmanjših kvadratov. Zaradi statične obremenitve konstrukcije so bile za nas pomembne statične karakteristike merilne opreme. Na slikah 12 in 13 je v shemah prikazana izbira merilne opreme.

Meritve bočnih deformacij smo izvedli na treh nakrčenih stopalkah in treh varjenih stopalkah. Dobljeni rezultati meritev so potrdili naše domneve, ki so izhajale iz rezultatov trdnostnih analiz z MKE. S slike 14 je razvidno, da so razlike med analitičnimi in eksperimentalnimi rezultati, pri obremenitvi 1000 N, manjše kakor pri obremenitvi 1500 N, kar je posledica omejitev linearne trdnostne analize, saj ta ne upošteva plastifikacije materiala. Dobljeni rezultati potrjujejo domneve, da so rezultati pri varjeni izvedbi bližje rezultatom analize z MKE. Ugotovimo lahko, da nakrčena izvedba stopalke zavore omogoča večje bočne pomike pri preobremenitvi s silo 1500 N kakor varjena izvedba. Prav tako pa se pojavijo večje trajne deformacije

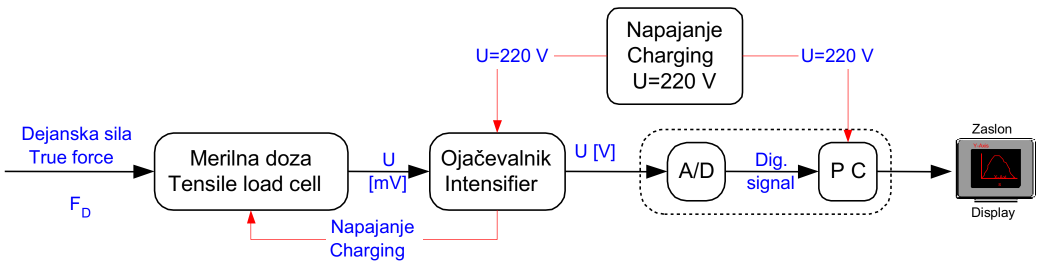
The prescribed testing conditions state that the measurement system should be able to control the true input signal given by the reference input signal (F_D vs. F_R). During the testing procedure a data acquisition of the displacements of the point P should be performed automatically.

The selection of the elements for the measurement system (the measurement range of the sensors and other equipment) was influenced by the results of the strength analysis. The measurement uncertainty for both measurement systems was checked. It needed to be lower than 0.5%. The measurement uncertainty was calculated with a mean-square method. The implied load was static, and that is the reason why we were only interested in the static characteristics of the measurement equipment. Figures 12 and 13 show the equipment that was chosen for both measurement systems.

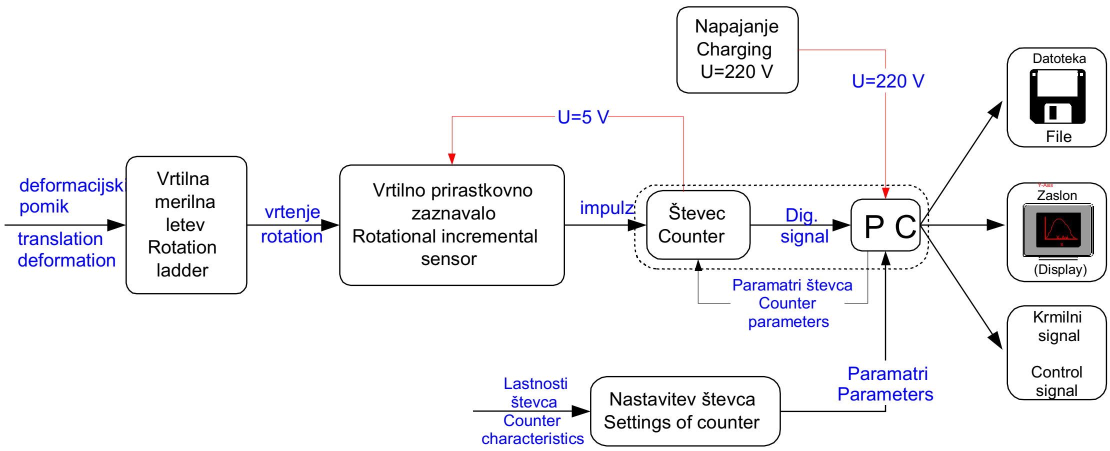
A measurement of the deformation was carried out on three brake pedals with a compression-formed joint and on three pedals with a welded joint. The results of the experiment confirmed our assumptions based on the FEA results. Figure 14 shows that the differences between the analytical and the experimental results at the lower load (1000N) are smaller than at the higher load (1500N). The reason for this is that the linear strength analysis does not consider different material properties after the yield-stress limit is reached. The results of the experiment for the welded pedal also confirmed our assumption that the FEA results should be closer to the experimental results. We concluded that the compressed joint allows a larger lateral deformation when an overload of 1500N is applied. After the load is



Sl. 11. *Shema merilnega sistema*
Fig. 11. *The measurement system scheme*



Sl. 12. *Merilna shema - merilna veriga nadzora vstopnega signala*
Fig. 12. *Measurement scheme - measurement system: control of input*



Sl. 13. *Merilna shema - veriga I*
Fig. 13. *Measurement scheme - system I*

po razbremenitvi stopalke. To je potrdilo rezultate trdnostne analize, da je pedal eden kritičnih delov, ki jih moramo spremeniti, da bi izpolnili zahtevane pogoje. Stopalka zavore prispeva precejšen delež k velikosti zaostalih deformacij tudi takrat, ko je montiran v sestavu stopalke.

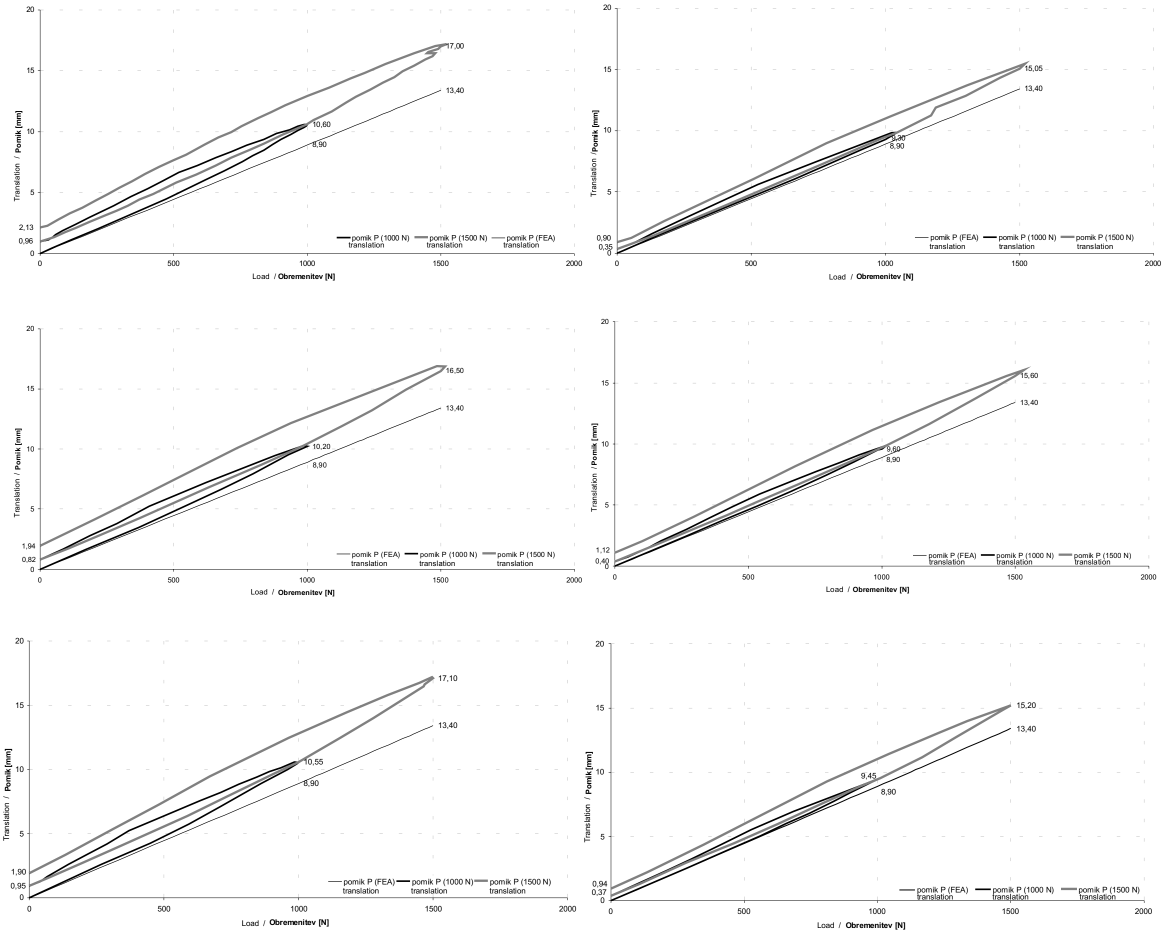
Nakrčen spoj očitno omogoča lokalne deformacije oziroma popustitev pri preobremenitvi. Varjena izvedba se zato izkaže za ugodno spremembo pri postopku izdelave, kljub temu, da to prispeva nekaj dodatnih stroškov. Ta izvedba pomeni zmanjšanje elastične in trajne bočne deformacije pedala. Slednja se zmanjša za približno 1 mm.

Izkazalo se je, da je način s katerim smo se lotili reševanja problema pravilen in da se s tem precej skrajša celoten postopek popravljanja sedanje konstrukcije. Z izdelavo analize sedanje konstrukcije smo dovolj dobro ocenili kritična mesta in sestavne dele, ki pojasnujejo problem, tj. prevelika trajna bočna deformacija sredine stopalke zavore. Na vsak način je treba poznati omejitve programa, s katerim je bilo opravljeno analitično delo, in seveda vse poenostavitve, ki smo jih privzeli pri izdelavi modela, ki naj bi pomenili približek k dejanskemu stanju. Rezultate trdnostnih analiz smo uporabili le kot smernice k načrtovanju merilnega mesta za testiranje, saj zaradi poenostavitev modela ne morejo biti izraz dejanskega stanja. Dejansko stanje smo določili z eksperimentalnim delom. Dobljene smernice so pomenile predvsem določitev kritičnega elementa konstrukcije (stopalka zavore) in pričakovano merilno območje (0 do 20 mm), ki ga bodo morala pokrivati zaznavala. Po teh podatkih je potekalo načrtovanje merilnega mesta in določitev merilne negotovosti za posamezno merilno verigo. Pokazala se je pomembnost te faze načrtovanja merilnega mesta, saj se je izkazalo, da izbrana oprema omogoča zahtevano natančnost meritev (0,5%). Rezultati testiranj so potrdili kritičnost sestavnega dela, ki smo ga določili s trdnostno analizo. Ker so razlike med analitičnimi in eksperimentalnimi rezultati razmeroma velike, se je z opisanim postopkom ustvarila pomembna primerjalna baza podatkov za vrednotenje rezultatov podobnih analiz z MKE.

removed, the remaining permanent deformation is also bigger. That is why we are convinced that the pedal is one of critical parts in the structure that had to be changed to satisfy structural demands. The brake pedal contributes a significant share to the total deformation of a structure when it is mounted.

A compression-formed joint obviously allows local deformations to appear when an overload is applied. We saw that this joint suddenly relaxes. Although the welded joint is more expensive it does have benefits. This modification results in a reduction of the elastic and residual plastic deformation of the brake pedal by approximately 1mm.

We showed that the method used for resolving the problem was correct. The process of design modification was shortened. Based on the results of the FEA we are able to correctly define the weakest part of a structure, which is the reason for the inadequate stiffness of the overall structure. However, we have to keep in mind the limitations of the FEA software and all the simplifications used to create the finite-element model. The results of the FEA were only used as guideline for system measurement planning and they are not a true representation of reality. The real stress-strain state of the structure was defined by the experiment. Guidelines were used to define the weakest part of structure (the brake pedal) and to define the measurement range (0-20mm) of the sensors. Based on those data we planned the measurement systems and later defined the measurement uncertainty. Our work showed the importance of this phase, because it proved that the measurements were accurate (0.5% deviation). The test results proved that using FEA the defined critical part is the actual one. Because the differences between the analytical and the experimental results were still relatively large, the described method helped us to supplement the comparative database for similar structures and similar analyses.



nakrčen spoj
compressed joint

varjen spoj
welded joint

Sl. 14. *Primerjava rezultatov meritev in trdnostne analize nakrčene in varjene izvedbe spoja na stopalki zavore*

Fig. 14. *Comparisons of the experimental results and the results of the FEA on compressed and welded joints*

3 SKLEP

Glavni cilj raziskave je vpeljava trdnostnih analiz z metodo končnih elementov v zgodnje faze konstrukcijskega postopka. Rezultati tovrstnih analiz brez ustrezne razlage žal nimajo prave vrednosti. V prispevku je zato predlagana in na stvarnih primerih prikazana metoda za pridobitev primerjalne baze podatkov, na podlagi katere poteka vrednotenje rezultatov numeričnih izračunov. Glavna značilnost omenjene metode je ugotoviti ujemanje rezultatov preračuna z metodo končnih elementov in rezultatov eksperimentalne analize, s čimer se dokaže pravilnost v numeričnem modelu narejenih predpostavk in poenostavitev. Prednost numeričnih analiz, kakor je npr. analiza z metodo končnih elementov, je velika stopnja prilagodljivosti, saj tovrstne analize omogočajo izračun napetostno-deformacijskih in drugih stanj izdelka pri različnih vrednostih konstrukcijskih parametrov brez izdelave fizičnih prototipov, če so na voljo le ustrezni trirazsežni računalniški modeli.

3 CONCLUSION

The objective of the study was to introduce structural analyses based on the finite-element method in the early phases of the design process. Unfortunately, the results of such analyses without a proper interpretation are of almost no use. Therefore, in this article we suggest a method for acquiring the reference database, which serves for the validation of the FEA results. The main characteristic of this method is to find out the consistency of the results computed on the basis of the FEM model with the experimental analyses, which proves the correctness of the assumptions concerning the static scheme of the mechanical structure. The advantages of the FEM lie in its great flexibility, which means that many design parameters can be changed to predict how they can influence the mechanical behaviour of the product without prototyping new models, once the 3D CAD files are available.

Če povzamemo, numerične in eksperimentalne analize imajo pomembno vlogo pri konstruiranju zanesljivih izdelkov. Prve so uporabne za vrednotenje rešitev v zgodnjih fazah konstrukcijskega postopka, ko se ukvarjamo z izbiro materialnih lastnosti, izmer posameznih komponent, strukturo, obliko dotikalnih površin itn. Eksperimentalne analize se v tem primeru uporabljajo le za potrditev ustreznosti končnega fizičnega prototipa, pri katerem se izvaja testiranje oblike, materiala in tehnološkega postopka.

In conclusion, both computational and experimental methods play an important role in designing reliable products. The former is useful in the evaluation of the initial designing phase, where some parameters dealing with material properties, dimensions of components, structures and the shapes of contacting surfaces have to be chosen. The latter finds its proper application in the validation phase where a final prototype, which includes shape, material and technological process, has to be tested.

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Naslov avtorjev: Tomaž Bučar
Miha Janežič
Primož Pangeršič
prof.dr. Matija Fajdiga
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
tomaz.bucar@fs.uni-lj.si
miha.janezic@fs.uni-lj.si
primoz.pangersic@fs.uni-lj.si
matija.fajdiga@fs.uni-lj.si

Authors' Address: Tomaž Bučar
Miha Janežič
Primož Pangeršič
Prof.Dr. Matija Fajdiga
University of Ljubljana
Faculty of Mechanical Eng.
Aškerčeva 6
SI-1000, Ljubljana, Slovenia
tomaz.bucar@fs.uni-lj.si
miha.janezic@fs.uni-lj.si
primoz.pangersic@fs.uni-lj.si
matija.fajdiga@fs.uni-lj.si

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